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## A Multidisciplinary Approach

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# Foreword

Many of the buildings in 2050 are the ones that exist today; so refurbishment is vitally important to understand how they can continually adapt to change and retain an effective sustainability profile. The focus here is on energy performance and the steps necessary to ensure the actual energy performance is as designed for.

The book explains how to tackle the challenges of building refurbishment towards nearly zero energy. A central theme throughout is the importance of taking a multi-disciplinary approach not only across disciplines but the need for consultants, contractors and facilities managers to share a unified view. Energy covers a wide range of considerations during various phases of a project whether it be design, management or operation.

Choice of materials as well as systems determine the energy profile for the building in respect of embodied and operational energy. However, a low carbon building has to also satisfy the human needs because if it does not, the whole resource is wasted. Sustainability drivers are aimed to improve the quality of life in terms of health and well-being with minimum resources.

Poor facilities management and occupancy behaviour can make any low energy design ineffective. So it is important that the users understand how the building works. Controls need to be user friendly. Facilities managers need to carry out post-occupancy evaluations continually to diagnose weaknesses. Feedback can be used with self-adapting algorithms to ensure a continual good performance.

Experience from research, the Energy Performance of Buildings Directive as well as case studies provide the evidence for successful energy retrofitting and argued thoroughly by a distinguished team of international authors.

In the next few years, all buildings have to follow the regulatory pressures and become low carbon or net zero energy. This book is welcome at this time and sets the scene for professionals whether practitioners or researchers to learn more about how we can make whether old or new buildings more efficient and effective in terms of energy performance.

Derek Clements-Croome University of Reading

# Contents

# Introduction

**Fernando Pacheco Torgal**

**Abstract** This chapter starts with an overview on $CO_2$ emissions and climate change addressing key investigations and important related events. The situation of the European Union concerning energy efficiency is described. A short analysis of the nearly zero-energy building (NZEB) concept is presented. A book outline is also presented.

## 1 $CO_2$ Emissions and Climate Change

Four decades ago several investigators used a computer model based on the fixed-stock paradigm to study the interactions between population, food production, industrial production, pollution and the consumption of non-renewable resources. As a result, they predicted that during the twenty-first century the Earth's capacity would be exhausted resulting in the collapse of human civilization as we know it (Meadows et al. 1972).

Two decades after that an update of this study was published showing that some limits had already been crossed (Meadows et al. 1992).

Climate change is one of the most important environmental problems faced by the Planet Earth (IPCC 2007; Schellnhuber 2008).

This is due to the increase of carbon dioxide ($CO_{2eq}$) in the atmosphere for which the built environment is a significant contributor. In the early eighteenth century, the concentration level of atmospheric $CO_{2eq}$ was 280 parts per million (ppm); at present, it is already 450 ppm (Fig. 1).

Keeping the current level of emissions (which is unlikely given the high economic growth of less developed countries with consequent increases in emission rates)

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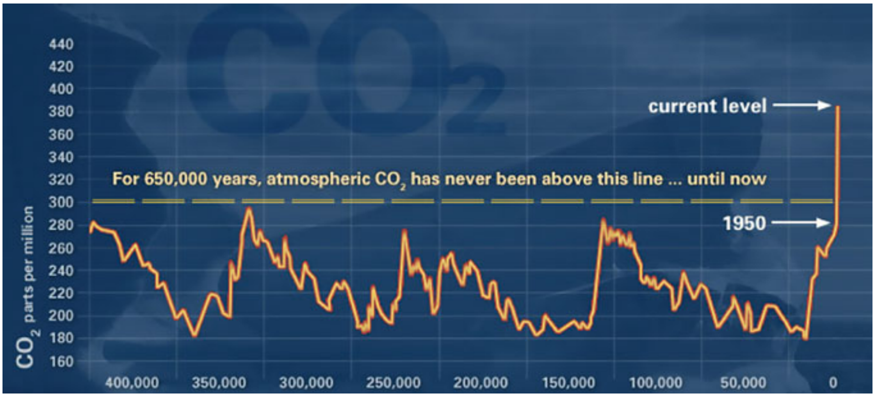

**Fig. 1** $CO_2$ (ppm) trend over years (VijayaVenkataRaman et al. 2012)

will imply a dramatic increase in $CO_{2eq}$ concentration to as much as 731 ppm in the year 2130 leading to a 3.7 °C global warming above pre-industrial temperatures (Valero et al. 2011).

Global warming will lead to a rise in the sea level caused by thermal expansion of the water. When the sea level rises above 0.40 m, it will submerge 11 % of the area of Bangladesh, and as a result, this fact will lead to almost 10 million homeless (IPCC 2007).

Another consequence of global warming is the occurrence of increasingly extreme atmospheric events. Global warming may also be responsible for the thawing of the permafrost (permanently frozen ground), where approximately $1 \times 10^6$ million tons (1,000 $GtCO_2eq$) is still retained. This astonishing figure is equivalent to the current worldwide production (34 $GtCO_2eq$) during 30 years.

It is important to mention the probable meltdown of the world economy associated with climate change. According to Stern (2007) if we act now, the cost of all the services and products to tackle climate change will be 1 % of the GDP; otherwise, an economic depression of about 20 % GDP may take place.

Increasing atmospheric carbon dioxide levels is also responsible for ocean acidification (Hofmann and Schellnhuber 2010; Harrould-Kolieb and Herr 2012). This will lead to severe negative consequences in coral reefs putting habitats of high economic value at risk.

The coral reefs habitats represent fish resources that feed more than 1,000 million people and have an economic value estimated at 20,000 million euro (Bourne 2008; Anthony et al. 2008).

In this context is important also to bear in mind the value of services provided free of charge by Nature that reaches almost 33 billion ($10^{12}$) dollars/year (Constanza et al. 1998). As a comparison, the global GDP in the same period was of 18 billion ($10^{12}$) dollars per year, roughly half the value of the services and products provided by Nature.

Even if all the greenhouse gas emissions suddenly ceased, the inertia associated with climatic systems would mean that the rise in the sea level, ocean acidification and extreme atmospheric events will continue at least in the next one hundred years.

The majority of $CO_2$ emissions come from burning fossil fuels for energy production. Oil accounts for 32.8 %, coal for 27.2 % and natural gas for 20.9 % (Hook and Tang 2013).

In 2009, China became the largest energy consumer (IEA 2010), and Chinese coal plants are responsible for 80 % of electricity generation (Shealy and Dorian 2009). Still is fair to say that although China is the responsible for the major $CO_2$ emissions in the world (9,700 million tonnes), it has just a 7.2 tonnes per capita. While for instance Canada, the USA and Australia have, respectively, 16.2, 17.3 and 19 tonnes per capita (JCR 2012).

The 2009 Copenhagen Summit recognized the scientific view "*that the increase in global temperature should be below* 2 degrees Celsius" despite growing views that this might be too high. However, a comprehensive agreement that could have a significant impact on reducing carbon emissions was not reached (Dimitrov 2010; New et al. 2011).

Instead different countries decide to adopt different targets. The European Union agreed to reduce its overall emissions by 20 % in the year 2020 in the reference to the year 1990. The USA agreed to reduce its overall emissions by 17 % in 2010, in the reference to the year 2005. China and India did not accept a reduction in their total emissions, but rather a reduction in their carbon intensity (carbon/unit of GDP) relative to 2005 levels until 2020, between 40 and 45 % for China and between 20 and 25 % for India.

Goldenberg and Prado (2010) reviewed the above-cited goals and reported that they simply follow the standard "*business as usual*" for the period 1990–2007, which is clearly insufficient to achieve significant reductions by the year 2020. This view is confirmed by other authors (Peterson et al. 2011).

The World Business Council for Sustainable Development estimates that by 2050 a fourfold–tenfold increase in efficiency will be needed (COM (2011c) 571). According to the World Energy Outlook 2012, energy-efficiency improvements show the greatest potential of any single strategy to abate global GHG emissions from the energy sector (IEA 2012). However, worldwide investment in energy-efficiency projects is very scarce. A recent report shows that energy efficiency amounts to a very small portion of the US$343–385 billion flowing into climate finance each year (Ryan et al. 2012).

## 2 European Union Situation

Europe has the world's highest net imports of resources per person, and its open economy relies heavily on imported raw materials and energy.

The building sector is the largest energy user responsible for about 40 % of the EU's total final energy consumption (Lechtenbohmer and Schuring 2011.

Energy-related emissions account for almost 80 % of the EU's total greenhouse gas emissions (COM (2010) 639).

To address smart, sustainable and inclusive growth until 2020 and beyond the European Union has been on the lead of seven paramount flagship initiatives. One of such "A resource-efficient Europe—Flagship initiative under the Europe 2020 Strategy" highlights the importance of increasing resource efficiency as key to bring major economic opportunities, improve productivity, drive down costs and boost competitiveness.

To tackle climate change, EU has agreed that by 2020 greenhouse gas, emissions have to be reduce by 20 % compared with the 1990 emissions level as well as to increase by 20 % the energy consumption from renewable resources (COM (2008) 30).

Between 2010 and 2020, energy investments in the order of € 1 trillion will be needed, both to diversify existing resources and replace equipment and to cater for challenging and changing energy requirements (COM (2010) 639).

According to the Energy Road Map 2050 (COM (2011a) 885/2), higher energy efficiency in new and existing buildings is key for the transformation of the EU's energy system.

Of the several areas related to the built environment energy efficiency and renewable energies are the only ones that will be funded under the HORIZON 2020 EU Framework Program (COM (2011b) 808 final).

Energy efficiency is the most cost-effective way to reduce emissions, improve competitiveness, as well as create employment (COM (2010) 639).

According to Lund and Hvelplund (2012), the implementation of a district heating and individual heat pump scenario in Denmark over a period of 10 years will create 7–8000 jobs.

A recent report shows that the global market for energy-efficient building will go from 68 billion dollars in 2011 surpassing 100 billion dollars by 2017 (Pike Research 2011.

Unfortunately, as the same EU Communication recognizes that "*The quality of National Energy Efficiency Action Plans, developed by Member States since 2008, is disappointing, leaving vast potential untapped*". This means that technologies and methods to improve energy efficiency (Clements-Croome 2011) are therefore required.

Another important aspect related to energy efficiency concerns indoor air quality. Many buildings currently suffer from problems related to excessive moisture with mould formation, or present low humidity levels, giving rise to respiratory diseases. Moreover, since 1930, more than 100,000 new chemical compounds have been developed, and insufficient information exists for health assessments of 95 % of chemicals that are used to a significant extent in construction products (Pacheco Torgal et al. 2012).

Increasing ventilation rate reduces the concentration of indoor air pollutants (except for of buildings in urban areas with a high level of air pollutants); however, this also increases energy consumption.

Some investigations (Fisk et al. 2011) show that improving indoor environmental quality in the stock of US office buildings would generate a potential annual economic benefit of approximately $20 billion. Unfortunately, most occupants are unaware of such health risks and prefer to reduce ventilation rates. It is then no surprise to find out that ventilation measurement across Europe shows that ventilation is in practice often poor, resulting in reduced ventilation rates (Dimitroulopoulou 2012).

A recent study (Galvin 2013) carried out in the city of Aachen, Germany, shows an interesting case of energy-inefficient manual ventilation, which means that energy efficiency is most influenced by occupants' behaviour.

In the context of energy efficiency, it is preferable to reduce the toxicity of building materials, and avoiding the use of materials that release pollutants. EU has recently passed regulations that will make mandatory the environmental assessment of construction and building materials.

On 9 March 2011, the European Union approved Regulation (EU) 305/2011, the Construction Products Regulation (CPR), that replaced Directive 89/106/EEC, already amended by Directive 1993/68/EEC, known as the Construction Products Directive (CPD). The new CPR was published in the *Official Journal of the European Union* (OJEU) on 4 April 2011. In accordance with Article 68, the CPR entered into force on 24 April, the 20th day following its publication in the OJEU. This includes Articles 1 and 2, 29–35, 39–55, 64, 67 and 68, and Annex IV. However, Articles 3–28, 36–38, 56–63, 65 and 66, as well as Annexes I, II, III and V, shall apply from 1 July 2013.

When comparing the basic requirements of the CPR and CPD, one can see that the CPR has a new requirement, no. 7 (Sustainable use of natural resources), and also that no. 3 (Hygiene, health and the environment) and no. 4 (Safety and accessibility in use) have been refined. This means that a new and more environment-friendly approach will determine the manufacture of construction products. A crucial aspect of the new regulation relates to the information regarding hazardous substances.

This means that commercialization of construction materials in Europe beyond 1 July 2013, will make their environmental assessment mandatory, thus facilitating choosing low-toxicity materials.

## 3 Nearly Zero-Energy Buildings

In the last decade, several high-energy performance building (HEPB) concepts have been proposed, from low-energy building through passive building and zero-energy building to positive energy building and even autonomous building (Thiers and Peuportier 2012). For the Building Technologies Program of the US Department of Energy (DOE), the strategic goal is to achieve "*marketable zero energy homes in 2020 and commercial zero energy buildings in 2025*". However, commercial definitions maybe tainted by biased view, allowing for energy-inefficient buildings to achieve the status of zero energy thanks to oversized PV systems (Sartori 2012).

Rules and definitions for near zero-energy buildings or even zero-energy buildings are still subject to discussion at the international level (Dall'O et al. 2013).

Some authors (Adhikari et al. 2012) use ZEB as "net zero-energy buildings" and NZEB as "nearly zero-energy buildings". "Net" refers to a balance between energy taken from and supplied back to the energy grids over a period of time. Therefore, net ZEB refers to buildings with a zero balance as well that the NZEB concept applies to buildings with a negative balance.

The European Energy Performance of Buildings Directive 2002/91/EC (EPBD) has been recast in the form of the 2010/31/EU by the European Parliament on 19 May 2010.

One of the new aspects of the EPBD is the introduction of the concept of NZEB. Of all the new aspects set out by the new directive, this one seems to be the one with most difficult enforcement member states. The article 9 of the European Directive establishes that, by the 31 December 2020, all new constructions have to be NZEBs; for public buildings, the deadline is even sooner—the end of 2018.

Article 2 of the EPBD recast states that "'*NZEB*' *means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*". The directive does not specify what is the concept of "low amount of energy". The EPBD is also dubious on the meaning of "nearby" renewable resources. This broad definition could encompass 1 km or even 10 km and even any national energy grid in countries where the majority of the energy supply comes from renewable resources.

Since in the preliminary drafts, the directive was referring to "net zero-energy buildings", some authors (Adhikari et al. 2012) believe that the global economic crisis of recent years has prompted lawmakers to scale back targets due to the fact that evidently that a ZEB (net zero) would be too expensive.

Although each EU member state need to transpose into national laws, the directive's provisions to account to its specific situation (climate conditions, economic aspects, building practices, etc.) so far only three countries had already made that transposition (Denmark, Sweden and Ireland). Therefore, in 21 September 2012, infringement procedures were started on 21 September 2012, against the 24 member states that did not declare full transposition.

This is the best proof of the difficulties felt by the different EU members in the transposition of such "unspecified" and "dubious" regulation.

Another novelty of the EPBD recast that can complicate transposition into national laws is the cost-optimality requirement. According to the Article 4 (1),

> Member States shall take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels. The energy performance shall be calculated in accordance with the methodology referred to in Article 3. Cost-optimal levels shall be calculated in accordance with the comparative methodology framework referred to in Article 5 once the framework is in place.

Cost-optimal level is defined as "*the energy performance level which leads to the lowest cost during the estimated economic lifecycle*". In order to calculate the cost-optimal level of minimum energy performance, member states are required to create a set of reference buildings, at national or regional level, to be used in the calculations. Recent investigations are helpful concerning this subject (Corgnati et al. 2013; Hamdy et al. 2013; Kurnitski et al. 2011).

To complicate things, a little bit more let us considered for instance the impact of climate change itself on the energy requirements of the buildings. Crawley (2008) mentioned that "*the impact of climate change will result in a reduction in building energy use of about 10 % for buildings in cold climates, an increase of energy use of up to 20 % for buildings in the tropics, and a shift from heating energy to cooling energy for buildings in temperate climates*". Depending on the climate zone, cooling loads are likely to increase by 50 to over 90 % until the end of the century (Roetzel and Tsangrassoulis 2012). In addition to increased mean temperatures, there are likely to be more frequent heat waves like for instance the 2003 European heat wave that claimed the lives of over 35,000 people (Porritt et al. 2012). This means that current climate conditions of each member state can no longer be viewed as static which will complicate even more the transposition of EPBD recast for national laws. So, Kwok and Rajkovich (2010) suggested mitigation of GHGs as well as adaptation to climate change should be added into building energy codes and comfort standards. Recently, Ren et al. (2011) analysed climate change adaptation measures for buildings and their cost-effectiveness.

Be there as it may, new buildings have limited impacts on overall energy reduction as they represent just a tiny fraction of the existent building stock. Popescu et al. (2012) mentioned that the building stock renews slowly, by only 1–2 % per year. Existing buildings constitute, therefore, the greatest opportunity for energy-efficiency improvements (Xing et al. 2011).

Besides, new homes use four to eight times more resources than an equivalent refurbishment (Power 2008), which constitutes an extra argument in favour of building refurbishment. However, Silva et al. (2013) mentioned that most of the current buildings regulations present simplified methodologies that do not allow the correct assessment of the buildings retrofit interventions.

The words refurbishment, retrofit and renovation are generally used interchangeably in the literature and by organizations involved in reducing the energy use and carbon emissions of the existing housing stock (Fawcet 2011).

Some authors (Torcellini et al. 2006; Jensen et al. 2009) mention that energy building refurbishment is a two-step approach, i.e. application of energy efficiency measures to a cost-optimal level and suppression of the remaining energy needs through on-site renewable energy production. More recently, Dall'O et al. (2013) defends a 3-step sequence to achieve a ZEB: retrofitting building materials to reduce energy demand, installing energy-efficient equipment, and finally, installing microgeneration technologies.

And if the concept NZEB is not easy to apply to new buildings, it will be much more difficult to apply in existent buildings.

Besides, energy-efficiency refurbishment has a sociological dimension that must be also addressed (Banfi et al. 2008).

The decision process is influenced by several factors like for instance the household size, household income, age composition of the household members and members' education levels each affect retrofit decisions (Gamtessa 2013).

Stieß and Dunkelberg (2013) mention that reaching homeowners not yet aware of the benefits of such energy-efficiency improvements constitute a major challenge that requires the "the implementation of coordinated campaigns at the local level with participating energy agencies, consultants, tradesmen, the local authorities, and the local press".

It is truth that the EPBD recast does not cover existent buildings; however, the Energy Efficiency Directive (2012/27/EU) approved by the European Parliament on 25 October 2012, that each member states will have to transpose into national laws until 5 June 2014, addresses this types of buildings (Articles 4 and 5).

According to Article 4, member states will have to define "*establish a long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings, both public and private. This strategy shall encompass*:

(a) *an overview of the national building stock based, as appropriate, on statistical sampling*;
(b) *identification of cost-effective approaches to renovations relevant to the building type and climatic zone*;
(c) *policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations*;
(d) *a forward-looking perspective to guide investment decisions of individuals, the construction industry and financial institutions*;
(e) *an evidence-based estimate of expected energy savings and wider benefits*.

*A first version of the strategy shall be published by 30 April 2014 and updated every three years thereafter and submitted to the Commission as part of the National Energy Efficiency Action Plans*".

As to Article 5 content, it requires that "*each Member State shall ensure that, as from 1 January 2014, 3 % of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year to meet at least the minimum energy performance requirements*".

Many books have been written about building refurbishment and some recent ones even contain interesting insights on "sustainable" refurbishment. However, some of those books are not focused on energy efficiency, several others lack any content on toxicity aspects or nanotech high-performance building materials, but most of them have absolutely nothing on complex decision support systems. This book thus provides essential reading to everyone that deals with energy-efficiency building refurbishment.

## 4 Book Outline

The Deutsch policy framework related to the energetic refurbishment of buildings is the subject of "Policy Instruments: The Case of Germany". It includes relevant strategies and concepts as well as governmental targets. The specific cases of the Deutsch building code "Energy Saving Ordinance" and the "Renewable Energy Heat Law" are analysed. This chapter also includes an overview on financial incentive programmes related to energy-related refurbishments. Important market instruments are described.

"Built Environment Life Cycle Process and Climate Change" deals with the influence of climate change on the built environment. It presents a model of the built environment life cycle process for climate change mitigation and adaptation.

"Benefits of Refurbishment" describes some of the benefits associated with refurbishment actions.

It summarizes the results of the energy and environmental assessment of a set of retrofit actions implemented in the framework of the EU Project (Bringing Retrofit Innovation to Application in Public Buildings).

The modelling of the occupant behaviour impact on the buildings energy prediction is the subject of "Modelling the Occupant Behaviour Impact on Buildings Energy Prediction". It suggests a "model for occupant behaviour within the building in relation to energy consumption, along with a building energy consumption model, is proposed based on stochastic Markov models".

"Uncertainty in Refurbishment Investment" identifies and classifies uncertainties that characterize and make refurbishment investment a highly uncertain endeavour over the project life cycle. Recommendations about managing these uncertainties during the project evaluation phase are provided. This chapter includes "a new approach to project evaluation based on the option pricing theory is presented along with a case study example".

"Energy Performance of Buildings: A Comparison of Standard Assessment Methods" addresses the uncertainties arriving from the use of different energy performance assessment methods.

"Life Cycle Energy Performance Evaluation" presents the "concepts and methodology to evaluate life cycle energy performance of buildings, including embodied energy of the different components, systems and processes". The chapter introduces the concept of "net energy ratio" to the built environment, presenting it as an indicator to support optimization of building refurbishment strategies from a life cycle energy perspective. A practical application for the refurbishment of an Irish typical house is also shown.

"Refurbishment Scenario to Shift Nearly Net ZEBs Toward Net ZEB Target: An Italian Case Study" addresses an Italian case study concerning several refurbishment scenarios to shift nearly net zero-energy building towards net zero target. The refurbishment strategy is based on a LCA, in which the LCI model is carried out by using the SimaPro software. Energy payback time and the emission payback time are assessed inn order to compare the different scenarios.

"A Multiple-Case Study of Passive House Retrofits of School Buildings in Austria" covers the refurbishment of four Austrian schools towards the energy-efficiency level of the Passivhaus standard.

"State of the Art on Retrofit Strategies Selection Using Multi-Objective Optimization and Genetic Algorithms" reviews "the research and development in the decision support processes in building retrofit. The advantages and drawbacks of the various methods in each category are also discussed".

"Multiple-Criteria Analysis of Life Cycle of Energy-Efficient Built Environment" describes a life cycle of energy-efficient built environment model as well as two systems (Energy Efficient House DSS for Cooling and Decision support system for assessment of energy generation technologies).

"Toxicity Issues: Indoor Air Quality" reviews "main indoor pollutants and their sources. Considering existing World Health Organization (WHO) guidelines for IAQ and toxicity, the pollutants considered here are: asbestos, biological pollutants, benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, particulate matter, polycyclic aromatic hydrocarbons, radon, tetrachloroethylene, and trichloroethylene".

"Toxicity Issues: Radon" is related to radon as a source of indoor air contamination. It shows that post-construction remediation like soil depressurisation systems seems to be more cost-effective than the use of protection measures installed during construction like radon-barrier membranes which have a significant failure rate. Since radon concentration is very dependent on the air change rate (ACH), it is important to maintain adequate air ventilation. However, in some situations, the cost of additional heating to eliminate the heat losses would exceed the total costs of remediation by soil ventilation as much as eightfold. This chapter also shows that there are optimum temperature and relative humidity which minimize radon levels.

"Ventilation: Thermal Efficiency and Health Aspects" focus "on the performance of ventilation, both in reducing adverse effects of indoor air on building occupants and in reducing the energy required for this". It explores the specific merits and limitations of ventilation as a strategy to renew air. It discusses the different ventilation concepts and their performance focusing on "technologies that allow to reduce ventilation heat loss without increasing the exposure of occupants to airborne pollutants, more specifically air to air heat exchangers, exhaust air heat pumps and demand controlled ventilation".

"Insulation Materials Made with Vegetable Fibres" provides a guide to the fundamentals and latest developments in building insulation technology based on vegetable fibre materials.

"High-Performance Insulation Materials" addresses two classes of superinsulation technology: vacuum insulation panels (VIP) and microporous thermal insulations. The chapter discusses he special features of these thermal insulations and presents best-practice examples. The chapter also includes an overview on future trends in R&D for thermal insulation.

"Thermal Energy Storage Technologies" gives a general overview on thermal energy storage (TES) technologies.

"Phase-Change Materials Use in Nearly Zero Energy Building Refurbishment" displays several examples concerning the use of PCMs for new buildings, highlighting the more appropriate options for refurbishment.

Application of "highly energy-efficient windows and skylights with silica nanogel as a strategy in the building refurbishment" is the subject of "Nanogel Windows".

This new window "seems to have the largest potential for improving the thermal performance and daylight in fenestration industry, because of very low conductivity and density and a good optical transparency". The chapter includes a state-of-the-art review of nanogel windows in building applications. It also includes a discussion on the proprieties of nanogel glazing in terms of thermal, lighting and acoustic insulation solutions. The "potential of the nanogel windows for energy saving in order to achieve a nearly zero-energy building is described thanks to the results of a case study".

"Switchable Glazing Technology: Electrochromic Fenestration for Energy-Efficient Buildings" outlines the basics of electrochromic glazing technology. It "allow the transmittance of visible light and solar energy to be changed reversibly and persistently by the use of an electrical signal", which is an important feature in energy-efficiency technologies. The chapter discuss device designs and component materials. Several practical electrochromic glazing designs are introduced with focus on a foil-type construction applicable as a lamination material between glass panes.

The "global market potential of solar thermal, photovoltaic (PV) and combined photovoltaic/thermal (PV/T) technologies in current time and near future" are the subject of "Solar Photovoltaic/Thermal Technologies and Their Application in Building Retrofitting". The chapter covers "major features, current status, research focuses and existing difficulties/barriers related to the various types of PV/T". It describes "research methods, including theoretical analyses and computer simulation, experimental and combined experimental/theoretical investigation, demonstration and feasibility study, as well as economic and environmental analyses, applied into the PV/T technology were individually discussed, and the achievement and problems remaining in each research method category".

## References

Adhikari R, Aste N, Del Pero C, Manfren M (2012) Net zero energy buildings: expense or investment? Energ Procedia 14:1331–1336

Anthony K, Kline D, Diaz-Pulido G, Dove S, Hoegh-Guldberg O (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. Proc Natl Acad Sc USA 105:17442–17446

Banfi S, Farsi M, Filippini M, Jakob M (2008) Willingness to pay for energy-saving measures in residential buildings. Energy Econ 30:503–516

Bourne J (2008) Temperature has already changed. National Geographic Magazine, Washington

Clements-Croome D (2011) Sustainable intelligent buildings for people: a review. Intell Build Int 3:67–86

Corgnati S, Fabrizio E, Filippi M, Monetti V (2013) Reference buildings for cost optimal analysis: method of definition and application. Appl Energy 102:983–993

Costanza R, D'arge R, De Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill R, Paruelo J, Raskin R, Sutton P, Van Den Belt M (1998) The value of the world's ecosystem services and natural capital. Nature 387:253–260

COM (2011) 808 final. Horizon 2020—the framework programme for research and innovation

COM (2011) 885/2. Energy Roadmap 2050

COM (2011) 571 final. Roadmap to a resource efficient Europe

COM (2010) 639 final. Energy 2020 a strategy for competitive, sustainable and secure energy

COM European Commission (2008) Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: 20 20 by 2020—Europe's climate change opportunity

Crawley DB (2008) Estimating the impacts of climate change and urbanization on building performance. J Build Perform Simul 1:91–115

Dall'O' G, Bruni E, Sarto L (2013) An Italian pilot project for zero energy buildings: towards a quality-driven approach. Renew Energy 50:840–846

Dimitroulopoulou C (2012) Ventilation in european dwellings: a review. Build Environ 47:109–125

Dimitrov R (2010) Inside UN climate change negotiations: the Copenhagen conference. Rev Policy Res 27(6):795–821

Directive 2012/27/EU of 25 October 2012 on energy efficiency

Goldenberg J, Prado L (2010) The "decarbonization" of the world's energy matrix. Energy 38: 3274-3276. doi: 10.1016/j.enpol.2010.03.040

European Union. Directive 2010/31/EU of the European Parliament and of the Council of May 19th, 2010 on the energy performance of buildings (recast). Official Journal of the European Union; 18 June, 2010

Fawcet T (2011) Home time: an exploration of the time dimensions of eco-renovation of housing. In: Proceedings of the energy and people: futures, complexity and challenges conference, Oxford

Fisk WJ, Black D, Brunner G (2011) Benefits and costs of improved IEQ in U.S. offices. Indoor Air 21(5):357–367

Galvin R (2013) Impediments to energy-efficient ventilation of german dwellings: a case study in Aachen. Energy Build 56:32–40

Gamtessa S (2013) An explanation of residential energy-efficiency retrofit behavior in Canada. Energy Build 57:155–164

Hamdy M, Hasan A, Siren K (2013) A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy Build 56:189–203

Harrould-Kolieb ER, Herr D (2012) Ocean acidification and climate change: synergies and challenges of addressing both under the UNFCCC. Climate Policy 12(3):378–389

Hofmann M, Schellnhuber HJ (2010) Ocean acidification: s millennial challenge. Energy Environ Sci 3(12):1883–1896

Hook M, Tang X (2013) Depletion of fossil fuels and anthropogenic climate change—a review. Energy Policy 52:797–809

IEA (2012) World energy outlook 2012. OECD/IEA, Paris

IEA (2010) World energy outlook 2010. OECD/IEA, Paris

IPCC (Intergovernmental Panel on Climate Change) (2007) Climate change 2007: synthesis report. IPCC, Geneva

JCR. Trends in global CO2 emissions. 2012 Report. http://edgar.jrc.ec.europa.eu/CO2REPORT2012.pdf

Jensen O, Wittchen K, Thomsen K (2009) EuroACE. towards very low energy buildings. Danish Building Research Institute SBi, Hørsholm, p 03

Kurnitski J, Saari A, Kalamees T, Vuolled M, Niemelä J, Tark T (2011) Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation. Energy Build 43:3279–3288

Kwok A, Rajkovich N (2010) Addressing climate change in comfort standards. Build Environ 45:18–22

Lechtenbohmer S, Schuring A (2011) The potential for large-scale savings from insulating residential buildings in the EU. Energ Effi 4:257–270

Pike Research (2011) Energy efficient buildings: global outlook

Lund H, Hvelplund F (2012) The economic crisis and sustainable development: the design of job creation strategies by use of concrete institutional economics. Energy 43:192–200

Meadows DL, Meadows DH, Behrene JRW (1972) The limits to growth. MIT Press, Cambridge

Meadows DL, Meadows DH, Randers J (1992) Beyond the limits: global collapse or a sustainable future. Earthscan, London

New M, Liverman D, Schroder H, Anderson K (2011) Four degrees and beyond: The potential for a global temperature increase of four degrees and its implications. Philos Trans R Soc A: Math Phys Eng Sci 369(1934):9–19

Pacheco Torgal F, Jalali S, Fucic A (2012) Toxicity of building materials. Woodhead Publishing Limited, Cambridge

Peterson EB, Schleich J, Duscha V (2011) Environmental and economic effects of the copenhagen pledges and more ambitious emission reduction targets. Energy Policy 39(6):3697–3708

Popescu D, Bienert S, Schutzenhofer C, Boazu R (2012) Impact of energy efficiency measures on the economic value of buildings. Appl Energy 89:454–463

Porritt S, Cropper P, Shao L, Goodier C (2012) Ranking of interventions to reduce dwelling overheating during heat waves. Energy Build 55:16–27

Power A (2008) Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? Energy Policy 36: 4487–4501.doi:10.1016/j.enpol.2008.09.022

Ren Z, Chen Z, Wang X (2011) Climate change adaptation pathways for Australian residential buildings. Build Environ 46:2398–2412

Ryan L, Selmet N, Aasrud A (2012) Plugging the energy efficiency gap with climate finance

Roetzel A, Tsangrassoulis A (2012) Impact of climate change on comfort and energy performance in offices. Build Environ 57:349–361

Sartori I, Napolitano A, and Voss K (2012) Net zero energy buildings: A consistent definition framework. Energy and Buildings 48: 220–232.doi: 10.1016/j.enbuild.2012.01.032

Shealy M, Dorian J (2009) Growing Chinese coal use: dramatic resource and environmental implications. Energy Policy 38:2116–2122

Schellnhuber H (2008) Global warming. Stop worrying, start panicking? Proc Natl Acad Sci USA 105:14239–14240

Silva P, Almeida M, Bragança L, Mesquita V (2013) Development of prefabricated retrofit module towards nearly zero energy buildings. Energy Build 56:115–125

Stern NH, Treasury GB (2007) The economics of climate change: the stern review. Cambridge University Press, Cambridge

Stieß I, Dunkelberg E (2013) Objectives, barriers and occasions for energy efficient refurbishment by private homeowners. J Clean Prod (in press)

Thiers S, Peuportier B (2012) Energy and environmental assessment of two high energy performance residential buildings. Build Environ 51:276–284

Torcellini P, Pless S, Deru M, Crawley D (2006) Zero energy buildings: a critical look at the definition. In: Conference paper NREL/CP-550-39833, National Renewable Energy Laboratory

Valero A, Agudelo A, Valero A (2011) The crepuscular planet. A model for the exhausted atmosphere and hydrosphere. Energy 36:3745–3753

Vijayavenkataraman S, Iniyan S, Goic R (2012) A review of climate change, mitigation and adaptation. Renew Sustain Energy Rev 16(1):878–897

Xing Y, Hewitt N, Griffiths P (2011) Zero carbon buildings refurbishment—a hierarchical pathway. Renew Sustain Energy Rev 15:3229–3236. doi:doi.org/10.1016/j.rser.2011.04.020

# Policy Instruments: The Case of Germany

**Sven Schimschar**

**Abstract** Buildings in Germany are responsible for more than 40 % of the total final energy consumption. The government already acknowledged the importance of the building sector in the late 1970s and thus started to develop a comprehensive policy framework. On an international level, Germany is especially known for its successful KfW incentive programmes related to energetic refurbishments of buildings that achieved significant reductions in terms of energy and emissions. But these programmes are just one piece of the entire framework. Thus, this chapter describes all parts of the policy framework that relate to the energetic refurbishment of buildings. It starts by describing the current status of a national nearly zero-energy building definition before presenting all relevant strategies and concepts including the targets of the government. After that, the regulatory policies, including the national building code the 'Energy Saving Ordinance' and the 'Renewable Energy Heat Law', are introduced before having a detailed look at the financial incentive programmes related to energy-related refurbishments and finally describing the most important market instruments.

## 1 Introduction

Buildings are responsible for about 44 % of the German energy consumption, of which space heating and domestic hot water represent the most significant share of about 75 % (BMWI 2011b). The most crucial issue is the energy inefficiency of the existing building stock, of which three quarters were constructed before the first 'Thermal Insulation Ordinance' in 1977. The improvement in the building envelope through energy-related refurbishments, the slow replacement of heating

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systems with more efficient ones and the overall slow refurbishment rate of existing buildings of currently about 1 % annually are the main bottlenecks within the energy efficiency progress of the existing built environment in Germany and Europe in general (Boermans et al. 2012).

For the purpose of reducing the energy consumption and protecting the climate, the Federal Government developed the Energy Concept for an environmentally friendly, secure and affordable energy supply in 2010 (BMWi 2010b).

The energy-related refurbishment of buildings plays an important role in the Energy Concept. It states that:

> […]the energy related renovation of the building stock is the main issue for the modernization of the energy supply and for achieving the climate protection targets (Author's translation).

The main targets of the German government for the building sector are (BMWi 2010b; BMWI 2011a):

- 20 % reduction in the useful space heating demand of the building stock by 2020 and 80 % of the primary energy demand by 2050 compared to 2008 (Schimschar et al. 2013a), with the aim of achieving an almost climate-neutral building stock by 2050;
- Overall savings for the buildings and installation area that amount to 775 PJ in the period 1995–2016;
- Expected savings in the construction sector for the 2008–2016 commitment period amount to 610 PJ;
- These objectives should mainly be achieved by doubling the energy-related refurbishment rate from currently about 1 % to annually 2 % of the entire building stock. To achieve this increase, a refurbishment road map (according to the Energy Efficiency Directive) begins in 2013.

As the actual instruments are not sufficient to achieve the targets, among other things, the Energy Concept stipulates a further development of the 'Energy Saving Ordinance' (EnEV) and the 'Act on the Promotion of Renewable Energies in the Heat Sector' (EEWärmeG). 'These instruments must be updated to achieve renovation targets, to the extent that this is economically feasible' (BMWi 2010b). Accordingly, it will explicitly be examined whether the EEWärmeG can be formulated to be more technology-open for all kinds of renewable energy systems and whether it can be expanded to the existing building stock. With the EnEV 2013/14, it is planned to introduce the level of 'carbon-neutral buildings' for new buildings as from 2020 onwards as the Energy Performance of Buildings Directive (EPBD) (European Parliament and the Council of the European Union 2010) requires that after 31 December 2020, all newly constructed buildings are 'nearly zero-energy buildings'. Federal buildings should act as a role model in the reduction in energy consumption.

In order to assure further development of the renewable energies in the building stock, it was planned to provide additional financial means for the 'Market Incentive Programme for Renewable Energies' (MAP). In addition, an 'Energy

Efficiency Fund' was planned and has finally been established in 2011. Further details of the Energy Concept are the extension of opportunities for contracting in the area of rented residential living space and the support of municipalities in efficiency measures, pilot projects, information and education.

The most important refurbishment and incentive programmes are within the jurisdiction of the Federal Ministry of Transport, Building and Urban Development (BMVBS). The BMVBS additionally plans to create tax incentives for the building sector in order to attract more owner groups for energy-related refurbishments (BMVBS 2011). At the same time, established programs will be further developed and new priorities will be set. Besides individual buildings, old building quarters in the inner city have to also become more energy efficient. For this purpose, a comprehensive construction law amendment has been developed, for example, also facilitating the approval for photovoltaic systems in buildings. Beyond that, new incentives for energy efficiency and energy savings on municipal level will take place, such as the new promotional programme 'Urban energy efficiency rehabilitation'. On 15 November 2011, the programme started with a pilot phase in close collaboration with the communes. The financing resources for this project come from the 'Energy and Climate Fund' (BMVBS 2011; KfW 2011).

Figure 1 shows the development of the final energy consumption in the German building sector since 1990 and until 2020 depending on different refurbishment rates, and Fig. 2 shows the associated $CO_2$ emissions.

No separate subtarget has been set for the greenhouse gas emissions in the building sector. Therefore, the 40 % reduction target specified for all sectors according to the Coalition Agreement 2009 and the Energy Concept 2010 is included in the figure.

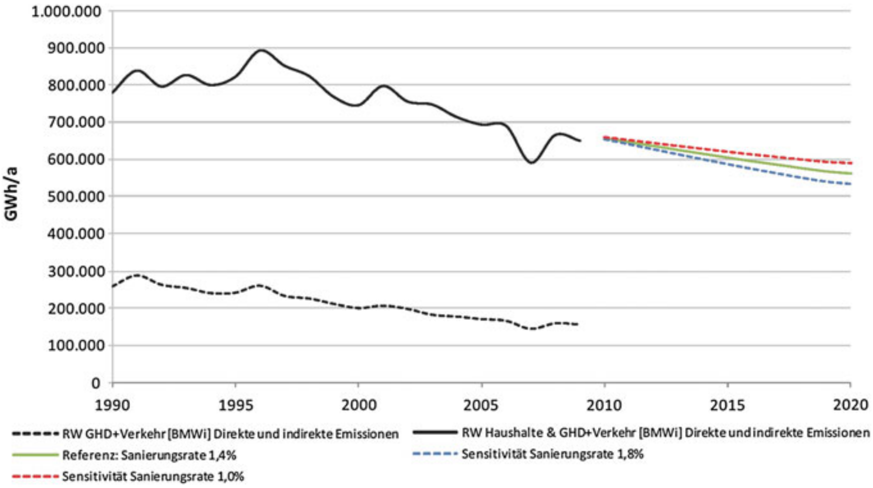

**Fig. 1** Final energy consumption in the German building sector dependent on different renovation rates, years 1990–2020 (Bettgenhäuser et al. 2012)

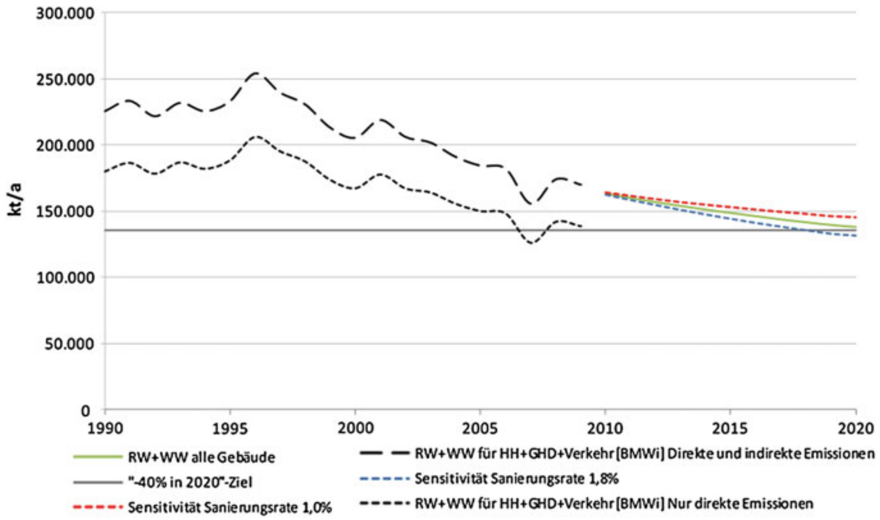

**Fig. 2** $CO_2$ emissions from the German building stock dependent on different renovation rates, years 1990–2020 (Bettgenhäuser et al. 2012)

It becomes obvious, how important the energy-related refurbishment of the building stock is. Figure 2 shows that the emission target of the government will just be reached, if it is possible to at least increase the major energy-related refurbishment rate to a value of about 1.8 % per annum. But even if the topic of energy-related building refurbishments is generally acknowledged as an important issue, currently there still is no source of information which frequently measures the renovation rate in the building stock. However, there are several sources of information, which present very diverse numbers. According to Friedrich et al. (2008), the refurbishment rate was 2.2 % in 2006; according to KfW (2009), it was 2 % in 2009; according to BMWi (2010b), it was 1 % in 2010; according to Discher (2010), it was 0.9–1.3 %; and according to Diefenbach et al. (2010), for existing buildings constructed before 1979, it was 1.28 % in the period 2000–2004, 0.95 % in the period 2005–2008 and 1.12 % in 2009. As can be seen, the presented numbers are all in a range between 0.9 and 2.2 %, and as different approaches and definitions have been used by the respective authors, it cannot clearly been determined which rate is the most reliable. Nevertheless, Friedrich et al. (2008) and Diefenbach et al. (2010) conducted quite comprehensive surveys in their research projects, and thus, these values have a better scientific basis than the values of the other sources although they present the minimum and the maximum value. The main difference is the definition of 'refurbishment'. Friedrich et al. (2008) defined it as complete energy-related refurbishments and Diefenbach et al. (2010) just focused on measures that improve the building shell of buildings. However, when considering all presented estimations, it becomes more realistic that the current major renovation rate is still far below the necessary 1.8 %.

Diefenbach et al. (2010) identified interesting results about the refurbishment characteristics in the German building stock. Accordingly, the refurbishment rates of different building shell components vary significantly. Thus, the building roof, respectively topmost ceiling, is refurbished most frequently (ca. 1.5 %), followed by the façade insulation (ca. 0.8 %) and ground floor, respectively basement ceiling (ca. 0.3 %). No considerable difference between single- and multi-family buildings has been identified.

Diefenbach et al. (2010) analysed that in about 20 % of the single- and two-family buildings and approximately 26 % of the multi-family buildings, the façade has subsequently been insulated. Almost 50 % of the roofs have subsequently been insulated but just about 10 % of the ground floors, respectively basement ceilings. In total, it is estimated that between 25 and 30 % of all building component areas have subsequently been insulated after their construction. As some of the buildings constructed before 1979 have already been insulated partly, Diefenbach et al. (2010) estimate that the share of insulated area in the building stock is about 10 % higher.

## 2 Definition of Nearly Zero-Energy Buildings in Germany

As the overarching topic of this book relates to nearly zero-energy building (nZEB) refurbishments, it is important to know how the standard of nZEB is defined in Germany. As the German government has not yet finally published a definition, this chapter aims to collect and describe all available information in order to give a good overview of the current status.

'For a long time, Germany's development of energy performance requirements for buildings has been accompanied by research and demonstration projects that showed further strengthenings to be technically feasible, which became due to market adaptations some years later also economically feasible. Figure 3 shows the minimum energy performance requirements (in 6 steps) as the upper line, the pilot projects (solar houses, low-energy buildings, three-litre houses, zero-heating energy houses and plus energy houses) as the lower line and the actual building practice in between. The requirements followed the pilot projects with 10 to 20 years time difference' (Erhorn-Kluttig et al. 2011).

'With the last tightening of the minimum energy performance requirements by the energy decree, EnEV 2009 (Regierung der Bundesrepublik Deutschland 2009), Germany has again become one of the countries in Europe with the strictest requirements for new buildings' (Erhorn-Kluttig et al. 2011). But so far, the German Federal Government has not yet defined a precise national definition for nearly zero-energy buildings according to the EPBD. This fact can also be explained as the EPBD requirements on the definition of nearly zero-energy buildings are quite vague (Boermans et al. 2011b) and have just been clarified recently within the European Commission's (EC) research project 'Towards nearly zero-energy buildings–Definition of common principles under the EPBD' (Schimschar et al. 2013b). However, already since years, the German government

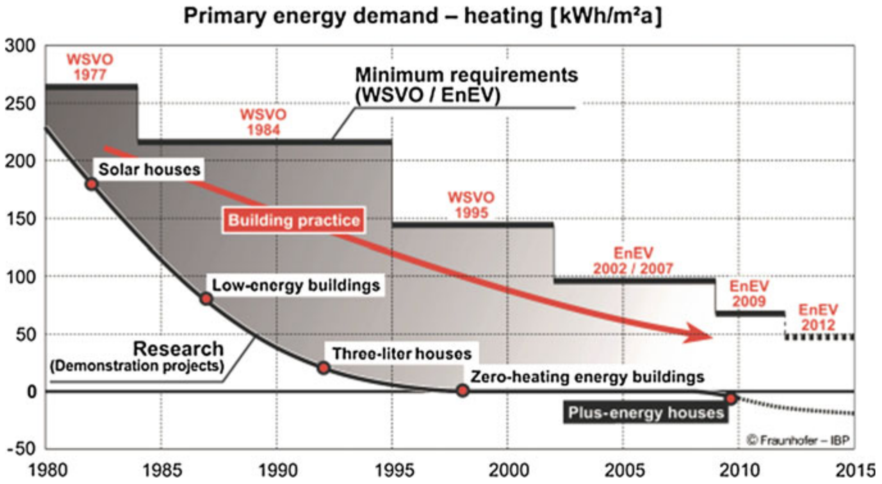

**Fig. 3** The historic development of pilot projects, minimum requirements and the building (Erhorn-Kluttig et al. 2011)

is financing research projects in order to support the national transposition. Thereof, on national level, two projects within the 'Zukunft Bau' initiative of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) are especially important for getting more clarity about an appropriate level of requirements:

1. 'Investigation for the amendment of the buildings ordinance—Identification and analysis of obstacles for the construction of highly efficient buildings and development of a concept for the market penetration by 2020' (author's translation of the German title: 'Untersuchung zur Novellierung der Gebäude-Richtlinie—Identifikation und Analyse von Hemmnissen beim Neubau von hocheffizienten Gebäuden und Entwicklung eines Konzepts zur Marktdurchdringung bis 2020') (Erhorn et al. 2012).
2. 'Accompanying investigation for the European reporting requirement on the cost-optimal-level' (author's translation of the German title: 'Begleituntersuchung zur europäischen Berichterstattung "Cost-Optimal-Level"—Modellrechnungen') (Offermann et al. 2013).

Erhorn et al. (2012) was already published whereas Offermann et al. (2013) is still under development and is expected to be published in the second half of 2013. The cost-optimality requirement is relevant for the technical requirements for new and existing nearly zero-energy buildings as Article 4(1) EPBD states:

> Member States shall take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels.

This means that this level is the maximum allowed level of energy demand of a building, but more stringent requirements are possible. For more information about the cost-optimality methodology, please see Boermans et al. (2011a).

Erhorn et al. (2012) have analysed two possible approaches for defining suitable performance requirements within a German nearly zero-energy building definition: (1) based on economic aspects (as this is also required through the 'energy conservation act') and (2) based on the expectable technological development of relevant building components. The following descriptions are mainly based and translated from Erhorn et al. (2012).

*Performance Requirements based on Economic Aspects*

In Germany, the 'Energy Conservation Act' (EnEG) requires that the energy performance obligations for buildings need to be cost-effective. Nevertheless, the EnEG allows wider interpretation that it is usually required in the German building code 'Energy Saving Ordinance' (EnEV). The EnEG allows the extension of the payback time up to the time span of the usual lifetime of the measure, whereas the EnEV often requires payback times of less than 20 years (for more information, also see Sect. 3.2.1). The usual lifetime of structural and technical components is often considerably longer than 20 years (Association of German Engineers 2000; Bahr and Lennerts 2010; BBSR 2009, 2011).

The consideration of the cost-effectiveness requires a full understanding of various parameters, such as:

- Efficiency of energy efficiency measures
- Investment costs for efficiency measures
- Maintenance costs for efficiency measures
- Lifetime of efficiency measures
- Development of energy costs
- Changes in interest rates on the capital market.

The development of each parameter is not 100 % predictable. For example, from the historical development of the crude oil price during the last 40 years, it is not possible to make any clear future projection.

In the same way, the further development of the energy efficiency of different measures and associated costs cannot be reliably predicted until 2020. For example, considering the development of the heat conductivity of high-quality insulating materials, a wide technical spectrum of materials already exists today, implicating that there is further potential. However, in the construction praxis, this potential is only partially exploited due to current relatively high investment costs of these materials. New production methods may significantly improve the cost-effectiveness of high-end products. Therefore, it does not seem suitable to develop future 2020 requirements based on the present technological and economical assessment parameters. This would probably lead to pessimistic requirements.

*Performance Requirements based on the expectable Technological Development* According to Erhorn et al. (2012), a second possibility for estimating the development of cost-effective efficiency measures is the approximation of the future development based on recent decades. Although the energy price remained quite stable in Germany between 1970 and 2000, the energetic requirements for insulation and HVAC systems have been strengthened significantly during this time (see Fig. 3). This was possible as available technologies have developed considerably and thus become much more efficient. If analysing Fig. 3 under this aspect, it can be seen that in the illustrated case of a one-family house, the primary energy demand has been reduced by approximately 180 kWh/m$^2$a in 30 years. This is equal to an average yearly reduction of 6 kWh/m$^2$a (initially about 8, today about 4 kWh/m$^2$a). A stringent forward projection of this trend would lead to a further reduction of about 30 kWh/m$^2$a until 2020. This would implicate a reduction potential of about 60 % compared to today's values. Thus, this target value would be comparable to today's KfW building standard 'Effizienzhaus 40' (efficiency house 40) which has already been constructed almost 13,000 times in Germany so far (status 30 September 2012 (KFW 2012; Schimschar et al. 2011)). The KfW efficiency house 40 standard requires a primary energy demand of about 25–30 kWh/m$^2$a (depending on the kind of building) (Schimschar et al. 2011).

Erhorn et al. (2012) finally propose to determine the nZEB requirements based on this latterly described approach. As already explained, for the range until 2020, a yearly primary energy reduction of 3–4 kWh/m$^2$a seems to be realistic. This would lead to a reduction potential of at least 50 % by 2020, and an interim reduction target for 2015 could be in a range of about 20 %.

In order to improve public understanding and to show how these buildings can be constructed, the future requirements could refer to today's KfW classification of building standards that exceed the requirements of the EnEV (for example, efficiency house 70 as from 2015, efficiency house 85 as from 2018 and efficiency house 40 as from 2020). Table 1 shows examples for the realisation of today's existing KfW efficiency houses.

As Offermann et al. (2013) is still under development, specific outcomes cannot be addressed here. However, it is expected that the proposed level of Erhorn et al. (2012) of about 30 kWh/m$^2$a seems to be achievable.

The German government has to define and publish the specific national definition for nearly zero-energy buildings soon as member states need to come up with national plans for how to define such buildings and how market introduction is planned until 2021. Additionally, plans need to be developed for ambition level and introduction of existing buildings renovated to nearly zero-energy buildings.

According to Erhorn-Kluttig et al. (2011), the German definition of nZEB will consider the following aspects:

- Assessment parameters (energy performance indicators): both delivered energy and primary energy (non-renewable part).
- Balancing period: one year of operation.

**Table 1** Different variants for the realisation of KfW efficiency house standards. The energy-related level of the KfW efficiency house 40 corresponds to the proposed nZEB standard by Erhorn et al. (2012)

| | KfW efficiency house 70 | KfW efficiency house 55 | KfW efficiency house 40 (EnEV 2020 level) |
|---|---|---|---|
| Façade ($W/(m^2K)$) | $U \leq 0.16$ | $U \leq 0.16$ | $U \leq 0.12$ |
| Ground floor/basement ceiling ($W/(m^2K)$) | $U \leq 0.24$ | $U \leq 0.24$ | $U \leq 0.18$ |
| Outer basement wall ($W/(m^2K)$) | $U \leq 0.24$ | $U \leq 0.24$ | $U \leq 0.18$ |
| Roof ($W/(m^2K)$) | $U \leq 0.16$ | $U \leq 0.16$ | $U \leq 0.11$ |
| Topmost ceiling ($W/(m^2K)$) | $U \leq 0.16$ | $U \leq 0.14$ | $U \leq 0.11$ |
| Windows | $U_W \leq 1.1$ $W/(m^2K)/g \geq 0.55$ | $U_W \leq 0.95$ $W/(m^2K)/g \geq 0.55$ | $U_W \leq 0.8$ $W/(m^2K)/g \geq 0.6$ |
| Heat bridges ($W/(m^2K)$) | $\Delta U_{WB} \leq 0.025$ | $\Delta U_{WB} \leq 0.025$ | $\Delta U_{WB} \leq 0.025$ |
| Air tightness (1/h) | $n \leq 0.6$ | $n \leq 0.6$ | $n \leq 0.6$ |
| System variants | Condensing boiler with solar DHW supply or GSHP or ASHP | Condensing boiler with solar DHW supply and ventilation system with heat recovery or GSHP with DHW supply or ASHP with DHW supply or GSHP with ventilation system with heat recovery | GSHP with solar DHW supply and ventilation system with heat recovery or ASHP with solar DHW supply and ventilation system with heat recovery |

*DHW* domestic hot water, *GSHP* ground source heat pump, *ASHP* air source heat pump

- Energy aspects to be included: heating energy, ventilation and cooling energy all including auxiliary energy, lighting for non-residential buildings, energy generated from renewables (self-used and fed into the grid) if produced on-site.

# 3 Building Sector Policy Framework

Germany is known as one of the most ‘energy efficient and greenest economies in the world while enjoying competitive energy prices and a high level of prosperity’ (BMWi 2010b). The deployment process of energy efficiency and renewable energy technologies has given the country the reputation of a forerunner on European and international level with regard to energy, climate and innovation strategies (BMWi 2010b). However, the topic of energy savings and energy supply was not always just driven by ecological but also economical reasons. With the first oil crisis in 1973, the country started seeking solutions to the fuel shortage and in the 1970 s introduced the first energy-related policies. In 1977, the German government implemented the first ‘Thermal Insulation Ordinance’ defining requirements on the energy-related quality of buildings. In 1995, the first national $CO_2$-emission reduction target of 25 % in 2005 compared to 1990 was announced. Since that time, the regulatory requirements have been tightened continuously. Nevertheless, about 44 % of the total energy in Germany is still consumed by buildings (BMWI 2011b). Therefore, the building sector still holds a large potential for saving energy and, thus, is the most important sector for achieving the energy-related targets of the German government. For the determination of the specific reduction targets, Germany orientates on the strategies of the European Union (EU) and tries to outreach the EU targets on national level (Bigalke et al. 2012).

Generally, it is possible to describe the German building sector policy framework as the following: it is based on 4 main pillars: two relate to regulatory policies (the EnEV and the EEWärmeG) and the others are incentives (KfW programs and the MAP) and everything is accompanied by a large number of market instruments (see Fig. 4).

The ‘Energy Saving Ordinance’ is the German building code and, apart from anything else, gives obligations concerning the energy performance in the form of both the maximum primary energy consumption and building components depending on the kind and geometry of the building for both new and existing buildings, see Sect. 3.2.2. It is the most important instrument.

The ‘Act on the Promotion of Renewable Energies in the Heat Sector’ gives obligations for the usage of renewable energies that have to produce a certain amount of the used heat in newly constructed buildings, see Sect. 3.2.3.

The KfW’s most important support programs for the building sector are the ‘energy efficient refurbishment’, see Sect. 3.3.1, and the ‘energy efficient construction’, see Sect. 3.2.2. The ‘Market Incentive Programme for Renewable Energies’ provides grants for renewable energy systems in newly constructed and existing buildings, see Sect. 3.3.5.

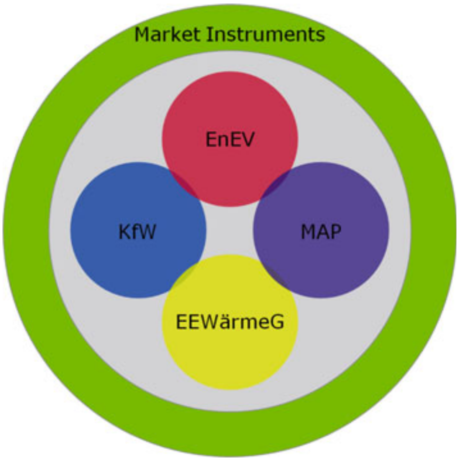

**Fig. 4** Simplified illustration of the German building sector policy framework

## 3.1 *Strategies and Concepts Influencing the Building Sector*

The Federal Government continually develops strategies and concepts influencing the building sector. Based on these strategies and concepts, the government develops suitable regulatory policies, financial incentives and market instruments. In addition to that, Federal State governments may also develop concepts on local level which, however, are not described here. The following strategies and concepts are chronologically sorted in order to give a good overview about the development of the ambitions of the German Federal Government (Bigalke et al. 2012).

### 3.1.1 National Climate Protection Programme 2000 and 2005

The objectives of the National Climate Protection Programme are the reduction in greenhouse gas emissions and increasing the share of renewable energies. To achieve these goals, the Federal Government implemented different measures such as the 'Energy Saving Ordinance' (EnEV), the further development of the $CO_2$ building refurbishment programme (today: Energy Efficient Refurbishment) and the extension of public relations and consultation programmes. Simultaneously, it established the 'Renewable Energy Sources Act' (EEG). The National Climate Protection Programme was updated in 2005, and in this process, the government also introduced the energy performance certificates, market incentive programmes for solar and biomass technologies, the on-site energy advice programme and advanced training and further qualification of the handcraft sector (BMU 2005).

### 3.1.2 Perspectives for Germany, 2002

The document ‘Perspectives for Germany’ was published in 2002 and represents the national sustainable development strategy of the Federal Government. It outlines the objectives to be achieved in each sector and the suggested set of measures. Within this strategy, the building stock has been recognised to have a high potential. Furthermore, the EnEV 2002 and the $CO_2$ building refurbishment programme present a crucial role in this strategy (Bundesrepublik Deutschland 2002).

### 3.1.3 Integrated Energy and Climate Protection Programme (IEKP), 2007

In 2007, within the Integrated Energy and Climate Programme (IEKP), the Federal Government has transposed the European policy instructions at national level. The programme and associated resolutions defined the following relevant 2020 targets:

- the reduction of 40 % greenhouse gas emissions compared to 1990,
- to increase the share of renewable heat production to 14 %,
- to increase the share of renewable electricity production to 30 %.

To achieve the energy efficiency goals and enhance the use of renewable energies, 29 measures have been designed. Most of the building sector-related measures have been established in the EnEV amendment. In this context, especially important was the tightening of requirements regarding the energy efficiency of buildings by approximately 30 %. Furthermore, the funding programmes for the refurbishment of existing buildings have been strengthened and the Act on the Promotion of Renewable Energies in the Heat Sector (EEWärmeG) has been implemented (BMWi 2007).

### 3.1.4 National Energy Efficiency Action Plan (NEEAP), 2007 and 2011

The National Energy Efficiency Action Plan (NEEAP) was first designed in 2007 as a documentation of the efforts towards the implementation of the 2006 EU ‘Energy Efficiency Directive’ (European Parliament and the Council of the European Union 2006). The objective of these national action plans is to present the strategies and measures that Germany is taking in order to achieve the energy reduction target set in the EU directive. Apart from others, the presented measures intend to tighten and further develop the energetic requirements for buildings, the $CO_2$ refurbishment programme and the extension of the energy research in the field of energy efficiency improvement (BMWI 2011c).

### 3.1.5 German Strategy for Adaption to Climate Change (DAS), 2008

With this document, in 2008, the Federal Cabinet presented the commitment of the Federal Government to the United Nations Framework Convention on Climate Change (UNFCCC) to develop national programs in order to facilitate an appropriate adaptation to climate change. This medium-term strategy is the basis for assessing the risks of climate change and to identify possible needs for action. Objectives and possible adaptation measures were developed, such as long-term goals towards the reduction in vulnerability, enhancement of preservation and adaptability of natural, social and economic systems (The Federal Government 2008).

### 3.1.6 National Renewable Energy Action Plan, 2010

The National Renewable Energy Action Plan displays the German contribution to the EU target to cover 20 % of the total energy consumption with renewable energies by the year 2020. It is an important document in the Federal Government's aim to promote renewable energy, alongside the Energy Concept 2010. The plan describes existing and planned measures, instruments and policies that should lead to the Europe-wide target. Huge emphasis is put on the use of renewable energies in the building stock. Furthermore, the basic condition of the rental law is analysed to promote the use of renewable energy in this area (Bundesrepublik Deutschland 2010).

### 3.1.7 Energy Concept, 2010

The Energy Concept is a long-term strategy with objectives in the policy fields of climate change and energy. It contains nine fields of action, one of those addressing energetic building restoration and energy efficient construction. The target of the Federal Government is a nearly climate-neutral building stock until 2050. To reach that objective, the heat demand shall decline by 20 % in 2020 and the primary energy demand by 80 % until 2050. In a large offensive of modernisation of the building stock, the rate of rehabilitation shall double from one to two percent until 2020 and a timetable for rehabilitation between 2020 and 2050 is envisioned. Concerning the electricity consumption, a share of 35 % of renewable resources and a general decrease in power consumption by 35 % until 2020 are indicated. The Energy Concept intensifies the goals of the IEKP regarding the use of renewable energies (BMWi 2010b).

### 3.1.8 Energy Transition, Energiewende 2011

Motivated by the reactor catastrophy in Fukushima, the Federal Cabinet approved various laws and adaptations of laws to accelerate the implementation of the consisting Energy Concept. Part of the ‘Energy Transition’ is the legally binding nuclear phaseout, the faster extension of wind energy and electricity grids as well as the enhancement of energy efficiency and energy savings in buildings (BMWI 2012a).

### 3.1.9 Climate Change Adaptation Action Plan, 2011

The Climate Change Adaptation Action Plan from 2011 solidifies the implementation of the ‘German Strategy for Adaption to Climate Change’ (DAS) by giving specific courses of action. Adaptation measures for the building sector are contained as well (The Federal Government 2012b).

### 3.1.10 National Reform Programme (NRP), 2012

The National Reform Programme serves as a central strategic instrument for the member states of the European Union to report the development of the Europe 2020 Strategy. The implementation of the European goals on the national level is presented (BMWI 2012c).

### 3.1.11 Energy and Climate Protection Concept of the BMVBS for the Sectors ‘Buildings’ and ‘Transport’, 2013

To face the ambitious targets of the government, the ‘Federal Ministry of Transport Building and Urban Development’ (BMVBS) has decided, in the framework of its sectoral responsibility, to develop an own energy and climate protection concept for the sectors ‘transport’ and ‘buildings’. The concept aims to identify possible potentials for achieving the energy and climate protection targets. Through an impact assessment, it is planned to continuously update the concept in order to adapt to new boundary conditions. It will be based on the Energy Concept of the government as well as on existing results of the examination of the IEKP (see Sect. 3.1.3) and will consequently define concrete measures (Schimschar et al. 2013a).

### 3.1.12 Refurbishment Road map, 2013

The Energy Efficiency Directive requires member states to develop refurbishment road maps that describe the country’s vision on a long-term strategy (e.g. until 2050) to renovate their building stocks. The refurbishment road map is currently being developed by the BMVBS and should help to achieve the long-term targets of the governmental Energy Concept and of the energy and climate concept of the BMVBS. The road map is necessary to outline the large emission reduction

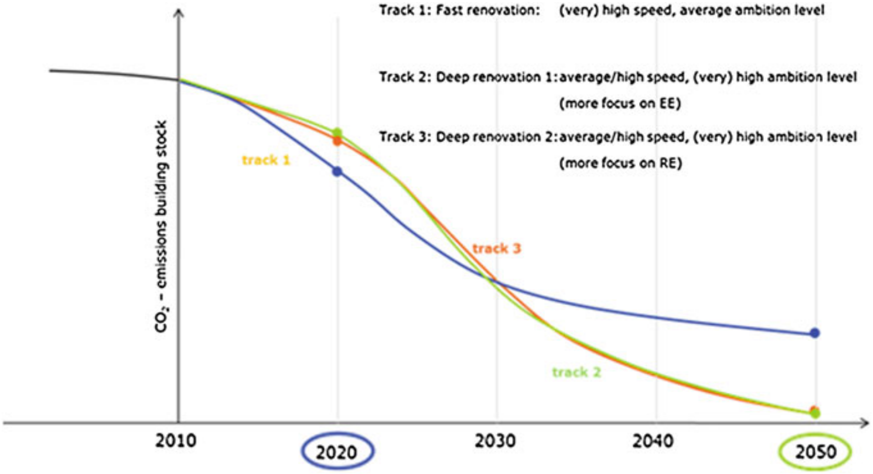

**Fig. 5** The long-term impact of different renovation tracks

potential in the building stock and thus achieve the targets. The road map should also help to give an orientation for the future development of the building stock and to identify a suitable path towards a climate-neutral building stock by 2050.

Figure 5 qualitatively shows the importance of choosing the right refurbishment track.

Accordingly, a refurbishment track with a very high speed but just an average ambition level can lead to fast reductions; however, due to the long renovation cycles of buildings, it can also lead to a lock-in effect which in the long term leads to a non-achievement of the reduction targets.

## *3.2 Regulatory Policies*

In Germany, the requirements concerning the energy performance of buildings reach back a long time (first Thermal Insulation Ordinance since 1977) and the requirements have been continuously tightened. The specifications of the ‘Energy Performance of Buildings Directive’ (EPBD) are transposed through the ‘Energy Saving Ordinance’ (EnEV) in Germany. According to the EnEV, new residential and commercial buildings have to limit their primary energy demand to a specified maximum value. Minimum requirements also exist on component level and for the specific transmission heat loss, which is calculated by using reference buildings. For existing buildings, there are also minimum requirements for building components in the case of a building modification and for the primary energy demand in the case of a major renovation that is 40 % less ambitious than those for new buildings. The calculation of the overall primary energy demand has to be conducted through the methodology as determined in the technical norm DIN V 18599 (or alternatively with the technical norms DIN V 4108-6 in combination with DIN V 4701-10). The last amendment of the EnEV entered into force in October 2009 and strengthened the requirements by an average of 30 % (Concerted Action Energy Performance of Buildings 2011). In 2013 (perhaps early 2014), the EnEV will be amended (this was originally planned for 2012 (BMWi 2010a) and will probably be tightened by approximately 12.5 % in January 2014 and further 12.5 % in January 2016 (see Sect. 3.2.1).

According to the Act on the Promotion of Renewable Energies in the Heat Sector (EEWärmeG), it is additionally obligatory to use renewable energies for covering a specific share of the heating demand (space heating and cooling as well as domestic hot water generation) in new buildings. Alternatively, other measures that significantly increase the energy efficiency of a building can also be applied. Additionally, the EEWärmeG will probably be amended in 2013 and it is currently discussed as to whether the requirement for the use of renewable energies will be expanded to existing buildings.

A chronology of relevant building regulations can be found in Table 2. The information is based on (Schimschar et al. 2010) and has been complemented with new developments in recent years. The most relevant regulatory policies for the energy-related refurbishment of buildings are furthermore described in the following Sects. 3.2.1–3.2.4. It should be noted that more relevant policies exist that provide the legal basis for the government in order to establish respective ordinances, incentive programmes, etc. (e.g. the 'European Law Adaptation Act for Renewable Energy' or the 'Ordinance on the Promotion of On-Site Advice for Rational Energy Use in Residential Buildings'). However, here, the focus is on the most important policies (Table 2).

### 3.2.1 Energy Conservation Act (EnEG), 2009

Germany introduced the first law establishing requirements on the energy performance of buildings in 1976. Due to the implementation of the 2002 EU Directive on the Energy Performance of Buildings (EPBD), the German EnEG was amended in 2005 and in 2009 and will again be amended in 2013.

The main target of the law is to ensure that buildings just consume as much energy as necessary and the wasting of energy should be avoided. For this purpose, the EnEG states general requirements for the construction and refurbishment of buildings, building elements, as well as heating, cooling, ventilation, lighting and hot water installations. The EnEG contains different permissions for the German government for issuing necessary ordinances in order to transpose European directives, etc. Thus, the EnEG is also the basis for the Energy Saving Ordinance—the EnEV.

Paragraph 5 of the EnEG is especially important as it clearly regulates that all kinds of building requirements have to be technically feasible and cost-effective. The author's translation of this paragraph is given below.

**Table 2** Chronology of relevant building legislation

| Regulation | Commencement | Short description (www.bbsr-energieeinsparung.de) |
|---|---|---|
| Energy conservation act (EnEG) | 1976 (change 1980 & 2001), 2005, 2009, 2013 (planned) | The act empowers the Federal Government to legislate ordinances aiming to reduce the energy consumption in buildings. Since then, ordinances that pose energetic requirements on buildings and their appliances can be legislated based on the EnEG |
| Thermal insulation ordinance (WSchV) | 1977, 1984, 1995 | This ordinance first time gave energy saving requirements through thermal insulation in buildings |
| Heating plant operation ordinance (Heiz.Betr.V.) | 1978 | Requirements for the maintenance of energy efficiency in the operation of central heating systems with water as heat carrier as well as of systems for hot water generation |
| Heating appliances ordinance (HeizAnlV) | 1978, 1984, 1989, 1994, 1998 | Mainly requirements for the equipment and dimensioning of central heating systems using water as the energy carrier as well as on hot water systems |
| Heating cost ordinance (Heizkosten V) | 1981, 1984, 1989, 2008 | Regulates the allocation of heating and warm water costs in centrally supplied buildings, obligation of consumption metering as well as regulating the technical equipment for the metering |
| Energy saving ordinance (EnEV) | 2002, 2004, 2007, 2009, 2013 (planned with changes 2014 and 2016) | The EnEV prescribes different technical requirements for new and existing residential and commercial buildings undergoing a refurbishment |
| Renewable energy sources act (EEG)[a] | 2000, 2004, 2009, 2012 | The EEG aims to increase the share of electricity generation from renewable sources |
| Act on the Promotion Of Renewable Energies in the Heat Sector (EEWärmeG) | 2009 (change 2011), 2013 (planned) | The EEG aims to increase the share of heat that is generated from renewable sources |
| Combined Heat and Power Act (KWKG)[b] | 2002, 2009 | This act aims to keep, modernise and increase the number of combined heat and power (CHP) plants |

[a] Described in Sect. 3.3.6 in Built Environment Life Cycle Process and Climate Change as the focus is on giving financial support

[b] Described in Sect. 3.3.7 in Built Environment Life Cycle Process and Climate Change as the focus is on giving financial support

*§ 5 Common requirements for statutory ordinances*

(1) *The requirements established in ordinances (…) shall be achievable according to the available technology and cost-effective for buildings of the same type and use. The requirements are cost-effective if the necessary expenditures can in general be paid back with the occurring energy savings during the useful lifetime of the measure. For existing buildings, the useful lifetime, which can still be expected, has to be taken into consideration.*

### 3.2.2 Energy Saving Ordinance (EnEV)

The EnEV was first introduced in 2002 and was then revised twice in 2007 and 2009. The next amendment of the ordinance is expected in 2013 (2014) although it was initially planned for 2012. The regulation serves as a guideline and establishes minimum requirements, calculation methods and recommendations for new residential and non-residential buildings, as well as for buildings undergoing modernisations, reconstructions and extensions. For example, the ordinance prescribes maximum primary energy demands, U-values of building elements, air tightness, transmission losses, etc. The primary energy requirements and average specific transmission heat loss (residential buildings), respectively average heat transfer coefficients (commercial buildings), are defined by means of a reference building which corresponds to the real building in terms of geometry, net floor area, orientation and utilisation, but whose technical structure is defined according to Appendix 1, respectively Appendix 2 of the EnEV ('reference building approach').

Furthermore, the EnEV establishes the start-up and maintenance of heating, hot water, cooling and ventilation equipment and determines technical DIN norms which have to be applied. Chapter 5 of the ordinance engages with the issuing and implementation of energy performance certificates and gives recommendations on energy efficiency optimisation techniques (Regierung der Bundesrepublik Deutschland 2009).

As for residential buildings, the requirements for new commercial buildings are also defined by the annual primary energy demand and U-values of components. However, in addition to the energy demands for heating, hot water and air-conditioning, the balance sheet also includes the proportion of energy for cooling and lighting installations. The new comprehensive calculation method is defined in the new German standard DIN V 18599 (dena 2013). Figure 6 shows the chronological development of EnEV requirements.

According to the EnEV, a refurbishment, triggering technical requirements, is defined as 'a change of an outer building component that exceeds 10 % of the total building area of the respective component'. Example: If you exchange two old windows with an area of 3 $m^2$ and the total window area of the building is 20 $m^2$, then you exceed the 10 % threshold and thus have to comply with the EnEV requirements.

In those cases, the EnEV primarily prescribes requirements on component level. Accordingly, modifications are to be designed in such a way that the heat transfer coefficients of the exterior components concerned as established in Table 3 are not exceeded.

Alternatively, these requirements are considered to be fulfilled if the modified residential or non-residential buildings do not exceed the overall requirements for new buildings by more than 40 percent. The requirements for new buildings are as follows (Regierung der Bundesrepublik Deutschland 2009):

1. Residential buildings to be constructed are to be designed in such a way that the annual primary energy demand for heating, hot water preparation, ventilation and cooling does not exceed the value of the annual primary energy demand for a reference building of the same geometry, building floor space and alignment with the technical reference design given in Table 4 and the maximum value of the specific transmission heat loss related to the heat-transmitting surface area in accordance with Table 5.
2. Commercial buildings to be constructed are to be designed in such a way that the annual primary energy demand for heating, hot water preparation, ventilation, cooling and lighting installations does not exceed the level of the annual primary energy demand for a reference building of the same geometry, net floor space, alignment and utilisation, including the arrangement of the utilisation units to the technical reference design indicated in Appendix 2 Table 5.1 of the EnEV (due to complexity not shown here) and the maximum levels of the average heat transfer coefficients of the heat-transmitting surface area in accordance with Table 6 are not exceeded.

The three mentioned tables can be found on the following pages.

Depending on the specific kind (single- or multi-family building) and architecture, the maximum primary energy demand of the reference building in average totals about 65 kWh/m$^2$a (Schimschar et al. 2011) (Tables 5, 6).

### *Amendment 2013/2014*

The EnEV has to be amended in order to transpose all requirements of the recast EPBD. Thus, the Federal Ministries of ‘Transport, Building and Urban Development’ and ‘Economics and Technology’ developed a ministerial draft (BMVBS,BMWI 2012) which is currently being commented on by the Federal States and associations in order to allow the drafting of an official final version of the government. Several months may still be necessary before the final version will enter into force; thus, it is possible that the new EnEV amendment will even be named ‘EnEV 2014’. The most important changes compared to the EnEV 2009 are as follows (status: last version from October 2012):

**Table 3** Maximum values of heat transfer coefficients in initial installation, replacement and renovation of components (Regierung der Bundesrepublik Deutschland 2009)

| Line | Component | Measure according to | Residential buildings and zones of commercial buildings with indoor temperatures $\geq 19$ °C | Zones of commercial buildings with indoor temperatures from 12 to $< 19$ °C |
|---|---|---|---|---|
| | | | Maximum values of heat transfer coefficients $U_{max}$ ¹⁾ | |
| | 1 | 2 | 3 | 4 |
| 1 | Outside walls | No. 1a to d | 0.24 W/(m$^2$K) | 0.35 W/(m$^2$K) |
| 2a | Outside windows, French doors | No. 2a and b | 1.30 W/(m$^2$K)$^{2)}$ | 1,90 W/(m$^2$K)$^{2)}$ |
| 2b | Skylights | No. 2a and b | 1.40 W/(m$^2$K)$^{2)}$ | 1.90 W/(m$^2$K)$^{2)}$ |
| 2c | Glazing | No. 2c | 1.10 W/(m$^2$K)$^{3)}$ | No requirement |
| 2d | Curtain walls | No. 6 sentence 1 | 1.50 W/(m$^2$K)$^{4)}$ | 1.90 W/(m$^2$K)$^{4)}$ |
| 2e | Glass roofs | No. 2a and c | 2.00 W/(m$^2$K)$^{3)}$ | 2.70 W/(m$^2$K)$^{3)}$ |
| 3a | Outside windows, French doors, skylights with special glazing | No. 2a and b | 2.00 W/(m$^2$K)$^{2)}$ | 2.80 W/(m$^2$K)$^{2)}$ |
| 3b | Special glazing | No. 2c | 1.60 W/(m$^2$K)$^{3)}$ | No requirement |
| 3c | Curtain walls with special glazing | No. 6 sentence 2 | 2.30 W/(m$^2$K)$^{4)}$ | 3.00 W/(m$^2$K)$^{4)}$ |
| 4a | Ceiling, roofs and roof pitch | No. 4.1 | 0.24 W/(m$^2$K) | 0.35 W/(m$^2$K) |
| 4b | Flat roofs | No. 4.2 | 0.20 W/(m$^2$K) | 0.35 W/(m$^2$K) |
| 5a | Ceilings and walls against unheated spaces or the earth | No. 5a, b, d and e | 0.30 W/(m$^2$K) | No requirement |
| 5b | Floor construction | No. 5c | 0.50 W/(m$^2$K) | No requirement |
| 5c | Ceilings bordering external air below | No. 5a to e | 0.24 W/(m$^2$K) | 0.35 W/(m$^2$K) |

1. Requirements for new buildings are further tightened towards the EPBD requirement of nearly zero-energy buildings: primary energy requirements in steps: first by 12.5 % (in January 2014); from January 2016 by 25 % (for all new buildings), both compared to the requirements of the EnEV2009;
2. Tightening of building shell requirements for residential buildings (specific transmission heat loss, see Table 7) and commercial buildings (average heat transfer coefficients, see Table 8) (Tables 7, 8).

1. Reduction in the primary energy factor of electricity from 2.6 currently to 2.0 in 2014 and then to 1.8 in 2016;
2. Introduction of the obligation for publishing energy performance indicators in real estate advertisements.
3. Rescaling of the 'Energy ranges' in energy performance certificates of residential buildings up to 250 kWh/m$^2$a and strengthening of modernisation recommendations;

**Table 4** Design of the residential reference building (Regierung der Bundesrepublik Deutschland 2009)

| Line | Component/system | Reference design/value (measuring unit) | |
|---|---|---|---|
| | | Parameter (for Lines 1.1 to 3) | |
| 1.1 | Outside wall, storey ceiling against external air | Heat transfer coefficient | $U = 0.28\ W/(m^2K)$ |
| 1.2 | Exterior wall against ground, foundation slab, walls and ceilings to unheated spaces (except those in accordance with Line 1.1) | Heat transfer coefficient | $U = 0.35\ W/(m^2K)$ |
| 1.3 | Roof, top-floor ceiling, walls to long pane of roof | Heat transfer coefficient | $U = 0.20\ W/(m^2K)$ |
| 1.4 | Windows, French doors | Heat transfer coefficient | $U_w = 1.30\ W/(m^2K)$ |
| | | Overall level of energy permeability of glazing | $g^{\perp} = 0.60$ |
| 1.5 | Skylights | Heat transfer coefficient | $U_w = 1.40\ W/(m^2K)$ |
| | | Overall energy transmittance of the glazing | $g^{\perp} = 0.60$ |
| 1.6 | Dome lights | Heat transfer coefficient | $U_w = 2.70\ W/(m^2K)$ |
| | | Overall energy permeability of the glazing | $g^{\perp} = 0.64$ |
| 1.7 | Outside doors | Heat transfer coefficient | $U = 1.80\ W/(m^2K)$ |
| 2 | Components according to Lines 1.1 to 1.7 | Heat bridge tolerance | $\Delta U_{WB} = 0.05\ W/(m^2K)$ |
| 3 | Air tightness of building cladding | Rated value $n_{50}$ | In the case of calculation according to<br>• DIN V 4108-6:2003-06: with leak, test<br>• DIN V 18599-2: 2007-02: according to Category I |
| 4 | Sunscreen device | No sun protection device | |
| 5 | Healing system | • Heat: generation through condensing boiler (improved), domestic fuel oil, Set-up:<br>- for building with up to 2 flats within the thermal cladding<br>- for building with more than 2 flats outside of the thermal cladding<br>• Layout temperature 55/45 °C, central distribution system within the heat-transmitting surface area, inside lines, and assigned pipes, pumps laid out (controlled, $\Delta p$ constant), pipeline network hydraulically aligned, thermal insulation of pipelines according to Appendix 5<br>• Heat transfer with free static heating surfaces, alignment to normal exterior wall, thermostat valves with proportional range 1 K | |

(continued)

**Table 4** (continued)

| Line | Component/system | Reference design/value (measuring unit) |
|---|---|---|
| | | Parameter (for Lines 1.1 to 3) |
| 6 | Hot water preparation system | • Central hot water preparation<br>• Joint heat preparation with heating system according to Line 5<br>• Solar plant (multi-purpose system with flat-plate collector) corresponding to the provisions of DIN V 4701-10: 2003-08 or DIN V 18599-5: 2007-02<br>• Storage tanks heated indirectly (standing), same set-up as heat-generating device, layout in accordance with DIN V 4701-10: 2003-08 or DIN V 18599-5 : 2007-02 as<br>- Small solar plant with $A_N$ smaller than 500 $m^2$ (bi-fuel solar storage)<br>- Large solar plant with $A_N$ greater than or equal to 500 $m^2$<br>• Distribution system within the heat-transmitting surface area, inside lines, common installation wall, thermal insulation of pipelines according to Appendix 5, with circulation, pump laid out if required (controlled, $\Delta p$ constant) |
| 7 | Cooling | No cooling |
| 8 | Ventilation | Central exhaust air system, demand-led with controlled DC ventilator |

**Table 5** Maximum values of the specific transmission heat loss related to the heat-transmitting surface area in residential buildings (Regierung der Bundesrepublik Deutschland 2009)

| Line | Type of building | | Maximum value of the specific transmission heat loss (W/(m$^2$K)) |
|---|---|---|---|
| 1 | Detached residential building | with $A_N \leq 350$ m$^2$ | $H'_T = 0.40$ |
| | | with $A_N > 350$ m$^2$ | $H'_T = 0.50$ |
| 2 | Semi-detached residential building | | $H'_T = 0.45$ |
| 3 | All other residential buildings | | $H'_T = 0.65$ |
| 4 | Extensions and expansion of residential buildings in accordance with Sect. 9 paragraph 5 | | $H'_T = 0.65$ |

**Table 6** Maximum values of the average heat transfer coefficients of the heat-transmitting surface area of commercial buildings (Regierung der Bundesrepublik Deutschland 2009)

| Line | Component | Maximum values of heat transfer coefficients, related to the average of the relevant components | |
|---|---|---|---|
| | | Zones with target room temperatures in the case of heating $\geq 19$ °C (W/(m$^2$K)) | Zones with target room temperatures in the case of heating from 12 to $< 19$ °C (W/(m$^2$K)) |
| 1 | Opaque exterior components, if not contained in components of Lines 3 and 4 | $\overline{U} = 0.35$ | $\overline{U} = 0.50$ |
| 2 | Transparent exterior components, if not contained in components of Lines 3 and 4 | $\overline{U} = 1.90$ | $\overline{U} = 2.80$ |
| 3 | Curtain wall | $\overline{U} = 1.90$ | $\overline{U} = 3.00$ |
| 4 | Glass roofs, light bands, dome lights | $\overline{U} = 3.10$ | $\overline{U} = 3.10$ |

**Table 7** Tightening of maximum values of the specific transmission heat loss related to the heat-transmitting surface area in residential buildings

| Type | Area $A_N$* (m$^2$) | En EV 2009 | New buildings till 31.12.2015 | New buildings from 1.1.2016 |
|---|---|---|---|---|
| Free standing | $A_N \leq 350$ | 0.4 | 0.38 (−5 %) | 0.36 (−10 %) |
| | $A_N > 350$ | 0.5 | 0.46 (−8 %) | 0.42 (−16 %) |
| One side attached | $A_N \leq 350$ | 0.45 | 0.4 (−11 %) | 0.36 (−20 %) |
| Two side attached | $A_N \leq 350$ | 0.65 | 0.45 (−30 %) | 0.38 (−41 %) |
| Extensions and add-ons (§9 Abs. 5) | | 0.65 | 0.65(0 %) | 0.65(0 %) |
| Other residential | | 0.65 | 0.5 (−23 %) | 0.45 (−30 %) |

**Table 8** Tightening of maximum values of the average heat transfer coefficients of the heat-transmitting surface area of commercial buildings

| Type | EnEV 2009 | New buildings till 31.12.2015 | New buildings from 1.1.2016 |
|---|---|---|---|
| Opaque outer elements | 0.35 | 0.32 (−8 %) | 0.28 (−20 %) |
| Transparent outer elements | 1.9 | 1.7 (−10 %) | 1.5 (−21 %) |
| Curtain wall | 1.9 | 1.7 (−10 %) | 1.5 (−21 %) |
| Glass roofs, skylight, etc. | 3.1 | 2.8 (−10 %) | 2.5 (−19 %) |

4. Introduction of control systems for the compliance towards energy performance certificates, inspection reports of air-conditioning systems;
5. No change for existing buildings undergoing a refurbishment. Just the heat transfer coefficient requirement for outer doors has been tightened by approximately 38 %, and the trigger moment for the refurbishment of façades has been changed slightly.
6. Introduction of the ‘Model Building Approach’ (also called EnEV easy) as another alternative primary energy calculation method for residential buildings;

### 3.2.3 Act on the Promotion of Renewable Energies in the Heat Sector (Heat Act, EEWärmeG)

The EEWärmeG is an important regulation enforcing the use of renewable energies in the heat sector. The law was introduced in 2009 and amended in 2011. Part 2 of the EEWärmeG states obligations for a specific share of the heating demand (space heating and domestic hot water) that has to be produced by renewable energy sources in all new buildings and public buildings undergoing a major renovation. The overall target stated in the law is a 14 % renewable energy share in the heat consumption of Germany by 2020.

The EEWärmeG defines a major renovation as ‘any measure within a period not exceeding two years, by which a building has:

1. its boiler replaced or the heating system switched to another fossil fuel and;
2. over 20 % of its envelope renovated’.

The EEWärmeG affects buildings with a useful floor area of more than 50 m$^2$ and which require heating or cooling. The requirements are clearly defined for each type of renewable energy source (technology). These have to cover a certain share of the total energy demand for heating and cooling and are defined as follows:

- Solar energy: 15 %
- Gaseous biomass: 30 %
- Liquid/solid biomass: 50 %
- Geothermal energy and ambient heat: 50 %.

An important amendment made in the latest version of the EEWärmeG is the role model of public buildings and the expansion of the definition of ‘heat’, now also considering ‘cold’. Special requirements for public buildings undergoing major renovations are stated in Articles 5a of the law. In case of a major renovation with the use of gaseous biomass, a minimum share of 25 % of the heating and cooling demand of the buildings has to be covered by the renewable source. For the deployment of all other renewable sources, the necessary share is 15 %.

All building owners obliged to fulfil the requirements of the EEWärmeG are also allowed to alternatively implement one of the following measures:

- Exhaust heat: If exhaust heat pumps are used, 50 % of the heating demand has to be covered. If a ventilation system with heat recovery is used, a heat recovery rate of at least 70 % and a coefficient of performance (usable heat/electricity input) of 10 have to be achieved.
- Combined heat and power (COP): The COP plant has to be highly efficient, which means that the generation needs to result in primary energy savings compared to a reference situation;
- Energy saving measures: The maximum allowed primary energy demand and insulation requirements according to the actual EnEV have to be reduced by at least 15 %. In new public buildings, the average heat transfer coefficient has to be reduced by 30 % and in the case of a major renovation by 20 % compared to the requirements of the EnEV.
- District hot or cold temperatures: Allowed if a significant share of the hot or cold temperature is generated from renewable sources or a minimum 50 % by exhaust heat or CHP or a combination of all.

The Federal States are allowed to set higher obligations (see the following example of Baden-Württemberg).

### *Example from Baden-Württemberg—EEWärmeG-BW*

One interesting transposition of the requirements on national level has been made in the Federal State of Baden-Württemberg. The EEWärmeG-BW already entered into force one year earlier than on national level (1 January 2008). Since January 2010, the obligation to use renewable energies in buildings has even be expanded to existing buildings, and thus, Baden-Württemberg was the first and still is the only Federal State where renewable energy systems have to be considered in the case of a refurbishment of residential buildings, when the heating system is exchanged. In this case, at least 10 % of the heating demand has to be covered by renewable energies (depending on the specific technology). Also, the EEWärmeG-BW offers the opportunity to use alternative measures. Deviating from the options on national level, in Baden-Württemberg, a ventilation system with heat recovery is not considered in the law; instead, a photovoltaic system can be installed.

The evaluation report of the EEWärmeG-BW (UM Baden-Württemberg 2011) has shown that in about 42 % of all refurbishment cases, a solar thermal system has been installed, in 18 % a solid biomass, in 15 % biogas/bio oil, 3 % installed a heat pump and about 7 % used an alternative measure according to the law. For about 15 %, the obligation did not apply. In new buildings, the distribution differed significantly, led to about 34 % by alternative measures, 30 % heat pumps, 24 % solar thermal systems and 10 % solid biomass.

Whether the introduction of the obligation for existing buildings has led to a permanent decrease in the modernisation rate of heating systems in Baden-Württemberg cannot clearly be confirmed at this time.

*Amendment of the EEWärmeG*

The EEWärmeG is expected to be amended in 2013. According to the evaluation report of the EEWärmeG (BMU 2012; Hofmann et al. 2012), an option is also the expansion of the obligation for renewable energy systems to existing buildings. The following possibilities are just examples extracted from (BMU 2012; Hofmann et al. 2012), which show how the building stock could generally be addressed.

A principal consideration of the building stock is already stated in the European Renewable Energy Directive (European Parliament and the Council of the European Union 2009):

> By 31 December 2014, Member States shall, in their building regulations and codes or by other means with equivalent effect, where appropriate, require the use of minimum levels of energy from renewable sources in new buildings and in existing buildings that are subject to major renovation. Member States shall permit those minimum levels to be fulfilled, inter alia, through district heating and cooling produced using a significant proportion of renewable energy sources.

One way to address the building stock in the EEWärmeG is a regulative consideration. Thus, the regulative requirement can be defined in different ways:

- Different minimum shares for renewable sources (technologies)
- Different trigger moments
- Temporally graduated regulations
- Combination with complementing financial incentives.

One concrete option to expand the obligation on existing buildings would be a similar obligation as for new buildings.

Alternatively, the obligation can specifically be adjusted to existing buildings, for example, through a reduced obligation in terms of minimum shares of the heating demand that has to be covered by renewable energies. In order to achieve the same effects as in the first option, a complementing financial incentive had to be offered. Thus, the buildings owners would be motivated to voluntarily exceed the obligation. This configuration would be similar to that in Baden-Württemberg.

A further way to address the building stock is to connect the reduced obligation with another trigger moment, adjusted to criteria related to energy efficiency and air pollution control (e.g. stepwise increase in requirements regarding existing heating systems). As a result, owners of inefficient heating systems that no longer comply with the new more ambitious standards exchange these systems and in this process would need to comply with the requirements of the EEWärmeG.

However, whether the EEWärmeG will finally be expanded to existing buildings is still unsure. But, especially as Directive 2009/28/EC requires that member states set requirements regarding the use of minimum levels of energy from renewable sources in existing buildings that are subject to major renovation and due to the positive experiences in Baden-Württemberg, it can be expected that the Federal Government, somehow, will extend the EEWärmeG.

### 3.2.4 Heating Cost Ordinance, 2008[1]

The ordinance was introduced for the first time in 1981 and was revised three times in 1984, 1989 and 2008 (started in 2009). The first version of the document deals mainly with the obligation of the building owners to install metering systems and to report costs of heating and hot water supply to the consumers/users. The regulation aims to create an incentive for more rational use of heat and hot water by providing information on energy consumption and costs. Whereas the 2009 amendment of the ordinance engages with energy policy goals, the previous revisions aimed to eliminate failures which occurred in the practice.

One important new element that has been introduced in the 2008 amendment is an exemption of the obligation for new or refurbished buildings which have an annual heating demand of less than 15 kWh/m$^2$ (passive houses). The aim is to create an additional incentive to achieve this passive house standard during new construction and refurbishment of buildings (Lilova 2012).

## *3.3 Incentives for Energy-Related Building Refurbishments*

The building-related incentive programmes on national level are mainly provided by the governmentally owned KfW bank and the Federal Office of Economics and Export Control (BAFA). The KfW bank group offers a large number of financing programmes for both energy efficient refurbishment and new energy efficient buildings (KfW 2013):

- Programme 151 ‘Energy Efficient Refurbishment—KfW Efficiency house’ (soft loan)
- Programme 152 ‘Energy Efficient Refurbishment—Single measures’ (soft loan)
- Programme 153 ‘Energy Efficient Construction’ (soft loan)
- Programme 274 ‘Renewable energies standard—Photovoltaic’ (soft loan)

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[1] (Verordnung über die verbrauchsabhängige Abrechnung der Heiz- und Warmwasserkosten (Verordnung über Heizkostenabrechnung—Heizkosten V)), 2009.

- Programme 430 ‘Energy Efficient Refurbishment—Grant’
- Programme 431 ‘Energy Efficient Refurbishment—Refurbishment supervision’ (grant).

All of these programmes influence the refurbishment activities in the German building stock, also the ‘Energy Efficient Construction’ programme which gives soft loans for efficient new constructions.

The BAFA provides incentives for on-site energy advice, renewable energy heating systems and combined heat and power (CHP). On regional and even on city level, many more programmes may exist which are not described here.

### 3.3.1 KfW Energy Efficient Refurbishment

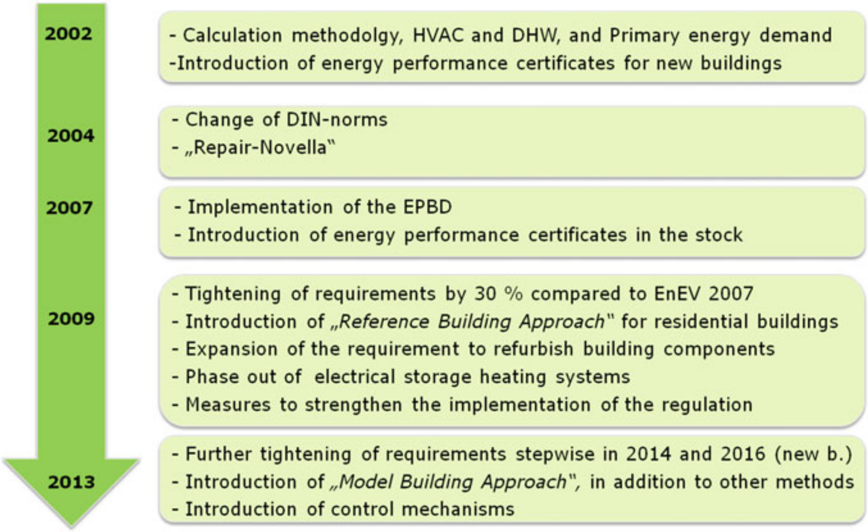
The $CO_2$ building refurbishment programme (today: Energy Efficient Refurbishment) started in 2001, when it became part of the National Climate Protection Programme, which aims to reduce the emissions of $CO^2$ in the building sector through energy-related refurbishments. To achieve the reduction targets of this programme, the KfW developed several measures for energy savings and climate protection in the building sector. The programme has shown a very positive impact regarding the reduction of $CO_2$ emissions (Bigalke et al. 2012; Diefenbach et al. 2012). Furthermore, the ‘Energy Efficient Refurbishment’ programme contributes to the introduction of efficient and modern technologies in the market of building refurbishment and, at the same time, incentivise individual measures towards energy savings (Diefenbach et al. 2012).

The annual budget for these programmes is set by the national government in the framework of the energy package. In 2012, the fund for the ‘Energy Efficient Refurbishment Programme’ was increased to 1.5 billion euros, and for 2013, it has again been increased by an additional 300 million euros to 1.8 billion euros. Figure 7 shows the development of funds from 2006 to 2013 [numbers from (Bigalke et al. 2012; SWR 2012)].

The programme is divided into several subprograms, namely the programme 430 for grants and subsidies, the programme 151 for loans for the development of KfW efficiency houses and the programme 152 for loans for individual measures or a combination of them. Programme 431 provides grants for a professional consultation of the refurbishment activity.

These programmes are all developed to enable house owners or renters to refurbish single- or two-family houses to KfW efficiency house standard or to take individual measures within an energy efficient refurbishment. The programme considers a wide variety of measures:

- the optimisation of the building envelope, for example, the thermal insulation of exterior walls, roofs, ceilings and basement floors, replacement of doors and windows, but also



- Calculation methodolgy, HVAC and DHW, and Primary energy demand
-Introduction of energy performance certificates for new buildings

- Change of DIN-norms
- „Repair-Novella"

- Implementation of the EPBD
- Introduction of energy performance certificates in the stock

- Tightening of requirements by 30 % compared to EnEV 2007
- Introduction of „*Reference Building Approach*" for residential buildings
- Expansion of the requirement to refurbish building components
- Phase out of electrical storage heating systems
- Measures to strengthen the implementation of the regulation

- Further tightening of requirements stepwise in 2014 and 2016 (new b.)
- Introduction of „*Model Building Approach*", in addition to other methods
- Introduction of control mechanisms

**Fig. 6** Chronological development of EnEV requirements

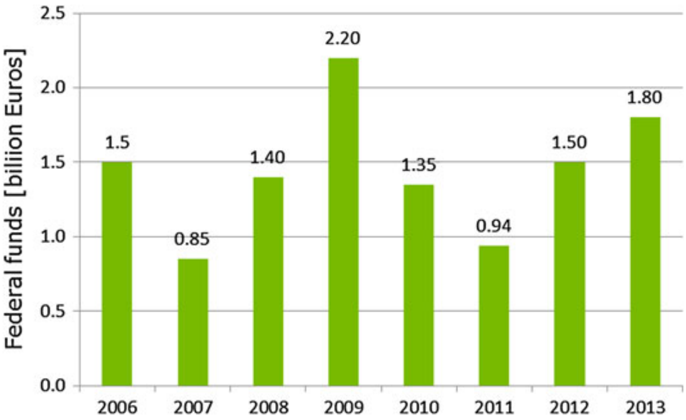


**Fig. 7** National available funds for the 'Energy Efficient Refurbishment Programme' between 2006 and 2013

- the supply side (HVAC) as, e.g. solar thermal installations, replacement of heating systems or equipments and optimisation of heat distribution (for existing heating systems, in the case of the programmes 152 and 430), installation of a ventilation system,
- additional construction costs (including the cost of the involved professionals), consulting, design and construction supervision. In the specific case of the programme 431, the incentive is intended to cover services for detailed

planning, assistance with tendering and incoming proposals, evaluation, control of the construction work and inspection, approval and evaluation of the refurbishment.

The better the achieved energy efficiency level of the building, the better the fund, either through lower interest rates or through larger grants that do not have to be paid back (Bigalke et al. 2012).

### *Programme 430*

Since 2013, within the programme 430 for individual measures, the households can get a grant that covers up to 10 % of the investment costs with a maximum of 5,000 euros. For an energy efficient refurbishment of the entire building, households can get a grant of up to 18,750 euros depending on which KfW standard was achieved with the renovation activity (SWR 2012).

### *Programme 151 + 152*

The KfW additionally offers soft loans for comprehensive building measures. In programme 151, building refurbishments achieving an ‘efficiency house standard’ get special conditions for loans up to 75,000 euros per dwelling and, depending on the achieved standard, get an additional redemption grant of varying sizes up to 12.5 %. Also, for individual measures, the KfW offers loans with low interest rates of up to 50,000 euros (programme 152).

### *Programme 431*

Within the programme 431, households can get a grant that covers up to 50 % and a maximum of 4,000 euros of the costs for a professional supervision of a refurbishment activity.

So far, the KfW does not provide incentives for KfW ‘efficiency house 40’ refurbishments. The most ambitious refurbishments that are promoted by the KfW are refurbishments to the standard ‘efficiency house 55’. The first year of incentives for this building standard was in 2010. The KfW statistics (KFW 2012) of recent years show that more than 400 of such buildings are directly supported by the KfW per year. But also other high-performance standards such as the efficiency house 70 and 85 have been achieved through refurbishments (see Fig. 8).

Figure 8 shows that even if the total number of promoted refurbishments decreased in the period 2010-3.Q 2012, the specific share of ‘efficiency house 55’ has increased from about 1.7 % in 2009 to about 10 % in 2012. However, no refurbishments have yet achieved the efficiency house 40 standard yet and it is still not clear whether the KfW will accept this standard into its programme in 2013.

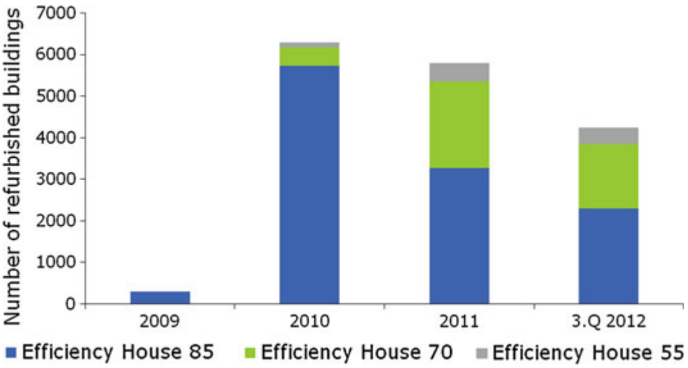


**Fig. 8** A number of high-performance building refurbishments in the KfW supports programme ‘Energieeffizient Sanieren’, 2009-3. quarter 2012 (KFW 2012)

### 3.3.2 KfW Energy Efficient Construction

The KfW programme ‘Energy Efficient Construction’ started in 2009. Similar to the previous programme called ‘Ecological building’, this programme provides financial support for energy efficient building projects through loans with low interest rates (Diefenbach et al. 2012).

The specific building standards under this programme go beyond the requirements for new buildings set by the actual EnEV. To achieve these standards, it is necessary to implement an extensive package of measures regarding thermal insulation and heat supply. Thereby, the support programmes from the KfW have an important role in trendsetting new energy efficiency standards and technologies as well as their introduction in the market.

For instance, it is interesting to observe the important contribution of the KfW funds in the new construction market: the number of new buildings funded by the KfW in 2011 represents 41 % of the total number of permissioned building in this year in Germany (Diefenbach et al. 2012).

In 2011, three different levels of the KfW efficient house were funded by the ‘Energy Efficient Construction’ programme, namely the KfW efficiency houses 40 (or passive houses), 55 and 70, which are defined in relation to the new building standards of EnEV 2009.

Although the efficiency house 40 and the passive house standard are not supported in the ‘Energy Efficient Refurbishment’ programme, they help to raise awareness for these standards which would be in line with the proposed nZEB standard of Erhorn et al. (2012), see Sect. 2. Thus, the ‘Energy Efficient Construction’ programme has an important impact on the refurbishment sector as it provides incentives for standards that are still more efficient than those of the KfW refurbishment programme. It also raises awareness of overly ambitious standards before they are supported later on in the refurbishment programme.

### 3.3.3 BAFA On-Site Energy Advice

This programme is coordinated by the Federal Office of Economics and Export Control (BAFA) and provides grants for consultation services in the field of energy efficiency and energy savings for home owners, companies of the building industry and agricultural.

After an individual analysis of the building, the energy expert creates a renovation concept for the building and an action plan with most recommended measures in order to achieve the eligible energy saving standards of a specific KfW efficiency house, based on the KfW 'Energy Efficient Refurbishment' programme (BMWI 2012b).

The energy consultant is responsible for applying for the grant. The cost for a single- or two-family house is 400 euros and 500 euros for a building with 3 or more residential units. The grant, however, only covers up to 50 % of the consultancy fees. In addition, the programme offers a bonus of 50 euros for the integration of additional electricity saving measures and up to 100 euros for thermographic inspections (BMWI 2012b).

### 3.3.4 Energy Advice for Private Customers

Through this programme, consultation is provided for customers by experienced experts in energy-related issues, including, among other topics, insulation measures, solar energy, energy efficient heat pumps and advice regarding available incentive programmes. This is provided by the 'consumer advice centres' of the Federal States and is funded by the Federal Ministry of Economics and Technology (BMWI). Within this programme, advice for private customers is given through personal consultation in the advice centre, case management through an on-site consultation with the household, telephone consultation, online consultation, basic check-up, building check and inspection of condensing devices. The services are not cost free but are partially financed by the BMWI and thus cost-reduced and comparably cheap (Verbraucherzentrale 2012).

### 3.3.5 BAFA Market Incentive Programme for Renewable Energies (Marktanreizprogramm, MAP)

The Market Incentive Programme for Renewable Energies (MAP) is financed by the Federal Office of Economics and Export Control (BAFA) and provides support for a variety of technologies in the field of renewable energy systems in the building sector, such as solar thermal installations, biomass (pellet) boilers and heat pumps. Therefore, the MAP programme represents the main financial instrument in this field. It offers grants for small-scale project refurbishments of existing or new single- and two-family houses.

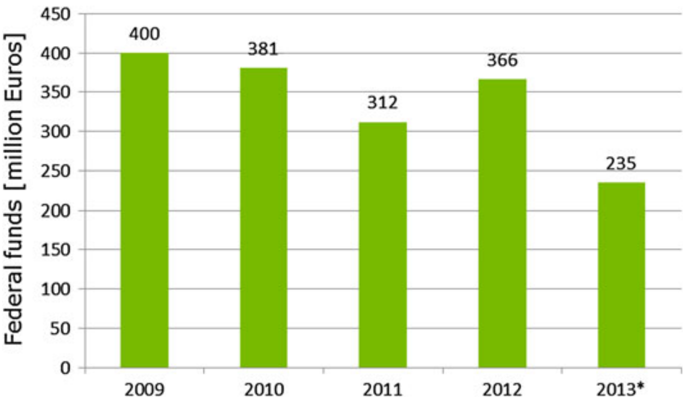


**Fig. 9** Federal funds available for the Market Incentive Programme for Renewable Energies (MAP). *: To be confirmed. Numbers from (Deutscher Bundestag 2012a, b)

Figure 9 shows the amount of funds available for the MAP programme between 2009 and 2012.

Since 2008, the promotion in this programme has consisted of a base incentive and a bonus incentive. The bonus incentive is available for especially effective systems or combinations of different renewable energy sources. Table 9 shows the promotion conditions for selected measures in the MAP programme (Numbers from (BAFA 2012; Enbausa 2012)) (Table 9).

Furthermore, the MAP evaluation report (Langniß et al. 2010) analysed how the Federal fund in the MAP has been used in recent years. The following Fig. 10 shows the distribution of funded systems distinguished by biomass systems, solar thermal systems and heat pumps.

Figure 10 shows that the majority of funded systems in the MAP are solar thermal systems with a share of approximately 60 % in 2011, followed by biomass plants with a share of about 30 % and heat pumps with about 10 %.

### 3.3.6 Renewable Energy Sources Act (EEG) 2012

The renewable Energy Sources Act (‘Act on granting priority to renewable energy sources’, EEG) was established in 2000. It is the main instrument for the expansion of renewable energy systems producing electricity. The objective is to increase the share of renewable energy sources in the German electricity supply by 35 % until 2020, 50 % until 2030, 65 % until 2040 and 80 % until 2050. The Act ensures that produced electricity from renewable sources is purchased by the local energy supplier and guaranties a specific price for each kWh electricity for the next 20 years. The act strongly promotes the spreading of photovoltaic plants (PV) on buildings and thus is an important instrument that opens the door for nZEB

**Table 9** Promotion conditions in the Market Incentive Programme for Renewable Energies (MAP)

| Selected measures supported by BAFA | | Amount of support | Bonus |
|---|---|---|---|
| Solar thermal collectors | Up to 40 m$^2$ gross collector area | 1.500 € to 3.600 €<br>90 €/m$^2$ | 500 € combination for solar thermal energy + heat pump or solar thermal energy + biomass<br>500 € for additional replacement of an old boiler without condensing technology with a new condensing boiler<br>Efficiency bonus for buildings that meet at least the requirements for an efficiency house 55: 0,5 × base funding |
| | Between 20 to 100 m$^2$ gross collector area in multi-family houses and large non-residential buildings (even in new construction) | 3.600 € to 18.000 €<br>135 €/m$^2$ | |
| | Up to 1.000 m$^2$ for the production of process heat | Up 50 % of the net investment costs | |
| | Expansion of existing facilities | 45 €/m$^2$ | |
| Biomass plants | Pellet stoves with water pocket | 1.400 € to 3.600 €<br>36 €/m$^2$ | 500 € combination for heat pump or solar thermal energy + biomass<br>Efficiency bonus for buildings that meet at least the requirements for a efficiency house 55: 0,5 x base funding |
| | Pellet boiler | 2.400 € to 3.600 €<br>36 €/m$^2$ | |
| | Pellet boiler with buffer storage (at least 30 l/kW) | 2.900 € to 3.600 € | |
| | Woodchip burning boilers with buffer storage | 1.400 € | |
| | Chopped wood gasification with buffer storage | 1.400 € | |
| Heat pumps | Brine/water and water/water heat pumps | 2.800 € to 11.800 € | 500 € combination for solar thermal energy + heat pump<br>Efficiency bonus for buildings that meet at least the requirements for an efficiency house 55: 0,5 x base funding |
| | Brine/water and water/water heat pumps with buffer storage | 3.300 € to 12.300 € | |
| | Air/water heat pumps | 1.300 € resp. 1.600 € | |
| | Air/water heat pumps with buffer storage | 1.800 € resp. 2.100 € | |

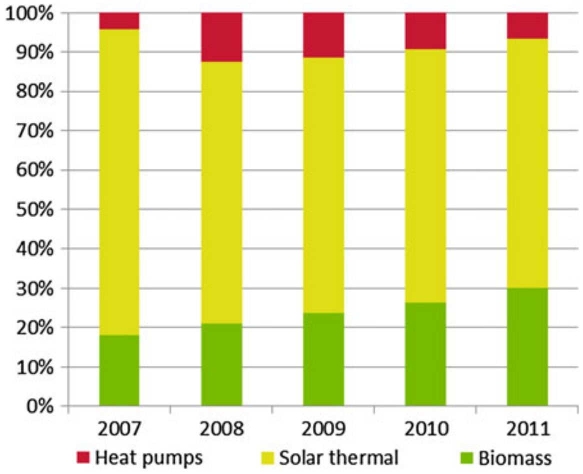
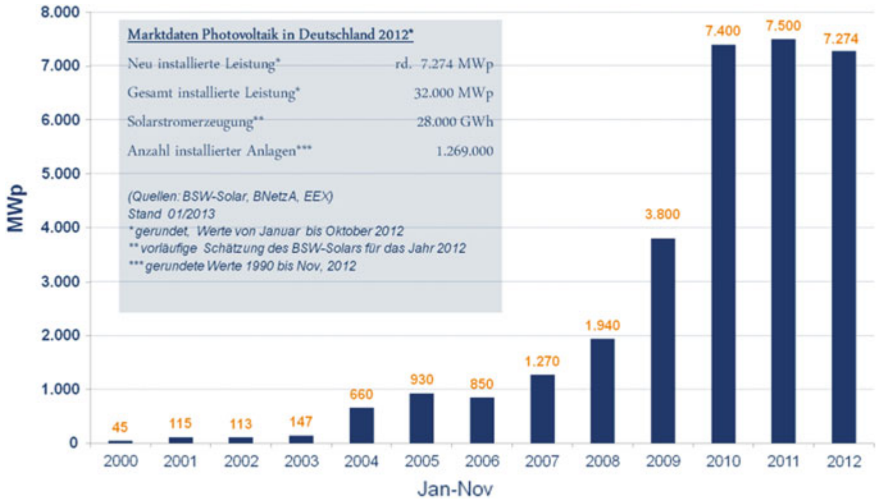


**Fig. 10** Number of funded systems in the MAP. Numbers based on (Kohberg 2012; Langniß et al. 2010)



Marktdaten Photovoltaik in Deutschland 2012*

| | |
|---|---|
| Neu installierte Leistung* | rd. 7.274 MWp |
| Gesamt installierte Leistung* | 32.000 MWp |
| Solarstromerzeugung** | 28.000 GWh |
| Anzahl installierter Anlagen*** | 1.269.000 |

(Quellen: BSW-Solar, BNetzA, EEX)
Stand 01/2013
*gerundet, Werte von Januar bis Oktober 2012
**vorläufige Schätzung des BSW-Solars für das Jahr 2012
***gerundete Werte 1990 bis Nov, 2012

**Fig. 11** Development of annual newly installed photovoltaic capacity in Germany in the period 2000–2012 (MWp)

refurbishments or even plus energy buildings in Germany (The Federal Government 2012a).

Figure 11 illustrates the annual newly installed photovoltaic capacity in Germany since 2000 (BSW-Solar 2013).

### 3.3.7 Combined Heat and Power Act, 2012

The Combined Heat and Power Act (KWKG) aims to promote and increase the generation of electricity from combined heat and power in the Federal Republic of Germany to 25 percent by 2020 in order to contribute to the energy conservation targets, environmental protection and the achievement of climate change objectives of the Federal Government. This act supports the modernisation and construction of combined heat and power plants (CHP), the market introduction of fuel cells and the funding for the construction and expansion of heating and cooling systems as well as the construction and extension of heat and cold storage in the heat or cold CHP plants. Based on this act, a specific amount of money is paid to system owners for each kWh electricity that is fed into the grid (Bundesrepublik Deutschland 2012).

## *3.4 Market Instruments Related to Building Refurbishments*

In Germany, different kinds of market instruments exist in order to stimulate the energy efficient transition of the existing building stock in order to achieve energy savings and climate protection targets. These market instruments work as tools for promoting and strengthening energy efficiency-related issues in the market (Bigalke et al. 2012). A selection of the most important instruments and stakeholders is described below.

### 3.4.1 State funded Agencies for the Dissemination of Information and Awareness Raising

The main objectives are the dissemination of information and the development of related policies linking the different stakeholders involved in the process.

*German Energy Agency (dena)—'Thema Energie'*

The 'dena' has diverse functions as a market instrument, especially regarding the promotion of energy efficient solutions and development of energy alternatives, through information, consultation and research programmes. It provides information for the general public regarding energy-related topics, such as intelligent energy systems, energy efficiency and renewable energy sources, and also, dena carries out research and analysis programmes and works together with stakeholders in order to develop projects in the mentioned topics (Lilova 2012).

For the dissemination of information, dena has created the Internet platform 'Thema Energie' and the 'Energy Hotline'. On the Website, professionals and customers can find information regarding energy efficiency, renewable energies, heating and power systems, consultation and funding opportunities, databases and catalogues. In the 'Energy Hotline', both professionals and homeowners cannot just find information but also advice regarding the aforementioned topics (dena 2012).

*Agency for Renewable Energies (AEE)*

The AEE is the result of a public–private partnership (state, companies and associations). It is partly financed by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and Federal Ministry of Food, Agriculture and Consumer Protection (BMELV). Its objectives are the promotion of alternative energy sources and to offer information concerning the advantages of energy systems based on renewable energy sources for electricity production (Lilova 2012).

*Agency for Renewable Resources (FNR)*

The FNR (Fachagentur Nachwachsende Rohstoffe e.V.) was founded in 1993 by the German Federal Ministry of Food, Agriculture and Consumer Protection. Its main responsibility is to support research and development in the area of renewable resources, but also to inform the public about current research results, to give advice on a range of applications of renewable resources and to organise and take part in scientific events.

*The Information service (BINE)*

This programme has been developed by the BMU and the BMWi in cooperation with the German Energy Agency (dena). The purpose is to provide information about financing opportunities for renewable energy and energy savings in the building and industrial sector (Lilova 2012).

### 3.4.2 Energy Performance Certificates

Energy performance certificates include details of the building use and construction, including its energy performance (building envelope and the systems for lighting, heating, ventilation, cooling and hot water). These certificates have been mandatory for new buildings and major refurbishments since 2002 and have a validity of 10 years. The certificates can be of two types: based on calculated demand and consumption based (according to the records of heating costs for at least 36 continuous months). An important component of these certificates is the recommendation for cost-efficient modernisation measures to bring down the energy consumption of the building. The general objective of these certificates is to bring more transparency to the market and raise the interest of owners to invest in the energetic refurbishments of their buildings (Bigalke et al. 2012; Schimschar et al. 2013b).

### 3.4.3 Information and Motivation: National Information and Communication Programs

One of the most important steps to promote the energetic refurbishment of buildings is the dissemination of information both for the users and for the professionals. The 'House of the Future' campaign and $CO_2$ building refurbishment programme are launched by the BMVBS and are part of the German support strategy. The main objectives are the motivation and information of consumers/owners, tenants, professionals of the building sector and the construction industry regarding energy efficient solutions and renewable energy alternatives (Bigalke et al. 2012; Schimschar et al. 2013b).

The 'Climate Seeks Protection' campaign is carried out by co2online GmbH and is cofunded by the German Federal Ministry for the Environment. The objective of the campaign is to motivate consumers (private households, trade and commerce) to get informed and to invest in energy efficiency heating and cooling systems and energy-related building refurbishments. The main components are online advises, prize competitions and media campaigns (co2online 2012).

### 3.4.4 Market Transparency and Quality Assurance

An important quality assurance instrument has been implemented with the EnEV 2009 amendment. Thus, a written declaration of the construction company has to be provided that certificates that all changes in the building and installed systems and equipment meet the requirements of the EnEV (Bigalke et al. 2012).

For the motivation of the households and building owners, it is also important to get access to professional advice assuring the selection of the best and most cost-effective refurbishment options. Thus, a list of energy efficiency experts for federal funding programmes was implemented in 2011. Qualified professionals can register in this database for the programmes 'on-site energy advice' from the BAFA (see Sect. 3.3.3) and KfW programme 431 'Energy Efficient Refurbishment—Refurbishment supervision'. Companies or private users can then search for a qualified professional according to the location and specialisation (Bigalke et al. 2012).

Another list of energy-related services is offered by the 'Federal Office for Energy Efficiency' (BfEE). This is a list of providers/suppliers of energy services, energy audits and different energy efficiency measures.

### 3.4.5 Research and Pilot Projects

It is very important to assess the energy efficiency potential in the building sector and therefore allowing the appropriate promotion of innovative, reliable and affordable solutions and ensuring their entry into the market. For this purpose, the German Ministries implemented many programmes related to applied investigation. A selection is presented here.

*Research for an environmentally sound, reliable and affordable Energy Supply*

Within this programme and the Federal Government's Energy Concept of 2010, the research and funding focus of the Federal Government's policies for the coming years is defined. The main objective is the improvement in the cooperation between economy, science and politics. Moreover, the programme promotes the research and development of innovative solutions for energy technologies in the field of renewable energies, energy efficiency, energy storage and energy network. In addition to this, the programme aims to build international cooperations in the field of research on energy technologies (Bigalke et al. 2012).

*'Future Building Campaign' (Zukunft Haus)*

The objective of this programme is to research and promote energy efficiency and the use of renewable energy on the building sector through the development of pilot projects, materials and technologies. The solutions found would then be brought into the market as tested, mature and approved solutions (dena Gebäudereport).

**Table 10** List of building sector-related associations in Germany

| Name of Association | URL |
|---|---|
| Federal Bio-energy Association (BBE) | http://www.bioenergie.de |
| Federal Renewable Energy Federation (BEE) | http://www.bee-ev.de |
| Federal Solar Industry Association (BSW) | http://www.solarwirtschaft.de |
| Federal Heat Pumps Association (BWP) | http://www.waermepumpe.de |
| Wood and Pellet Association (DEPV) | http://www.depv.de |
| Federal Industrial Association of Building Services (BTGA) | http://www.bhks.de |
| Federal Industrial Association of Germany House, Energy and Environmental Technology (BDH) | http://www.bdh-koeln.de |
| The energy efficiency association for heating, cooling and CHP (AGFW) | http://www.agfw.de/ |
| German Refrigeration and Air-Conditioning Association (DKV) | http://www.dkv.org |
| Association thermal insulation composite system | http://www.heizkosten-einsparen.de/ |
| Building Climate Association (FGK) | http://www.fgk.de |
| Association of Insulating Materials Industry (GDI)—http://www.gdi-daemmstoffe.de | http://www.gdi-daemmstoffe.de |
| German Engineering Federation (VDMA) | http://www.vdma.org |
| Association of the German Refrigeration and Air-Conditioning Specialized Companies (VDKF) | http://www.vdkf.de |
| Central Association for Sanitation, Heating and Air-conditioning (ZVSHK) | http://www.wasserwaermeluft.de |
| Association for insulation materials from renewable raw materials (ADNR) | |

***'On the way to the efficient house Plus'***

This is a programme for building refurbishments with the same principles as the 'Future Building' programme mentioned above. 'Dena' shows, through pilot projects, best practice examples of cost-effective energetic refurbishments that have the potential to be transferred and reproduced. Furthermore, this programme serves as a tool for the further development of political instruments in this field (Bigalke et al. 2012).

### 3.4.6 Relevant Associations

Associations are funded and formed by private companies and professionals of each specific operational area. The different associations have the main goal to increase the share of their specific technologies in the market. For this purpose, the associations aim to promote the dissemination of information among customers and stakeholders as well as to strengthen their political importance or impact. They have a strong political presence and are usually involved in both political relations and political advice. A selection of relevant agencies related to building technologies is listed below: (Table 10).

## 4 Conclusions

Germany has introduced a clear legislative framework with regard to nearly zero-energy building refurbishments. The German legislative system is well structured and organised and is easily accessible. The wide availability of financial instruments facilitates the penetration and further development of nZEB. The most important support instrument of the German government is the KfW scheme 'Energy Efficient Refurbishment'. Through soft loans and grants, it offers strong incentives for building owners to refurbish their buildings to a high-performance standard. However, the current research status regarding a possible nZEB definition and primary energy requirement is expected to be at a level of about 30 kWh/m$^2$a and such a refurbishment standard is so far not promoted by the KfW.

Nevertheless, the KfW incentive statistics show that already, many high-performance refurbishments take place in the building stock and the share of most ambitious building refurbishments is continuously growing. This trend is also supported by the strong 'Market Incentive Programme for Renewable Energies' (MAP), which is the main tool for the market expansion of renewable energy technologies in the domestic energy market. Furthermore, a comprehensive set of market instruments accompanies the process of high-performance refurbishments.

Information on current legislation, financing possibilities and benefits of high-performance buildings and renewable energy technologies is provided by ministries, organisations and associations to all actors of the energy market—from energy suppliers to the general public. The clear structure of the German legislative system in combination with the availability of financing tools and information campaigns has ensured overcompliance with the EU guidelines. In its effort to remain leader in the field of high-performance buildings and renewable energy technologies, the Federal Government has established stringent obligations and has set very ambitious goals for the further development of high-performance building refurbishments. If the German government does not stop the financial support in this area, a significant development of nZEB refurbishments can furthermore be expected in coming years.

However, while the draft of the EnEV 2013/2014 introduces stricter requirements for new buildings with a view to achieving nearly zero-energy buildings in 2020, there are no major impulses related to high-performance refurbishments. This leaves a gap on how to achieve the ambition of an ‘almost climate-neutral building stock by 2050’, but also reflects the circumstance that a refurbishment road map for Germany is still under discussion.

## References

Association of German Engineers (2000) VDI 2067: wirtschaftlichkeit gebäudetechnischer Anlagen—Grundlagen und Kostenberechnung. Verein Deutscher Ingenieure, German

BAFA (2012) Web Page: Heizen mit Erneuerbaren Energien. Available: http://www.bafa.de/bafa/de/energie/erneuerbare_energien/index.html. Last Accessed 12 Jan 2013. In German

Bahr C, Lennerts K (2010) Lebens- und Nutzungsdauer von Bauteilen. Available: http://www.bbsr.bund.de/cln_032/nn_340546/BBSR/DE/FP/ZB/Auftragsforschung/2NachhaltigesBauenBauqualitaet/2009/LebensNutzungsdauer/Endbericht,templateId=raw,property=publicationFile.pdf/Endbericht.pdf. Last Accessed 10 Jan 2013. Bundesamtes für Bauwesen und Raumordnung (BBR), Berlin, Deutschland. In German

BBSR (2009) Lebensdauer von Bauteilen und Bauteilschichten: Tragkonstruktion, Nichttragende Konstruktion, Installationen und betriebstechnische Anlagen, Außenanlagen (Info Blatt Nr. 4.2) Available: http://www.ekiba.de/download/Blatt_4-2_Lebensdauer-von-Bauteilen.pdf. Last Accessed 10 Jan 2013. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR), Bonn, Germany. In German

BBSR (2011) Nutzungsdauern von Bauteilen für Lebenszyklusanalyse nach Bewertungssystem Nachhaltiges Bauen. Available: http://www.nachhaltigesbauen.de/fileadmin/pdf/baustoff_gebauededaten/BNB_Nutzungsdauern_von_Bauteilen__2011-11-03.pdf. Last Accessed 10 Jan 2013, Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), Berlin, Germany. In German

Bettgenhäuser K, Boermans T, Grözinger J (2012) Entwicklung eines Referenzszenarios im Gebäudebereich für das Gesamtziel, 40% $CO_2$-Einsparung bis 2020“Ecofys. Available:http://www.bbsr.bund.de/cln_032/nn_187722/BBSR/DE/Veroeffentlichungen/BMVBS/Online/2012/DL__ON262012,templateId=raw,property=publicationFile.pdf/DL_ON262012.pdf. Last Accessed: 3 Jan 2013, Federal Ministry of Transport, Building and Urban Development, Berlin, Germany. In German

Bigalke U, Discher H, Lukas H, Zeng Y, Bensmann K, Stolte C (2012) Der dena-Gebäudereport 2012—Statistiken und Analysen zur Energieeffizienz im Gebäudebestand. Deutsche Energie-Agentur (dena), Berlin, Germany. In German

BMU (2005) Nationales Klimaschutzprogramm 2005—Sechster Bericht der Interministeriellen Arbeitsgruppe, $CO_2$—Reduktion. Available: http://www.bmu.de/fileadmin/bmu-import/files/

klimaschutz/downloads/application/pdf/klimaschutzprogramm_2005_lang.pdf. Last Accessed: 16 Jan 2013, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Berlin, Germany. In German

BMU (2012) Erfahrungsbericht zum Erneuerbare-Energien-Wärmegesetz (EEWärmeG-Erfahrungsbericht) Available: http://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/eewaermeg_erfahrungsbericht.pdf. Last Accessed 08 Jan 2013, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, Germany. In German

BMVBS (2011) Web Page: Weltmeister im Energiesparen. Available: http://www.bmvbs.de/SharedDocs/DE/RedenUndInterviews/2011/ramsauer-namensartikel-handelsblatt-07-06-2011-energiekonzept.html?nn=35708. Last Accessed 10 Jan 2013, In German

BMVBS,BMWI (2012) Ministerial draft for the change of the Energy Saving Ordinance 2009. Available: http://www.zukunft-haus.info/fileadmin/zukunft-haus/energieausweis/Gesetze_Verordnungen/EnEV/Lesefassung_Entw_2.VO_zur_Aenderung_EnEV.pdf. Last Accessed: 8 Jan 2013, In German

BMWi (2007). Eckpunkte für ein integriertes Energie- und Klimaprogramm. Available: http://www.bmwi.de/BMWi/Redaktion/PDF/E/eckpunkt-fuer-ein-integriertes-energie-und-klima-programm,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf. Last Accessed: 16 Jan 2013, Federal Ministry for Economy and Technology, Berlin, Germany. In German

BMWi (2010a) Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Available: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/energiekonzept-2010,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf. Last Accessed 12 Mar 2012, Bundesministerium für Wirtschaft und Technologie (BMWi), München, Deutschland

BMWi (2010b) Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply. Available: http://www.bmwi.de/English/Redaktion/Pdf/energy-concept,property=pdf,bereich=bmwi,sprache=en,rwb=true.pdf. Last Accessed: 10 Jan 2013. Federal Ministry of Economics and Technology (BMWi), Berlin, Germany

BMWI (2011a) 2. Nationaler Energieeffizienz-Aktionsplan (NEEAP) der Bundesrepublik Deutschland gemäß EU-Richtlinie über Endenergieeffizienz und Energiedienstleistungen (2006/32/EG). Available: http://www.bmwi.de/Dateien/BMWi/PDF/zweiter-nationaler-energieeffizienz-aktionsplan-der-brd,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf. Last Accessed 10 Jan 2013. Federal Ministry of Economics and Technology (BMWi), Berlin, Germany. In German

BMWI (2011b) Endenergieverbrauch nach Anwendungsbereichen 2010. Available: http://www.bmwi.de/BMWi/Redaktion/Binaer/Energiedaten/energiegewinnung-und-energieverbrauch5-eev-nach-anwendungsbereichen,property=blob,bereich=bmwi2012,sprache=de,rwb=true.xls. Last Accessed 10 Jan 2013, Federal Ministry of Economics and Technology (BMWi), Berlin, Germany. In German

BMWI (2011c) Second National Energy Efficiency Action Plan (NEEAP) of the Federal Republic of Germany Pursuant to the EU Directive on Energy End-use Efficiency and Energy Services (2006/32/EC). Available: http://www.bmwi.de/English/Redaktion/Pdf/zweiter-nationaler-energieeffizienz-aktionsplan-der-brd. Last Accessed 16 Jan 2013, Federal Ministry of Economics and Technology (BMWi), Berlin, Germany. In German

BMWI (2012a) Die Energiewende in Deutschland—Mit sicherer, bezahlbarer und umweltschonender Energie ins Jahr 2050. Available: http://www.bmwi.de/Dateien/BMWi/PDF/energiewende-in-deutschland,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Last Accessed 16 Jan 2013, Federal Ministry of Economics and Technology (BMWi), Berlin, Germany. In German

BMWI (2012b) Energiesparberatungvor Ort—Ein Förderprogramm des Bundesministeriums für Wirtschaft und Technologie. Available: http://www.bafa.de/bafa/de/energie/energiesparberatung/publikationen/sonstiges/energie_vob_bmwi_faltblatt.pdf. Last Accessed 12 Jan 2013, Federal Ministry of Economics and Technology (BMWi), Berlin, Germany. in German

BMWI (2012c) Nationales Reformprogramm 2012. Available: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/nationales-reformprogramm-2012,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Last Accessed 16 Jan 2013, Federal Ministry of Economics and Technology (BMWi), Berlin, Germany. In German

Boermans T, Bettgenhäuser K, Hermelink A, Schimschar S (2011a) Cost optimal building performance requirements: calculation methodology for reporting on national energy performance requirements on the basis of cost optimality within the framework of the EPBD. Ecofys. Available: http://www.eceee.org/buildings/cost_optimality/cost_optimality-eceeereport.pdf. Last Accessed 03 Jan 2013, European Council for an Energy Efficient Economy (ECEEE), Stockholm, Sweden

Boermans T, Bettgenhäuser K, Offermann M, Schimschar S (2012) Renovation tracks for Europe up to 2050: building renovation in Europe—what are the choices? Ecofys. Available: http://www.eurima.org/uploads/ModuleXtender/Publications/90/12-06-08_Ecofys_X_Renovation_tracks_for_Europe_FINAL.pdf. Last Accessed 03 Oct 2012, European Insulation Manufacturers Association, Brussels, Belgium

Boermans T, Hermelink A, Schimschar S, Grözinger J, Offermann M, Thomsen KE, Rose J, Aggerholm SO (2011b) Principles for Nearly Zero Energy Buildings—Paving the way for effective implementation of policy requirements. Ecofys, Danish Building Research Institute (SBi). Available: http://www.ecofys.com/files/files/ecofys_bpie_2011_nearlyzeroenergybuildings.pdf. Last Accessed 08 Jan 2013, Building Performance Institute Europe (BPIE), Brussels, Belgium

BSW-Solar (2013). Entwicklung des deutschen PV-Marktes Jan-Nov 2012. Available: http://www.solarwirtschaft.de/fileadmin/media/pdf/bnetza_0111_kurz.pdf. Last Accessed 12 Jan 2013, Bundesverband Solarwirtschaft e.V. (BSW-Solar) Berlin, Germany. In German

Bundesrepublik Deutschland (2002) Perspektiven für Deutschland—Unsere Strategie für eine nachhaltige Entwicklung. Available: http://www.bundesregierung.de/Content/DE/_Anlagen/2006-2007/perspektiven-fuer-deutschland-langfassung.pdf?__blob=publicationFile. Last Accessed 15 Feb 2012, Bundesregierung Deutschland, Berlin, Germany

Bundesrepublik Deutschland (2010) Nationaler Aktionsplan für erneuerbare Energie gemäß der Richtlinie 2009/28/EG zur Förderung der Nutzung von Energie aus erneuerbaren Quellen. Available: http://www.bmu.de/files/pdfs/allgemein/application/pdf/nationaler_aktionsplan_ee.pdf. Last Accessed 16 Jan 2013, In German

Bundesrepublik Deutschland (2012) Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung (Kraft-Wärme-Kopplungsgesetz). Available: http://www.gesetze-im-internet.de/bundesrecht/kwkg_2002/gesamt.pdf. Last Accessed 12 Jan 2013, In German

co2online (2012) Web Page: climate Seeks Protection. Available: http://www.klima-sucht-schutz.de/english.html. Last Accessed 10 Jan 2013

Concerted Action Energy Performance of Buildings (2011) Implementing the energy performance of buildings directive (EPBD). Available: http://www.epbd-ca.org/Medias/Downloads/CA_Book_Implementing_the_EPBD_Featuring_Country_Reports_2010.pdf. Last Accessed 10 Jan 2013). European Union, Brussels, Belgium

dena (2012) Web page: energy information service. Available: http://www.dena.de/en/projects/energy-services/energy-information-service.html. Last Accessed 10 Jan 2013

dena (2013). Web Page: German Energy Saving Ordinance (EnEV 2009). Available: http://www.zukunft-haus.info/index.php?id=11883. Last Accessed 03 Jan 2013

Deutscher Bundestag (2012a) Änderungsantrag der Fraktion der SPD zu der zweiten Beratung des Gesetzentwurfs der Bundesregierung—Drucksachen 17/10200, 17/10202, 17/10823, 17/10824, 17/10825–. Available: http://dipbt.bundestag.de/dip21/btd/17/115/1711524.pdf. Last Accessed 12 Jan 2013. Deutscher Bundestag, Berlin, Germany. In German

Deutscher Bundestag (2012b) Stenografischer Bericht 171. Sitzung. Berlin, Mittwoch, den 28. März 2012. Available: http://dipbt.bundestag.de/dip21/btp/17/17171.pdf#P.20169. Last Accessed 12 Jan 2013. Deutscher Bundestag, Berlin, Germany. In German

Diefenbach N, Cischinsky H, Rodenfels M,Clausnitzer K-D (2010) Datenbasis Gebäudebestand—Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen Wohnugebäudebestand. Bremer Energie Institut, Institut Wohnen und Umwelt. Available: http://datenbasis.iwu.de/dl/Endbericht_Datenbasis.pdf. Last Accessed 10 Jan 2013. Bundesamt für Bauwesen und Raumordnung (BBR), KfW Bankengruppe, Hessisches Ministerium für Umwelt, Energie, Landwirtschaft und Verbraucherschutz, Darmstadt, Germany. In German

Diefenbach N, Stein B, Loga T, Rodenfels M, Gabriel J, Fette M (2012) Monitoring der KfW-Programme “Energieeffizient Sanieren” und “Energieeffizient Bauen” 2011 Institut Wohnen und Umwelt (IWU), Bremer Energie Institut. Available: http://www.kfw.de/kfw/de/I/II/Download_Center/Fachthemen/Research/PDF-Dokumente_Evaluationen/Monitoring_EBS_2011.pdf. Last Accessed 12 Jan 2013. KfW-Bankengruppe, Frankfurt am Main, Germany. In German

Discher H (2010) Energieeffizientes Bauen und Sanieren—Chancen und Aufgaben. Available: http://www.dena.de/fileadmin/user_upload/Download/Veranstaltungen/2010/dena_dialog_berlin/Discher.pdf. Last Accessed: 10 Jan 2013. German Energy Agency (dena), Berlin, Germany. In German

Enbausa (2012) Web Page: Bafa bietet Basisförderung plus Bonus. Available: http://www.enbausa.de/finanzierung-beratung/erneuerbare-zur-waermeerzeugung.html. Last Accessed 12 Jan 2013. In German

Erhorn-Kluttig H, Erhorn H, Thomsen KE, Nyffenegger U (2011) Trends in National Nearly Zero-Energy Building Approaches. Available: http://vbn.aau.dk/files/58112422/AIVC_Trends_in_NZEBs_Erhorn_Kluttig_02_10_11.pdf. Last Accessed: 03 Jan 2013. Fraunhofer Institute for Building Physics, Danish Building Research Institute, Amt für Umweltkoordination und Energie Bau-, Verkehrs- und Energiedirektion des Kantons Bern, Stuttgart, Hørsholm, Bern, Germany, Denmark, Switzerland

Erhorn H, Erhorn-Kluttig H, Maas A, Schiller H, Oschatz B,Ußner M, Mailach B, Hempel A, Kunkel S (2012). Untersuchung zur Novellierung der Gebäude-Richtlinie—Identifikation und Analyse von Hemmnissen beim Neubau von hocheffizienten Gebäuden und Entwicklung eines Konzepts zur Marktdurchdringung bis 2020. Fraunhofer-Institut für Bauphysik, Ingenieurbüro Hauser, schiller engineering, Institut für Technische Gebäudeausrüstung. Available: http://www.bbsr.bund.de/cln_032/nn_187722/BBSR/DE/Veroeffentlichungen/BMVBS/Online/2012/DL__ON162012,templateId=raw,property=publicationFile.pdf/DL_ON162012.pdf. Last Accessed: 03 Jan 2013. Federal Ministry of Transport, Building and Urban Development (BMVBS), Berlin, Germany. In German

European Parliament and the Council of the European Union (2006) Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:114:0064:0064:en:pdf. Last Accessed 16 Jan 2013

European Parliament and the Council of the European Union (2009) Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF. Last Accessed 08 Jan 2013

European Parliament and the Council of the European Union (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF. Last Accessed 01 Nov 2011

Friedrich M, Becker D, Grondey A, Laskowski F, Erhorn H, Erhorn-Kluttig H, Hauser G, Sager C, Weber H (2008) $CO_2$ Gebäudereport 2007. co2online gemeinnützige GmbH, Fraunhofer-Institut für Bauphysik. Available: http://www.buildup.eu/system/files/content/CO2-Gebaeudereport.pdf. Last Accessed 10 Jan 2013. Federal Ministry of Transport Building and Urban Development (BMVBS), Berlin, Germany. In German

Hofmann F, Becker L, Bettgenhäuser K, Breitschopf B, Bürger V, Fröhlich J, Hoffmann P, Horst J, Klinski S, Mahler M, Ragwitz M, Schimschar S, Steinbach J, Weissleder U (2012) Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichtes gemäß § 18 Erneuerbare-Energien-Wärmegesetz. Ecofys, Institut für ZukunftsEnergieSysteme (IZES), Fraunhofer-Institut für System- und Innovationsforschung (ISI), Öko-Institut e.V., Hochschule für Wirtschaft und Recht (HWR) (Unpublished) for Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. In German

KfW (2009) Energieeffizientes Bauen & Sanieren (KfW-Infodienst Ausgabe Mai 2009). Available: http://www.kfw.de/DE_Home/Presse/Materialien_fuer_die_Presse/Infodienst/Archiv/PDF-Dateien_Infodienst/2009/KfW-Infodienst_Mai_2009.pdf. Last Accessed 24 Sep 2010. KfW Bankengruppe, Frankfurt am Main, Germany. In German

KfW (2011) Web Page: German Federal Ministry of Transport, Building and Urban Affairs (BMVBS) and KfW launch new promotional programme "Urban energy efficiency rehabilitation". Available: http://www.kfw.de/kfw/en/KfW_Group/Press/Latest_News/PressArchiv/2011/20111115_54534.jsp. Last Accessed 10 Jan 2013

KFW (2012) Web page: Förderreport KFW Bankengruppe—2009-3. Quartal 2012. Available: http://www.kfw.de/kfw/de/KfW-Konzern/Unternehmen/Erfolg/Erfolg_in_Zahlen/Foerderreport/index.jsp. Last Accessed 03 Jan 2013. In German

KfW (2013) Web Page: KfW Programm 'Energieeffizient Bauen und Sanieren'—Finanzierungsangebote. Available: https://energiesparen.kfw.de/html/finanzierungsangebote. Last Accessed 12 Jan 2013. In German

Kohberg T (2012) Ergebnisse der Evaluation und Begleitung des Marktanreizprogramms (MAP). Fichtner GmbH & Co. KG. Presented at Berliner Energietage 2012 on 2012-05-25 in Berlin, Germany. Available: http://www.berliner-energietage.de/fileadmin/user_upload/2012/Tagungsmaterial/2.10_Tjark_Kohberg_-_Ergebnisse_der_Evaluation_und_Begleitung_des_Marktanreizprogramms__MAP_.pdf. Last Accessed 12 Jan 2013. In German

Langniß O, Markus Schüller, Wülbeck H-F, Nast M, Pehnt M, Frick S, Drück H, Streicher E, Hartmann H, Reisinger K (2010) Evaluierung von Einzelmaßnahmen zur Nutzung erneuerbarer Energien im Wärmemarkt (Marktanreizprogramm) für den Zeitraum 2009 bis 2011—Evaluierung des Förderjahres 2009. Fichtner, DLR, ifeu, GFZ, SWT, TFZ. Available: http://www.erneuerbare-energien.de/fileadmin/ee-import/files/erneuerbare_energien/downloads/application/pdf/marktanreizprogramm_evaluierung.pdf. Last Accessed 12 Jan 2013. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Berlin, Germany. In German

Lilova V (2012) Evaluation of EU Member States 'policy instruments for the use of renewable heat in the building sector. Thesis supervised by Johannes Hamhaber & Sven Schimschar. A thesis to the Institute for Technology and Resources Management in the Tropics and Subtropics (ITT) of Cologne University of Applied Sciences for the degree of Master of Science. Cologne, Germany

Offermann M, Hermelink A,von Manteuffel B (2013) Begleituntersuchung zur europäischen Berichterstattung "Cost-Optimal-Level"—Modellrechnungen. Ecofys (Unpublished) for Federal Ministry of Transport, Building and Urban Development (BMVBS). In German

Regierung der Bundesrepublik Deutschland (2009) Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden. (Energieeinsparverordnung—EnEV). Energieeinsparverordnung vom 24. Juli 2007 (BGBl. I S. 1519), die durch Artikel 1 der Verordnung vom 29. April 2009 (BGBl. I S. 954) geändert worden ist. Available: http://www.zukunft-haus.info/fileadmin/zukunft-haus/energieausweis/Gesetze_Verordnungen/EnEV_2009_aktuelle_nichtamtliche_Lesefassung_180309_englisch_Internetversion__ohne_Formulare_.pdf. Last Accessed 03 Jan 2013

Schimschar S, Bettgenhäuser K, Boermans T, Lindner S, Grözinger J, Walther C, Waßmuth V, Luchmann I, Kindl A (2013a) Wissenschaftliche und organisatorische Koordination und Bewertung der Maßnahmen in den Bereichen Gebäude und Verkehr zur Erarbeitung des Energie- und Klimaschutzkonzepts des BMVBS (Scientific and organisational coordination and assessment of the measures in the sectors 'Buildings' and 'Transport' for the preparation of the energy and climate protection concept of the Federal Ministry of Transport, Building and Urban Development). Ecofys, PTV (Unpublished) for Federal Ministry of Transport, Building and Urban Development. In German

Schimschar S, Blok K, Boermans T, Hermelink A (2011) Germany's path towards nearly zero-energy buildings—Enabling the greenhouse gas mitigation potential in the building stock. Energy Policy 39:3346–3360

Schimschar S, Boermans T, Urban D, Renner A, Lawrenz H-P (2010) Energy related requirements and accompanying measures for the building stocks in the central European neighbouring countries. Ecofys. Available: http://www.bbsr.bund.de/cln_016/nn_21272/BBSR/DE/Veroeffentlichungen/BMVBS/Online/2010/DL__ON232010,templateId=raw,property=publicationFile.pdf/DL_ON232010.pdf. Last Accessed 10 Jan 2013. Federal Institute for Research on Building Urban Affairs and Spatial Development (BBSR), Bonn, Germany. In German (summary available in English)

Schimschar S, Hermelink A, Boermans T, Pagliano L, Zangheri P, Voss K, Musall E (2013b) Towards nearly zero-energy buildings—Definition of common principles under the EPBD. Ecofys, Politecnico di Milano, University of Wuppertal (Unpublished) for European Commission

SWR (2012) Web page: Geld vom Staat für Gebäudesanierung. Available: http://www.swr.de/nachrichten/-/id=396/nid=396/did=10752314/x0h3b4/. Last Accessed 12 Jan 2013. In German

The Federal Government (2008) German strategy for adaptation to climate change adopted by the German federal cabinet on 17th December 2008 Available: http://ccsl.iccip.net/das_gesamt_en_bf.pdf. Last Accessed 16 Jan 2013

The Federal Government (2012a) Act on granting priority to renewable energy sources (Renewable Energy Sources Act—EEG) Available: http://www.erneuerbare-energien.de/fileadmin/ee-import/files/english/pdf/application/pdf/eeg_2012_en_bf.pdf. Last Accessed 12 Jan 2013

The Federal Government (2012b) Aktionsplan Anpassung der Deutschen Anpassungsstrategie an den Klimawandel vom Bundeskabinett am 31. August 2011 beschlossen. Available: http://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/aktionsplan_anpassung_klimawandel_bf.pdf. Last Accessed 16 Jan 2013. In German

UM Baden-Württemberg (2011) Erfahrungsbericht zum Erneuerbare-Wärme-Gesetz Baden-Württemberg. Available: http://www.um.baden-wuerttemberg.de/servlet/is/85287/Erfahrungsbericht-Kabinettsfassung.pdf?command=downloadContent&filename=Erfahrungsbericht-Kabinettsfassung.pdf. Last Accessed 08 Jan 2013. Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, Stuttgart, Germany. In German

Verbraucherzentrale (2012) Übersicht der Leistungen der Verbraucherzentrale zur Energieberatung. Available: http://www.verbraucherzentrale-energieberatung.de/web/Uebersicht_Beratungsangebot_vzbv_energie.pdf. Last Accessed 12 Jan 2013. Verbraucherzentrale Bundesverband e.V. (vzbv), Berlin, Germany. In German

# Built Environment Life Cycle Process and Climate Change

**Artūras Kaklauskas, Fernando Pacheco Torgal, Stelios Grafakos and Vilune Lapinskiene**

**Abstract** In order to design and realise an efficient built environment life cycle with focus on climate change mitigation and adaptation, it is necessary to carry out exhaustive investigations of all the decision and processes that form it. The efficiency level of the considered built environment life cycle depends on a great many micro, meso and macro factors. The authors of this paper participated in the different EU projects related with built environment and climate change [Linking European, Africa and Asian Academic Networks on Climate Change (LEAN CC), etc.]. One of the LEAN CC project's goals was to develop a Model and Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation. The presented Model and Intelligent System enables one to form up to 100 million alternative versions. Intelligent system allows one to determine the strongest and weakest points of each project and its constituent parts. In order to demonstrate the micro, meso and macro factors that influence the efficiency of the built environment in climate change mitigation and adaptation processes, the Model and Intelligent System will be considered as an example.

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# 1 Introduction

Climate change mitigation is action to decrease the intensity of radiative forcing in order to reduce the potential effects of global warming. In contrast, adaptation to global warming involves acting to tolerate the actual or expected effects of global warming (IPCC 2010). Most often, climate change mitigation scenarios involve reductions in the concentrations of greenhouse gases (GHGs), either by reducing their sources or by increasing their sinks (Molina et al. 2009).

Using data from 73 sites around the world, scientists have been able to reconstruct Earth's temperature history back to the end of the last Ice Age, revealing that the planet today is warmer than it has been during 70–80 % of the time over the last 11,300 years (Marcott et al. 2013).

Surface temperature reconstructions of the past 1,500 years suggest that recent warming is unprecedented in that time. Here, we provide a broader perspective by reconstructing regional and global temperature anomalies for the past 11,300 years from 73 globally distributed records. Early Holocene (10,000–5,000 years ago) warmth is followed by ~0.7 °C cooling through the middle to late Holocene (<5,000 years ago), culminating in the coolest temperatures of the Holocene during the Little Ice Age, about 200 years ago. This cooling is largely associated with ~2 °C change in the North Atlantic. Current global temperatures of the past decade have not yet exceeded peak interglacial values but are warmer than during ~75 % of the Holocene temperature history. Intergovernmental Panel on Climate Change model projections for 2100 exceed the full distribution of Holocene temperature under all plausible greenhouse gas emission scenarios (Marcott 2013).

The UN defines mitigation in the context of climate change, as a human intervention to reduce the sources or enhance the sinks of GHGs. Examples include using fossil fuels more efficiently for industrial processes or electricity generation, switching to renewable energy (solar energy or wind power), improving the insulation of buildings, and expanding forests and other 'sinks' to remove greater amounts of carbon dioxide from the atmosphere (GCCA 2012). The IAEA, an international organisation using the UN flag and reporting to the UN, asserts that nuclear power belongs to the set of options available to reduce greenhouse gas emissions in the power sector (IAEA 2008).

Scientific consensus on global warming, together with the precautionary principle and the fear of abrupt climate change (Schneider 2004) is leading to increased effort to develop new technologies and sciences and carefully manage others in an attempt to mitigate global warming. Most means of mitigation appear effective only for preventing further warming, not at reversing existing warming. The Stern Review identifies several ways of mitigating climate change. These include reducing demand for emissions-intensive goods and services, increasing efficiency gains, increasing use and development of low-carbon technologies and reducing fossil-fuel emissions (Stern 2007).

Residential sector carbon dioxide emissions originate primarily from: direct fuel consumption (principally, natural gas) for heating and cooking, electricity for cooling (and heating), appliances, lighting, and increasingly for televisions, computers, and other household electronic devices. Energy consumed for heating in homes and businesses has a large influence on the annual fluctuations in energy-related carbon dioxide emissions. In the longer run, residential emissions are affected by population growth, income and other factors. From 1990 to 2008, residential sector carbon dioxide emissions grew by an average of 1.3 % per year, U.S. population grew by an average of 1.1 % per year, per capita income (measured in constant dollars) grew by an average of 1.7 % per year, energy efficiency improvements for homes and appliances have offset much of the growth in the number and size of housing units. As a result, direct fuel emissions from petroleum, coal and natural gas consumed in the residential sector in 2008 were only 1.5 % higher than in 1990. Energy-related carbon dioxide emissions account for more than 80 % of U.S. greenhouse gas emissions (EIA report 2009). Other countries have similar proportions of energy-related carbon dioxide emissions.

Global Carbon Cycle buildings in North America contribute 37 % of total CO2 emissions, while US buildings correspond to 10 % of all global emissions. The buildings sector of North America was responsible for annual carbon dioxide emissions of 671 million tons of carbon in 2003, which is 37 % of total North American carbon dioxide emissions and 10 % of global emissions. Options for reducing the carbon dioxide emissions of new and existing buildings include increasing the efficiency of equipment and implementing insulation and passive design measures to provide thermal comfort and lighting with reduced energy. Current best practices can reduce emissions from buildings by at least 60 % for offices and 70 % for homes. Technology options could be supported by a portfolio of policy options that take advantage of cooperative activities, avoid unduly burdening certain sectors and are cost-effective (SOCCR 2008). Therefore, best practices utilisation is a key factor in productively executing a climate change mitigation and adaptation in built environment project. The main purpose of this paper is to present the Model and Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation which the authors of this paper have developed.

Sustainable material selection represents an important strategy in building design. Current building materials selection methods fail to provide adequate solutions for two major issues: assessment based on sustainability principles and the process of prioritising and assigning weights to relevant assessment criteria. Akadiri et al. (2013) proposes a building material selection model based on the fuzzy extended analytical hierarchy process (FEAHP) techniques, with a view to providing solutions for these two issues. Assessment criteria are identified based on sustainable triple bottom line (TBL) approach and the need of building stakeholders. A questionnaire survey of building experts is conducted to assess the relative importance of the criteria and aggregate them into six independent assessment factors. The FEAHP is used to prioritise and assign important weightings for the identified criteria. A numerical example illustrating the implementation of the model is given. The proposed model provides guidance to building designers in selecting sustainable building materials (Akadiri et al. 2013).

The structure of this chapter is as follows: Sect. 2, which follows this introduction, describes the Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation. Section 3 analyses the micro, meso and macro factors that influence the efficiency of the built environment in climate change mitigation and adaptation processes. Section 4 describes Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation and Case Study 'Energy-Efficient House Decision Support Sub-system for Africa'. Certain concluding remarks appear in Sect. 5.

## 2 Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation

By modelling and forecasting future perspectives and trends of climate change mitigation and adaptation in built environment, it is possible to get ready to respond to the variation of micro-, meso- and macro-level variables. Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation suggested by this research is based on presumption that the efficiency of climate change mitigation and adaptation depends on many micro-, meso- and macro-level variables. The presence of specific micro-, meso- and macro-level variable factors right away imposes objective limitations for efficient climate change mitigation and adaptation in built environment.

Therefore, basing oneself on main worldwide development trends and best practices, it is possible to issue recommendations on the increase of efficiency of climate change mitigation and adaptation in built environment in specific country. When rational variable micro-, meso- and macro-level factors determine for specific country have been realised, they should create better and more favourable conditions for efficient realisation of climate change mitigation's projects would be created.

The research aim was to produce a Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation in specific country by undertaking a complex analysis of micro, meso and macro environment factors affecting it and to give recommendations on the increase of its competitive ability.

The research was performed by studying the main worldwide development trends and best practice, taking into consideration specific countries' history, development level, needs and traditions. Simulation was undertaken to provide insight into creating an effective environment for the climate change mitigation and adaptation in built environment by choosing rational micro, meso and macro factors. The most of stakeholders of climate change mitigation cannot correct or alter the micro-, meso- and macro-level variables, but they can go into the essence of their effect and take them into consideration when realising various activities. Stakeholders, knowing the micro-, meso- and macro-level factors affecting the activities being realised, can organise their present and future activities more successfully.

To design and achieve effective built environment life cycle with focus on climate change mitigation a complex analysis of its stages as well as stakeholders, their aims and potentialities are needed. The effect of micro, meso and macro environmental factors should also be taken into account.

Dozens of millions of built environment life cycle with focus on climate change mitigation and adaptation alternative versions can be obtained. The diversity of solutions available contributes to more accurate evaluation of economical, political, technological, emotional, climatic and other conditions, risk exposure, as well as making the project cheaper and better satisfying different stakeholder's requirements. This also leads to better satisfaction of the needs of all parties involved in the project design and realisation.

Various stakeholders are involved in the life cycle of a climate change mitigation, trying to satisfy their needs and affecting its efficiency. The level of the efficiency of life cycle of a climate change mitigation depends on a number of variables at three levels: micro, meso and macro level.

The problem is how to define an efficient built environment life cycle with focus on climate change mitigation and adaptation when a lot of various stakeholders are involved, the alternative project versions come to hundreds million and the efficiency changes with the alterations in the environment conditions and the constituent parts of the process in question. Moreover, the realisation of some objectives seems more rational from the economic perspective thought from the other qualitative perspectives they have various significance. Therefore, it is considered that the efficiency of a sustainable built environment life cycle depends on the rationality of its stages as well as on the ability to satisfy the needs of the stakeholders and the rational character of micro, meso and macro environment conditions.

Formalised presentation of the research shows how changes in the micro, meso and macro environment and the extent to which the goals pursued by various stakeholders are satisfied cause corresponding changes in the value and utility degree of a sustainable built environment life cycle. With this in mind, it is possible to solve the problem of optimisation concerning satisfaction of the needs at reasonable expenditures. This requires the analysis of built environment life cycle with focus on climate change mitigation and adaptation versions allowing to find an optimal combination of goals pursued and finances available.

The research object is a built environment life cycle with focus on climate change mitigation and adaptation, stakeholders striving to attain their goals and micro, meso and macro environment making an integral whole.

Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation was developed with the goal of integrating different quantitative and qualitative aspects of the process over the life of the climate change mitigation. This six-stage model is presented in brief heretofore (see Fig. 1):

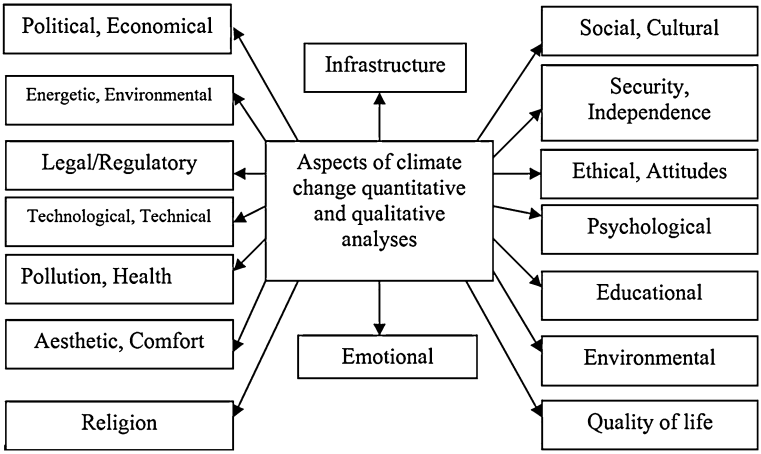


**Fig. 1** Climate change mitigation and adaptation in built environment quantitative and qualitative analyses aspects

Stage 1. Comparative description of the climate change mitigation basing oneself on main worldwide development trends and best practices (see Fig. 1):

- Determining a system of criteria characterising the efficiency of a climate change mitigation by employing relevant literature and expert methods.
- Describing, per this system of criteria, the present state of the climate change mitigation in countries under consideration in conceptual (textual, graphical, numerical, virtual and augmented reality and such) and quantitative forms.

Stage 2. Comparison and contrast of the climate change mitigation in countries under consideration:

- Identifying the global development trends (general regularities) of the climate change mitigation.
- Identifying the differences in climate change mitigations in countries under consideration.
- Determining the pluses and minuses of these differences.
- Determining the best practice for the climate change mitigation in countries under consideration as per actual conditions.
- Estimating the deviation between the knowledge stakeholders have of world-wide best practices and their practice-in-use.

Stage 3. Development of certain general recommendations on how to improve the knowledge levels of stakeholders.

Stage 4. Submission of certain recommendations to stakeholders including several particular alternatives for each general recommendation proposed.

Stage 5. A multiple criteria analysis of the composite parts of a climate change mitigation and selection of the most efficient built environment life cycle with focus on climate change mitigation and adaptation—henceforth interlinking the received compatible and rational composite parts of a climate change mitigation into a full climate change mitigation process.

Section 4 'Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation. Case Study: Energy-Efficient House Decision Support Sub-system for Africa' illustrates a part of the Stage 5 'A multiple criteria analysis of the composite parts of a climate change mitigation' of the Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation.

Stage 6. Transformational learning and the redesign of mental and practical behaviour of different stakeholders.

## 3 Micro, Meso and Macro Factors that Influence the Efficiency of the Built Environment in Climate Change Mitigation and Adaptation Processes

In order to assure the efficiency of a project, it should be executed within certain bounds that are determined by the built environment. The fact is that these factors are different in each country, so also the possibilities for efficient realisation of projects (see Fig. 2) will also vary.

Figure 2 indicates diagrammatically the factors at micro, meso and macro level which may impinge upon the efficiency of the built environment. This means that to be efficient the built environment must operate within certain boundaries

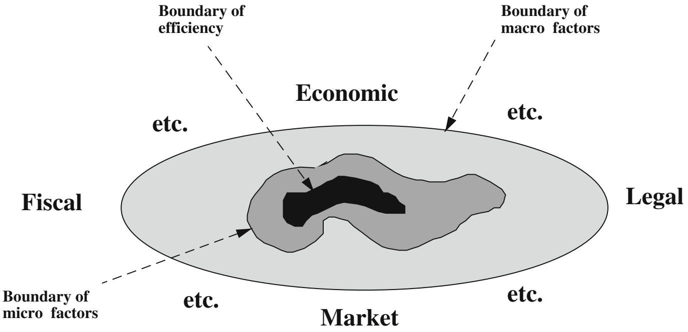


**Fig. 2** Micro, meso and macro factors that influence the efficiency of the built environment in climate change mitigation and adaptation processes

imposed by the micro, meso and macro factors. Recognising that in each country the factors will be different, this diagram will vary accordingly. It is necessary to utilise knowledge and experience about the micro-, meso- and macro-level factors, so as to increase the efficiency level in each country under consideration. This will be done by analysing the worldwide experience, knowledge and best practices and applying this to specific country.

Using carbon tax as an example of this, it can be appreciated that if the level of carbon tax is high, national firms could either go bankrupt because of increased tax liabilities, or they could decrease efficiency in the face of a lack of competition from international companies who will not attempt to enter the local market. Similarly, if the carbon tax level is lowered, this may cause national firms to lose market share to international companies entering the local market, or to force them to increase efficiency in the face of such competition.

Such changes in taxation will alter the boundary of efficiency of the built environment. Similar built environment changes can shift this boundary (the area within boundary of efficiency expresses the total satisfaction level of needs of all stakeholders). For example, the specific country government (in order to solve the most important problems for specific country society) may abolish VAT on new residential passive houses in order to promote investment in passive housing. Thus, the boundary of efficiency is extended to include this new development from the former situation. After development of the specific country passive house sector, the boundary will alter again (Fig. 3 illustrate a revised level of efficiency as an example of how to take account of these alterations).

Figure 4 graphically illustrates interrelationships between macro level factors and the built environment. The area inside the ellipse represents the positive action of specific macro-level factors on the efficiency of the built environment. The area outside the ellipse represents the negative effect of the macro-level factors on the efficiency of the built environment, where the macro-level factors overlap a better environment for the built environment is created. In this case, the optimum environment for the built environment is when all four ellipse areas are overlapping (i.e. economic, fiscal, legal and market). The greater the common overlapping

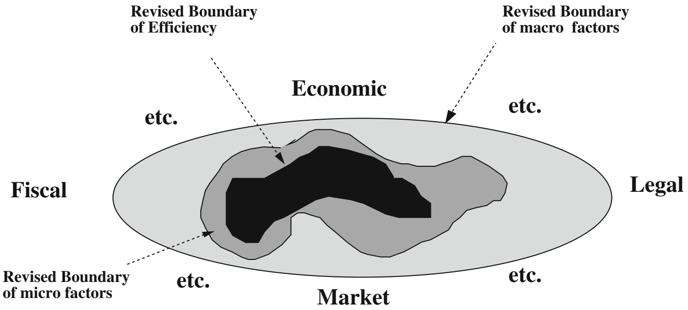


**Fig. 3** Fluctuation of efficient boundary of micro, meso and macro environment

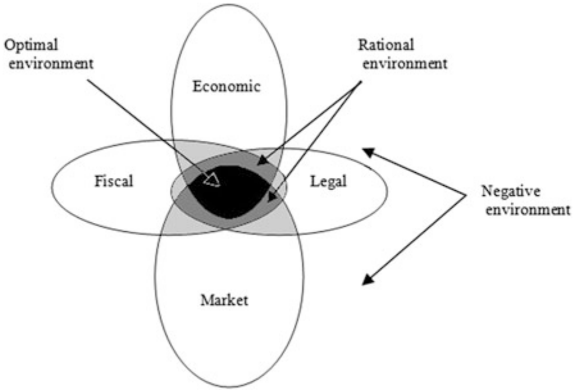


**Fig. 4** Determination of optimal, rational and negative environment for the built environment

area (taking into account the significance of the factors), the greater will be the efficiency level of the built environment. Having investigated the effects of the micro, meso and macro variables affecting built environment by using best practices, differences have been identified between these and specific country. On the basis of these differences, the main implications for specific country can be identified. Studying only some worldwide experience, knowledge and best practices could lead to any inferences being purely subjective. However, by studying a number of countries any bias can be diminished. In other words, the presence of specific micro-, meso- and macro-level variable factors immediately imposes objective limitations on the efficient activities of stakeholders. The stakeholders, in the presence of these objective limitations, try to perform their activities in a more rational way.

Based on the above considerations, it is possible to propose a Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation on the basis of the performed search for a rational variable environment for specific country (i.e. seek to explore ways of harmonising the relationship between the specific country built environment and its micro, meso and macro environment). Upon completion of such a model, the stakeholders by taking into consideration existing limitations of micro-, meso- and macro-level environment and existing possibilities will be able to use their resources in a more rational manner.

One of the major tasks of an organisation is to carry out its activities under the most favourable micro-, meso- and macro-level conditions. Efforts are made to ensure that the structure, goals, output, efficiency and quality of production of the organisation would be in maximum conformity with the existing environmental conditions. The pursuit of impracticable goals, for instance, trying to realise projects that surpass the organisation's capabilities or the environment (economical, social, legal, political, competitive and technological conditions) is adverse, may cause undesirable consequences.

In order to assure the efficiency of a project, it should be executed within certain bounds that are determined by micro-, meso- and macro-level factors.

Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation was developed with the goal of integrating the environmental, energetic, political, economical, legal/regulatory, infrastructural, technical, technological, pollution, health, quality of life, social, cultural, ethical, psychological, emotional, religious, ethnic and other aspects of the process over the life of the climate change mitigation. Description of some above micro, meso and macro factors are follows.

### *3.1 Macro-Level Factors*

The highest level at which factors may be considered is the macro-level factors. The level of efficiency and the scope of activities of the built environment depend on the next macro-level variable factors:

- a key economic indicators for the country as a whole,
- the global warming price,
- stakeholders,
- civil conflicts,
- human culture,
- religion,
- ethics,
- Easterlin paradox and happiness economics,
- intervention of government,
- physical infrastructure,
- Financial sector,
- interest rate,
- environment issues,
- unemployment,
- labour skill level,
- wages level,
- insurance,
- inflation,
- innovations,
- exchange rate,
- unofficial economy, etc.

A few examples regarding relations of climate change and macro-level factors (the global warming price, stakeholders, climate mobility social and civil conflicts, climate change and human culture, religion, ethics, easterlin paradox and happiness economics) are follows.

### 3.1.1 The Global Warming Price

The heated argument about economic costs, however, barely touched one vitally important issue: the costs of NOT taking action on climate. What if last summer's Russian heat wave and drought, which destroyed one-third of the country's wheat crop, or the catastrophic floods in Pakistan and China, or category 5 hurricanes like Katrina are just glimpses of future havoc from warming left unchecked? Certain events would have been extremely unlikely to have occurred without global warming and that includes the Russian heat wave and wild fires, and the Pakistan, Chinese, and Indian floods (Carey 2011).

Droughts, floods, wildfires, and hurricanes have already caused multibillion-dollar losses, and these extreme weather events will likely become more frequent and more devastating as the climate continues to change. Tourism, agriculture, and other weather-dependent industries will be hit especially hard, but no one will be exempt. Household budgets, as well as business balance sheets, will feel the impact of higher energy and water costs. Ruth et al. (2007) estimates what the United States will pay as a result of four of the most serious impacts of global warming in a business-as-usual scenario—that is, if we do not take steps to push back against climate change (Ruth et al. 2007):

- Hurricane damages: $422 billion in economic losses caused by the increasing intensity of Atlantic and Gulf Coast storms. In the business-as-usual climate future, higher sea-surface temperatures result in stronger and more damaging hurricanes along the Atlantic and Gulf coasts. Even with storms of the same intensity, future hurricanes will cause more damage as higher sea levels exacerbate storm surges, flooding and erosion. In recent years, hurricane damages have averaged $12 billion and more than 120 deaths per year. With business-as-usual emissions, average annual hurricane damages in 2100 will have grown by $422 billion and an astounding 760 deaths just from climate change impacts.
- Real estate losses: $360 billion in damaged or destroyed residential real estate as a result of rising sea levels. Our business-as-usual scenario forecasts 23 inches of sea-level rise by 2050 and 45 inches by 2100. If nothing is done to hold back the waves, rising sea levels will inundate low-lying coastal properties. Even those properties that remain above water will be more likely to sustain storm damage, as encroachment of the sea allows storm surges to reach inland areas that were not previously affected. By 2100, U.S. residential real estate losses will be $360 billion per year.
- Energy costs: $141 billion in increasing energy costs as a result of the rising demand for energy. As temperatures rise, higher demand for air conditioning and refrigeration across the country will increase energy costs, and many households and businesses, especially in the North, that currently do not have air conditioners will purchase them. Only a fraction of these increased costs will be offset by reduced demand for heat in Northern states. The highest net energy costs—after taking into consideration savings from lower heating bills—will fall on Southeast and Southwest states. Total costs will add up to more than $200

billion for extra electricity and new air conditioners, compared with almost $60 billion in reduced heating costs. The net result is that energy sector costs will be $141 billion higher in 2100 due to global warming.

- Water costs: $950 billion to provide water to the driest and most water-stressed parts of the United States as climate change exacerbates drought conditions and disrupts existing patterns of water supply. The business-as-usual case forecasts less rainfall in much of the United States—or, in some states, less rain at the times of year when it is needed most. By 2100, providing the water we need throughout the country will cost an estimated $950 billion more per year as a result of climate change. Drought conditions, already a problem in Western states and in the Southeast, will become more frequent and more severe.

### 3.1.2 Stakeholders

The Citizens' support for policies that aim to curb carbon emissions and energy use is often seen as informed by their values, attitudes and perceptions of the environmental problem in question. Fischer et al. (2011) argue that we also need to understand how people conceptualise policies and the governance approaches underpinning them to be able to judge the likely acceptance of policy change. Fischer et al. (2011) draw on qualitative interviews ($n = 202$) from five European countries to explore citizens' views on governance approaches to stimulate behavioural change in the field of resource use, including regulations, price changes, collective action, technological change and education. Fischer et al. (2011) found that many of our interviewees referred to generalised characteristics of humankind and contemporary society to back up their arguments for or against specific governance approaches. In particular, many interviewees concurred that people in general were so self-centred, driven by habit and money- and consumption-oriented that only strict regulations, drastic price changes and technological innovation could possibly achieve widespread behavioural change. As a consequence, such 'folk psychologies' can have substantial impact not only on public acceptance, but also on the success of policy measures that aim to reduce citizens' resource use (Fischer et al. 2011).

Climate change has been identified as potentially the biggest health threat of the twenty-first century. Canada in general has a well-developed public health system and low burden of health which will moderate vulnerability. However, there is significant heterogeneity in health outcomes, and health inequality is particularly pronounced among Aboriginal Canadians. Intervention is needed to prevent, prepare for, and manage climate change effects on Aboriginal health but is constrained by a limited understanding of vulnerability and its determinants. Despite limited research on climate change and Aboriginal health, however, there is a well-established literature on Aboriginal health outcomes, determinants, and trends in Canada; characteristics that will determine vulnerability to climate change. In this paper, Ford et al. (2010) systematically review this literature, using a vulnerability framework to identify the broad level factors constraining adaptive capacity and increasing sensitivity to climate change. Determinants identified include the following: poverty, technological capacity constraints, socio-political values and inequality, institutional capacity challenges, and information deficit. The magnitude and nature of these determinants will be distributed unevenly within and between Aboriginal populations necessitating place-based and regional-level studies to examine how these broad factors will affect vulnerability at lower levels. The study also supports the need for collaboration across all sectors and levels of government, open and meaningful dialogue between policy makers, scientists, health professionals, and Aboriginal communities, and capacity building at a local level, to plan for climate change. Ultimately, however, efforts to reduce the vulnerability of Aboriginal Canadians to climate change and intervene to prevent, reduce and manage climate-sensitive health outcomes will fail unless the broader determinants of socio-economic and health inequality are addressed (Ford et al. 2010).

In the United States, public support for federal, state and local efforts to reduce GHGs continues to be a crucial element of the political viability of these proposals. Shwom et al. (2010) present a detailed analysis of the reasons given by the general public of Michigan and Virginia for supporting or rejecting a number of policies that could be implemented to meet GHG reductions. The data allow us to analyse the relationships between reasons provided by respondents, social psychological and demographic characteristics and policy support. This analysis can provide policymakers pragmatic guidance in (1) developing tactics to engage the public that build on current concerns about climate change policies and (2) crafting and communicating policies that garner support from various segments of the public. This analysis also raises theoretical questions regarding the relationship between public discourse on environmental issues and the formation of public policy support. Shwom et al. (2010) suggest that future efforts to understand the U.S. dynamics of public support for climate change policies could benefit from understanding the public discursive and the reasoning processes that underlie public opinion formation (Shwom et al. 2010).

Anti-coal and some investment policies are widely justified with reference to global warming. Political analysis suggests that these policies are supported by the reinforcing interests of three powerful lobbies: scientific institutions engaged in atmospheric research and earth observation, energy corporations harmed by low fossil fuel prices or supplying 'clean' technologies, and numerous interlocking bureaucracies. Together they have succeeded in maintaining momentum in current climate negotiations (Boehmer-Christiansen 1997).

### 3.1.3 Climate Mobility Social and Civil Conflicts

The Climate change can increase societies' propensity to conflict by changes in socio-structural conditions (e.g. resource scarcity and migration). Climate change is expected to bring about major change in freshwater availability, the productive capacity of soils, and in patterns of human settlement. The direst predictions about the impacts of global warming warn about greatly increased risks of violent conflict over increasingly scarce resources such as freshwater and arable land (Raleigh and Urdal 2007). Raleigh and Urdal (2007) argue that our best guess about the future has to be based on our knowledge about the relationship between demography, environment and violent conflict in the past. Previous rigorous studies in the field have mostly focused on national-level aggregates. Raleigh and Urdal (2007) represent a new approach to assess the impact of environment on internal armed conflict by using georeferenced (GIS) data and small geographical, rather than political, units of analysis. It addresses some of the most important factors assumed to be strongly influenced by global warming: land degradation, freshwater availability, and population density and change. While population growth and density are associated with increased risks, the effects of land degradation and water scarcity are weak, negligible or insignificant (Raleigh and Urdal 2007).

Allouche (2011) looks at the interrelationship between water and food security. More specifically, Allouche (2011) examines the resilience and sustainability of water and food systems to shocks and stresses linked to different levels and intensity of conflict, global trade and climate change. Allouche (2011) makes four points: (1) that resource scarcity as a driver of conflict is inconclusive especially at regional and national levels (2) most insecurities surrounding water and food are explained by political power, social and gender relations; (3) global trade has enabled national food and water security but that is now threatened by increasing food prices, food sovereignty movements and land ‘grabbing’ (4) and that water and food security will face major challenges under conditions of climate change (Allouche 2011).

Climates more suitable for Eurasian agriculture are associated with a decreased likelihood of conflict, while freshwater resources per capita are positively associated with the likelihood of conflict. Moreover, positive changes in rainfall are associated with a decreased likelihood of conflict in the following year (Hendrix and Glaser 2007).

In climate change discourse, climate mobility is often characterised as the production of ‘refugees’, with a tendency to discount long histories of ordinary mobility among affected populations. The case of Tuvalu in the Pacific juxtaposes migration as everyday practice with climate refugee narratives (Farbotko and Lazrus 2012).

### 3.1.4 Climate Change and Human Culture

If solar variability affects human culture, it most likely does so by changing the climate in which the culture operates (Feynman 2007).

Geel et al. (2004) described hypothesis regarding climate change and the expansion of the Scythian culture after 850 BC. In southcentral Siberia, archaeological evidence suggests an acceleration of cultural development and an increase in the density of nomadic populations around 850 BC. Geel et al. (2004) hypothesise a relationship with an abrupt climatic shift towards increased humidity caused by a decline of solar activity. Areas that initially may have been hostile semi-deserts changed into attractive steppe landscapes with a high biomass production and high carrying capacity. Newly available steppe areas could be invaded by herbivores, making them attractive for nomadic tribes. The central Asian horse-riding Scythian culture expanded and an increased population density was a stimulus for westward migration towards southeastern Europe (Geel et al. 2004).

Tibetan culture and livelihoods depend on native plants for medicine, food, grazing, wood, as well as cash from market sales. The Medicine Mountains (part of the Hengduan Mountains) of the eastern Himalayas, with tremendous plant diversity derived from steep gradients of both elevation and precipitation, have traditionally been an important source of Tibetan medicinal plants (Salick et al. 2009). Salick et al. (2009) examine climate change in this area and vegetation patterns influenced by biogeography, precipitation and elevation. The Alpine environment has the highest plant diversity and most useful plants and is the most susceptible to climate change with impacts on traditional Tibetan culture and livelihoods—particularly Tibetan medicine and herding (Salick et al. 2009).

### 3.1.5 Religion

Biomass Different religion leaders call on all people and nations to recognise the serious and potentially irreversible impacts of global warming caused by the anthropogenic emissions of GHGs and other pollutants, and by changes in forests, wetlands, grasslands and other land uses. According to the New Scientist (2007), also religious leaders pray for cold weather to combat climate change. Leaders from world religions gather in Greenland to show unity on the problem of global warming and to pray for the planet (The New Scientist 2007). As example, we will present Vatican and Buddhism point of view regarding climate change.

A Vatican-appointed panel of scientists has reported what climate change experts have been warning for years: the Earth is getting warmer, glaciers are melting, and urgent measures are necessary to stem the damage. The scientists called for urgent reduction of carbon dioxide emissions and reductions in methane and other pollutants that warm the air, and for improved observation of mountain glaciers to better track their changes. The Pontifical Academy of Sciences, a Vatican advisory panel appeal to all nations to develop and implement, without delay, effective and fair policies to reduce the causes and impacts of climate change on communities and ecosystems, including mountain glaciers and their watersheds, aware that we all live in the same home (Vatican-appointed… 2011).

Buddhism is not a religion; it is a way of life. It teaches the moral and ethical conduct… for the happiness of oneself and the welfare of the community. The Buddhist doctrines… [analyse] human life and the intrinsic nature of things… based on reasoning and rational thinking… not based on an initial act of faith (Mendis 1993).

Firstly, Buddhism proposed that beliefs, values and ethics have a strong influence upon the behavioural outcomes that are manifest as the driving forces behind environmental pressures. Although this perspective underplays the role of structural forces that constrain human behaviour, the influence of beliefs and values can be seen to operate via their configuration of goals, wants, needs, intent and choices. Secondly, a more complete nexus with Buddhism requires an explicit shift in focus to human welfare as the key objective of both mainstream economic and policy prescriptions, and the Buddhist way of life (Daniels 2010a).

The Second Noble Truth reveals the source of this persistent dissatisfaction or disappointment. It comes from clinging or attachment to external, worldly phenomena in the belief that they will bring sustained and consummate satisfaction or happiness (French 2003). These objects of our desire include not just material goods or assets and the services they provide but people and other animate beings as well as ideas, social and economic roles, success and status (Webster 2005).

Desire for maximum consumption via material good accumulation, derived services, and control over people for self-satisfaction, drives economic and lifestyle choices and is the natural economic (if not the social) outcome of a belief system based on the principle that the external world is the ultimate source of happiness (Tideman 2001).

Buddhism makes to explain the ‘double whammy’ of the past 60 years of spectacular fossil-fuel-based economic growth where happiness levels within nations do not seem to be increasing (the ‘Easterlin Paradox’), and yet resource use and degradation have reached unsustainable and possibly ecosphere catastrophe levels (Baucells and Sarin 2007; Daniels 2007). The relentless drive for the economic extraction and transformation of nature for economic wealth has not had the anticipated positive impact on subjective well-being. Indeed, craving for material wealth has not only failed to significantly reduce ‘suffering’ (increase well-being) but has increased environmental destruction and instability (Mendis 1993).

Daniels (2010a) examines how central Buddhist world views and themes can contribute to effectively addressing climate change by looking deep within the ethical, economic and ecological nature of consumer market economies. A persistent theme of Daniels (2010a) approach is the structured analysis of climate change in terms of the drivers, pressures, and responses that stem from societal beliefs and world views about human actions and choices, and their links to human goals and well-being. Buddhist notions of interconnectedness, dependent origination, and mindful consumption and production can help explain and reshape human motives and actions for climate and other forms of environmental sustainability. The mode of analysis of Buddhism has had much in common with ecological economics—with primary conceptual and methodological roles ascribed to ethics, the ecologisation of society, social capital and sustainability, and ultimate means and ends via an extensive consideration of well-being and the goals of human endeavour (Daniels 2010a).

Environmental, economic, ethical and cosmological dimensions of Buddhism are presented as a logical and practical basis for reducing the climate change pressures deriving from prevailing global modes of production and consumption

(Daniels 2010b). Daniels (2010b) presents an analytical framework and philosophical base for understanding the causes and refining the goals behind human and societal endeavour. Buddhist notions of interconnectedness, dependent origination and mindful consumption and production can help explain and reshape human motives and actions for climate and other forms of environmental sustainability (Daniels 2010b).

### 3.1.6 Ethics

Climate change raises many questions with strong moral and ethical dimensions that are important to address in climate-policy formation and international negotiations (Wardekker et al. 2009).

The emotional and embodied practice of narrative ethics is offered as one possible response to the overemphasis on technical rationality within our society and its institutions (Willis 2012). Willis (2012) argues that the development of practical wisdom (phronesis) is essential to addressing issues such as climate change, which are not simply technical problems but are fundamentally rooted in the human condition.

Ecoethics is an emerging discipline that trains moral attention and critical reflection on the vastly expanded range of human productive and consumptive powers that are causing increasing and perhaps irreparable damage to many of Earth’s ecosystems and the human communities and non-human species who depend on those ecosystems’ well-being. Ecoethics ponders the significance of how the rapidly rising human population is so widely transforming natural ecosystems that increasing numbers of animal and plant species are being pushed via habitat destruction into endangerment or extinction. Likewise, ecoethics ponders the fate of both humanity and that of all other species as it confronts rising worries about anthropogenic or human-caused global warming or climate change trends (French 2008).

### 3.1.7 Easterlin Paradox and Happiness Economics

The Easterlin Paradox is a key concept in happiness economics. It is named for economist and USC Professor Richard Easterlin who discussed the factors contributing to happiness in the 1974 paper ‘Does Economic Growth Improve the Human Lot? Some Empirical Evidence’. Easterlin found that within a given country people with higher incomes are more likely to report being happy. However, in international comparisons, the average reported level of happiness does not vary much with national income per person, at least for countries with income sufficient to meet basic needs. Similarly, although income per person rose steadily in the United States between 1946 and 1970, average reported happiness showed no long-term trend and declined between 1960 and 1970. The implication for government policy is that once basic needs are met, and policy should focus not on economic growth or GDP, but rather on increasing life satisfaction or Gross national happiness (Wiki). There is no evidence of a marked increase in life satisfaction in China of the magnitude that might have been expected based on the fourfold increase in the level of per capita consumption during that period. In its transition, China has shifted from one of the most egalitarian countries in terms of distribution of life satisfaction to one of the least egalitarian. Life satisfaction has declined markedly in the lowest-income and least-educated segments of the population, while rising somewhat in the upper SES stratum (Easterlin et al. 2012).

Moreover, the life satisfaction pattern in China fits with the historical context. The factors shaping life satisfaction in China appear to be essentially the same as those in the European transition countries—the emergence and rise of substantial unemployment, dissolution of the social safety net, and growing income inequality. The failure of China's life satisfaction to increase despite its differing output experience—a rapid increase versus the collapse and recovery of output in the European countries—suggests that employment and the social safety net are critically important factors in determining life satisfaction. One may reasonably ask how it is possible for life satisfaction not to improve in the face of such a marked advance in per capita GDP from a very low initial level? In answer, it is pertinent to note the growing evidence of the importance of relative income comparisons and rising material aspirations in China, which tend to negate the effect of rising income. These findings are consistent with the view common in the happiness literature that the growth in aspirations induced by rising income undercuts the increase in life satisfaction related to rising income itself (Easterlin et al. 2012).

Moreover, there is more to life satisfaction than material goods. Other factors include home life and the need for a secure job to support it, health, friends and relatives, and the like. It is possible that the lack of a marked uptrend in overall life satisfaction in China might reflect an adverse impact on life satisfaction of changes in such factors as these, as has been true of the transition experience of East Germany, for which data on such circumstances are available (Easterlin 2010).

The GDP measure registers the spectacular average improvement in material living conditions, whereas the measure of life satisfaction demonstrates that among ordinary people, especially the less-educated and lower income segments of the population, life satisfaction has declined noticeably as material aspirations have soared and concerns have arisen about such critical matters as finding and holding a job, securing reliable and affordable health care, and providing for children and the elderly. Clearly, life satisfaction is the more comprehensive and meaningful indicator of people's life circumstances and well-being (Stiglitz et al. 2008).

It would be a mistake to conclude from the life satisfaction experience of China, and the transition countries more generally, that a return to socialism and the gross inefficiencies of central planning would be beneficial. However, our data suggest an important policy lesson that jobs and job and income security, together with a social safety net are of critical importance to life satisfaction. In the last few years, the government of China has begun serious efforts to repair the social safety net. These efforts are an encouraging portent for the future life satisfaction of the Chinese population, particularly for the least advantaged segments (Vodopivec and Tong 2008).

### *3.2 Micro- and Meso-Level Factors*

The second-level factors may be considered as the micro level and these depend upon those at the macro level.

It is obvious that in order to design and realise a high-quality passive house project, it is necessary to take care of its efficiency from the initial brief to the end of maintenance. The entire process must be planned and executed taking into account the specific goals of the participating parties. The designing and planning procedure must include multiple criteria optimisation, not only of the separate processes and decisions, but also of the whole life cost of the passive house. This must take into account the needs expressed by the parties involved in the project.

In order to efficiently design and implement projects in the built environment, it is necessary to investigate as many of the possible alternative solutions for each variable and to select the most rational one. The selected variables are then combined into one efficient project. Hence, the efficiency of a project will depend to a very great extent not only on the selected variables, but also on micro, meso and macro factors affecting them.

The level of efficiency and the scope of activities of the built environment depend on the next micro variable factors:

- information system of built environment,
- building's life cycle energy analysis,
- energy use in the built environment,
- pollution and health in cities,
- real estate losses as a result of sea-level rise,
- education and training,
- types of contracts,
- briefing process,
- design process,
- manufacture process,
- construction process,
- maintenance process,
- facilities management,
- holiday travels,
- festivals,
- etc.

As an example, further on we shall briefly discuss some above-mentioned micro-level factors (building's life cycle energy analysis, energy use in the built environment, pollution and health in cities, real estate losses as a result of sea-level rise, holiday travels, Cherry blossom festivals).

### 3.2.1 Building's Life Cycle Energy Analysis

Buildings demand energy in their life cycle right from its construction to demolition. Studies on the total energy use during the life cycle are desirable to identify phases of largest energy use and to develop strategies for its reduction. Ramesh et al. (2010) presented a critical review of the life cycle energy analyses of buildings resulting from 73 cases across 13 countries. The study includes both residential and office buildings. Results show that operating (80–90 %) and embodied (10–20 %) phases of energy use are significant contributors to building's life cycle energy demand. Life cycle energy (primary) requirement of conventional residential buildings falls in the range of 150–400 kWh/m$^2$/year and that of office buildings in the range of 250–550 kWh/m2/year. Building's life cycle energy demand can be reduced by reducing its operating energy significantly through use of passive and active technologies even if it leads to a slight increase in embodied energy. However, an excessive use of passive and active features in a building may be counterproductive. It is observed that low-energy buildings perform better than self-sufficient (zero operating energy) buildings in the life cycle context. Worldwide, 30–40 % of all primary energy is used for buildings, and they are held responsible for 40–50 % of green house gas emissions. It is therefore essential for the building built environment to achieve sustainable development in the society. Sustainable development is viewed as development with low environmental impact, and high economical and social gains. To achieve the goals of sustainability, it is required to adopt a multidisciplinary approach covering a number of features such as energy saving, improved use of materials including water, reuse and recycling of materials and emissions control. Life cycle energy analysis of buildings assumes greater significance for formulating strategies to achieve reduction in primary energy use of the buildings and control emissions (Ramesh et al. 2010).

Life cycle energy analysis is an approach that accounts for all energy inputs to a building in its life cycle. The system boundaries of this analysis) include the energy use of the following phases: manufacture, use and demolition. Manufacture phase includes manufacturing and transportation of building materials and technical installations used in erection and renovation of the buildings. Operation phase encompasses all activities related to the use of the buildings, over its life-span. These activities include maintaining comfort condition inside the buildings, water use and powering appliances. Finally, demolition phase includes destruction of the building and transportation of dismantled materials to landfill sites and/or recycling plants (Ramesh et al. 2010).

A large variety of materials are being used in building construction. Some of them may have a life-span less than that of the building. As a result, they are replaced to rehabilitate the building. In addition to this, buildings require some regular annual maintenance. The energy incurred for such repair and replacement (rehabilitation) needs to be accounted during the entire life of the buildings. It is the energy required for maintaining comfort conditions and day-to-day maintenance of the buildings. It is the energy for heating, ventilation and air conditioning (HVAC), domestic hot water, lighting and for running appliances. Operational energy largely varies on the level of comfort required, climatic conditions and operating schedules. At the end of buildings' service life, energy is required to demolish the building and transporting the waste material to landfill sites and/or recycling plants (Ramesh et al. 2010).

### 3.2.2 Impact of Climate Change on Energy Use in the Built Environment

Work on the subtropical climates had revealed an increasing trend of temperature and summer discomfort over the past decades, and it was found that the anticipated temperature rise could result in more cooling demand. More electricity use for air conditioning would lead to larger emissions, which in turn would exacerbate climate change and global warming. Even in regions with severe cold climates where the decrease in heating energy use could, in terms of final or delivered energy, outweigh the increase in cooling, the impact of climate change on the overall primary energy requirement and the environment would remain uncertain. This is because heating is usually provided by oil- or gas-fired boiler plants, whereas cooling relies on electricity-driven chillers (except gas-fired absorption systems). In terms of carbon footprint, electricity tends to have a much lower overall efficiency and higher $CO_2$ emissions per unit energy consumption. From a nationwide energy and environmental perspective, it is important to be able to estimate the magnitude of the likely changes in heating and cooling energy requirements due to climate change in different climate zones. Broadly speaking, there are two main approaches (Li et al. 2012):

- Degree-days method. The degree-days concept is widely used for measuring the influence of climate on heating and cooling requirements. Hekkenberg et al. (2009) argues that socio-economic changes may alter the temperature dependence pattern of energy demand in future years. However, to a good approximation heating and cooling energy requirements can be assumed to be proportional to the HDDs and CDDs, respectively. In recent years, this method has been used to assess the impact of climate change on regional energy demand as well as energy consumption in the built environment in different parts of the world. Pilli-Sihvola et al. (2010) chose five countries along the north–south gradient: Finland, Germany, the Netherland, France and Spain. Their main findings were as follows: in central and north Europe, the decrease in heating due to climate warming would dominate, and in southern Europe climate warming and the consequential increase in cooling and electricity demand would outweigh the decreasing need for space heating.
- Building energy simulation technique. There had been a number of studies on the impact of climate change on the built environment using sophisticated building energy simulation tools to perform hour-by-hour computation of the heating/cooling loads and corresponding energy use. Building energy simulation is an acceptable technique for assessing the dynamic interactions between the

external climates, the building envelope and the HVAC system and the corresponding energy consumption. It has played an important role in the development of simple design tools and building energy efficiency codes. This technique has also been used by a number of researchers to assess the impact of climate change on energy use in buildings. Gaterell and McEvoy (2005) assessed the impact of projected climate changes on the thermal performance of the built environment and the measures implemented to improve such performance. The air temperatures were raised by 2 and 2.9 °C to reflect the climate in 2050, and by 2.3 and 5.9 °C in 2100 in a study by Radhi (2009) to investigate the potential impact of global warming on residential buildings in United Arab Emirates. It was concluded that global warming was likely to increase the energy used for cooling by 23.5 % with a 5.9 °C increase in the ambient temperature. It was also found that energy design measures, such as thermal insulation and building thermal mass, were important to cope with global warming.

### 3.2.3 Climate Change, Pollution and Health in Cities

Excess morbidity and mortality related to extremely hot weather and poor air quality are found in cities worldwide. This is a major public health concern for cities now and looking towards the future, because the interactions of global climate change, urban heat islands and air pollution are predicted to place increasing health burdens on cities. The proposed mitigation and adaptation strategies in cities' climate risk management plans may produce health co-benefits by reducing emissions and cooling temperatures through changes in the built environment. There are challenges, however, to implementing the plans and the most widely documented beneficial policy to date is the adoption of heat warning and air quality alert systems to trigger emergency responses (Harlan and Ruddell 2011).

As the largest developing country, China has been changing rapidly over the last three decades and its economic expansion is largely driven by the use of fossil fuels, which leads to a dramatic increase in emissions of both ambient air pollutants and GHGs. China is now facing the worst air pollution problem in the world and is also the largest emitter of carbon dioxide. A number of epidemiological studies on air pollution and population health have been conducted in China, using time-series, case-crossover, cross-sectional, cohort, panel or intervention designs. The increased health risks observed among Chinese population are somewhat lower in magnitude, per amount of pollution, than the risks found in developed countries. However, the importance of these increased health risks is greater than that in North America or Europe, because the levels of air pollution in China are very high in general and Chinese population accounts for more than one-fourth of the world's totals. Meanwhile, evidence is mounting that climate change has already affected human health directly and indirectly in China, including mortality from extreme weather events; changes in air and water quality; and changes in the ecology of infectious diseases. If China acts to reduce the combustion of fossil fuels and the resultant air pollution, it will reap not only the health benefits associated with improvement of air quality but also the reduced GHG emissions. Consideration of the health impact of air pollution and climate change can help the Chinese government move forward towards sustainable development with appropriate urgency (Kan et al. 2012).

Urban centres in Latin American often face high levels of air pollution as a result of economic and industrial growth. Decisions with regard to industry, transportation, and development will affect air pollution and health both in the short term and in the far future through climate change. Bell et al. (2006) investigated the pollution health consequences of modest changes in fossil-fuel use for three case study cities in Latin American: Mexico City, Mexico; Santiago, Chile; and São Paulo, Brazil. Annual levels of ozone and particulate matter were estimated from 2000 to 2020 for two emissions scenarios: (1) business-as-usual based on current emissions patterns and regulatory trends and (2) a control policy aimed at lowering air pollution emissions. The resulting air pollution levels were linked to health endpoints through concentration–response functions derived from epidemiological studies, using local studies where available. Results indicate that the air pollution control policy would have vast health benefits for each of the three cities, averting numerous adverse health outcomes including over 156,000 deaths, 4 million asthma attacks, 300,000 children's medical visits, and almost 48,000 cases of chronic bronchitis in the three cities over the 20-year period. The economic value of the avoided health impacts is roughly \$21 to \$165 billion (US). Sensitivity analysis shows that the control policy yields significant health and economic benefits even with relaxed assumptions with regard to population growth, pollutant concentrations for the control policy, concentration–response functions and economic value of health outcomes. Bell et al. (2006) research demonstrates the health and economic burden from air pollution in Latin American urban centres and the magnitude of health benefits from control policies (Bell et al. 2006).

The contribution of the road transportation sector to emissions of air pollutants and GHGs is a growing concern in developing countries. Emission control measures implemented within this sector can have varying counteracting influences. In the city of Durban, South Africa, the growing dependence on privately owned motor vehicles and increasing usage of roads for freight transport have all resulted in significant air pollution and greenhouse gas emissions. In this study, an emissions inventory was developed for the road transport sector and was used as a basis to explore intervention opportunities that are likely to reduce simultaneously, air pollution and greenhouse gas emissions in this sector. It was found that reducing the vehicle kilometres travelled by privately owned motor vehicles and improving the efficiency of road freight transport offered the greatest potential for achieving co-benefits (Thambiran and Diab 2011).

Bollen et al. (2009) present the findings of a combined cost-benefit analysis of local air pollution and global climate change, two subjects that are usually studied separately. Yet these distinct environmental problems are closely related, since they are both driven by the nature of present energy production and consumption patterns. Bollen et al. (2009) also demonstrate that the discounted benefits of local air pollution reduction significantly outweigh those of global climate change mitigation, at least by a factor of 2, but in most cases of our sensitivity analysis much more. Still, Bollen et al. (2009) do not argue to only restrict energy policy today to what should be our first priority, local air pollution control, and wait with the reduction of greenhouse gas emissions. Instead, Bollen et al. (2009) propose to design policies that simultaneously address these issues, as their combination creates an additional climate change bonus. As such, climate change mitigation proves an ancillary benefit of air pollution reduction, rather than the other way around (Bollen et al. 2009).

### 3.2.4 Real Estate Losses as a Result of Sea-Level Rise

The effects of climate change will have severe consequences for low-lying U.S. coastal real estate. If nothing is done to hold back rising waters, sea-level rise will simply cause many properties in low-lying coastal areas to be inundated. Even those properties that remain above water will be more likely to sustain storm damage, as encroachment of the sea allows storm surges to reach inland areas that were not previously affected. More intense hurricanes, in addition to sea-level rise, will increase the likelihood of both flood and wind damage to properties throughout the Atlantic and Gulf coasts. To estimate the value of real estate losses from sea-level rise, we have updated a detailed forecast of coastal real estate losses in the 48 states developed by the Environmental Protection Agency (EPA). In projecting these costs into the future, Ackerman and Stanton (2008) assume that annual costs will be proportional to sea-level rise and to projected GDP. Ackerman and Stanton (2008) calculate the annual loss of real estate from inundation due to the projected sea-level rise, which reaches 45 inches by 2100 in the business-as-usual case. These losses amount to $360 billion by 2100, or 0.35 % of GDP (Ackerman and Stanton 2008).

No one expects coastal property owners to wait passively for these damages to occur; those who can afford to protect their properties will undoubtedly do so. But all the available methods for protection against sea-level rise are problematic and expensive. It is difficult to imagine any of them being used on a large enough scale to shelter all low-lying U.S. coastal lands that are at risk under the business-as-usual case. Elevating homes and other structures is one way to reduce the risk of flooding, if not hurricane-induced wind damage. A Federal Emergency Management Agency (FEMA) (1998) estimate of the cost of elevating a frame construction house on a slab-on-grade foundation by two feet is $58 per square foot, with an added cost of $0.93 per square foot for each additional foot of elevation (FEMA 1998). This means that it would cost $58,000 to elevate a house with a 1,000-square foot footprint by two feet. It is not clear whether building elevation is applicable to multi-storey structures; at the least, it is sure to be more expensive and difficult (Ackerman and Stanton 2008).

### 3.2.5 Holiday Travels and Cherry Blossom Festivals

Whilst much effort has been made to communicate to the public the importance of reducing carbon footprints in the home, one area where emissions are growing rapidly and little attempt has been made to increase consumer understanding of the impacts is holidays, particularly those involving air travel. Using focus group research, this paper explores tourists' awareness of the impacts of travel on climate change, examines the extent to which climate change features in holiday travel decisions and identifies some of the barriers to the adoption of less carbon-intensive tourism practices. The findings suggest that many tourists do not consider climate change when planning their holidays. The failure of tourists to engage with the climate change impact of holidays, combined with significant barriers to behavioural change, presents a considerable challenge in moving the tourism industry onto a sustainable emissions path. The findings are discussed in relation to theoretical perspectives from psychology and sociology (Hares et al. 2010).

Most global climate change models predict serious ecological and social problems. In Japan, biologists have found climate change is affecting species and ecosystems, including the earlier flowering time of cherry trees that are an important cultural symbol in Japan. Cherry blossom festivals are also important to local economies. This study explored the perceptions of Japanese residents regarding climate change impacts on culturally significant events such as flower timing of cherry trees. Sakurai et al. (2011) conducted interviews of stakeholders of three cherry blossom festivals, including sixteen organisers of festivals and 26 managers of festival-dependent businesses, to understand their awareness, attitudes and behaviours towards global climate change and impacts on cherry blossom festivals. Most organisers of the festival in Kakunodate were concerned about global warming and its impact on cherry blossom times while organisers of festivals in Nakano and Komoro felt it was unimportant if flower timing affected the festival schedule. Most (92 %) managers of festival-dependent businesses mentioned that global warming is occurring and affecting the flower timing of cherry trees, but there were diverse perceptions of global warming impacts on their business. Managers more dependent on income from cherry blossom festivals indicated greater concern for the effects of climate change (Sakurai et al. 2011).

As example, micro-level factors are more exhaustively described in the following sub-chapter (see Energy-Efficient House Decision Support Sub-system for Africa).

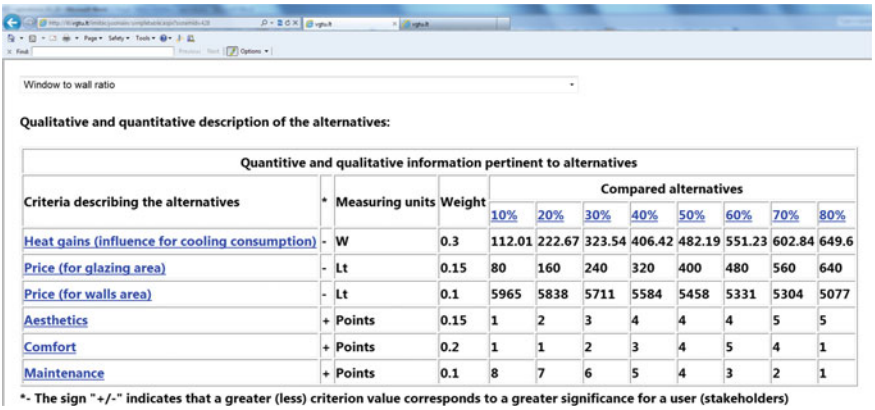
## 4 Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation. Case Study: Energy-Efficient House Decision Support Sub-System for Africa

Based on the analysis of existing intelligent systems a Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation (IS-BELCP-CCMA) consisting of a database, database management system, model-base, model-base management system and user interface was developed.

The following tables make IS-BELCP-CCMA database:

- Initial data tables. These contain general facts about the built environment and climate change considered. The reasons of regenerating of built environment and their significance as well as the money intended to be spent on it are also given.
- Tables assessing refurbishment of built environment solutions. They contain quantitative and conceptual information about alternative of built environment refurbishment solutions [as examples see Equity and Climate Change (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=390), Climate Change Policies (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=391), Operationalising a Resilience to Uncertain Climate Changes (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=392), Climate change and resilience management in built environment (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=409), Energy-Efficient House Decision Support Sub-system for Africa (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=428) (window to wall ratio: Table 1; orientation: Table 2; shading: Table 3)].
- Tables of multi-variant design. They provide quantitative and conceptual information on the interconnection of the elements of built environment to be

**Table 1** Fragment of a grouped decision-making matrix of window to wall ratio alternative's multiple criteria analysis. Qualitative and Quantitative description of the alternatives



Window to wall ratio

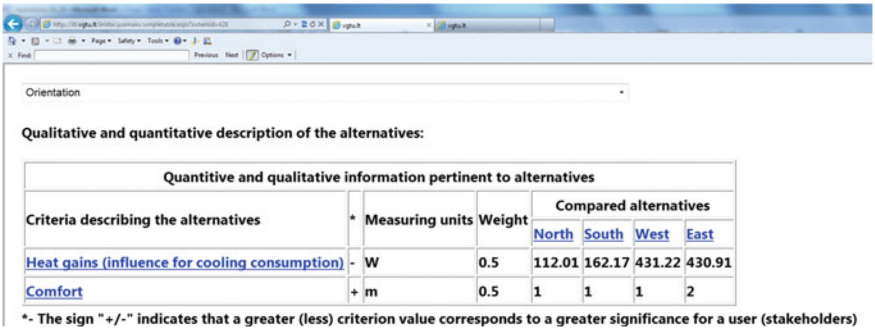
**Qualitative and quantitative description of the alternatives:**

Quantitive and qualitative information pertinent to alternatives

| Criteria describing the alternatives | * | Measuring units | Weight | Compared alternatives | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% |
| Heat gains (influence for cooling consumption) | - | W | 0.3 | 112.01 | 222.67 | 323.54 | 406.42 | 482.19 | 551.23 | 602.84 | 649.6 |
| Price (for glazing area) | - | Lt | 0.15 | 80 | 160 | 240 | 320 | 400 | 480 | 560 | 640 |
| Price (for walls area) | - | Lt | 0.1 | 5965 | 5838 | 5711 | 5584 | 5458 | 5331 | 5304 | 5077 |
| Aesthetics | + | Points | 0.15 | 1 | 2 | 3 | 4 | 4 | 4 | 5 | 5 |
| Comfort | + | Points | 0.2 | 1 | 1 | 2 | 3 | 4 | 5 | 4 | 1 |
| Maintenance | + | Points | 0.1 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

**Table 2** Fragment of a grouped decision-making matrix of orientation alternative's multiple criteria analysis. Qualitative and Quantitative description of the alternatives



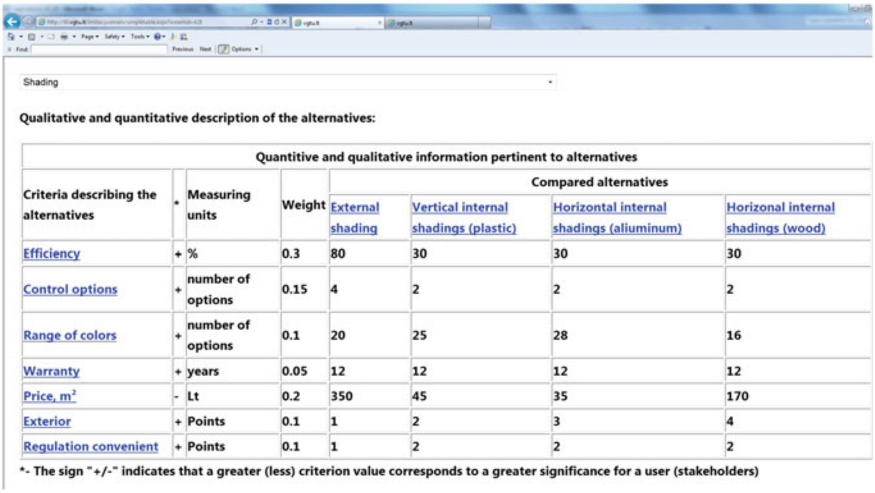
Orientation

**Qualitative and quantitative description of the alternatives:**

| Quantitive and qualitative information pertinent to alternatives | | | | | | | |
|---|---|---|---|---|---|---|---|
| Criteria describing the alternatives | * | Measuring units | Weight | Compared alternatives | | | |
| | | | | North | South | West | East |
| Heat gains (influence for cooling consumption) | - | W | 0.5 | 112.01 | 162.17 | 431.22 | 430.91 |
| Comfort | + | m | 0.5 | 1 | 1 | 1 | 2 |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

**Table 3** Fragment of a grouped decision-making matrix of shading alternative's multiple criteria analysis. Qualitative and Quantitative description of the alternatives



Shading

**Qualitative and quantitative description of the alternatives:**

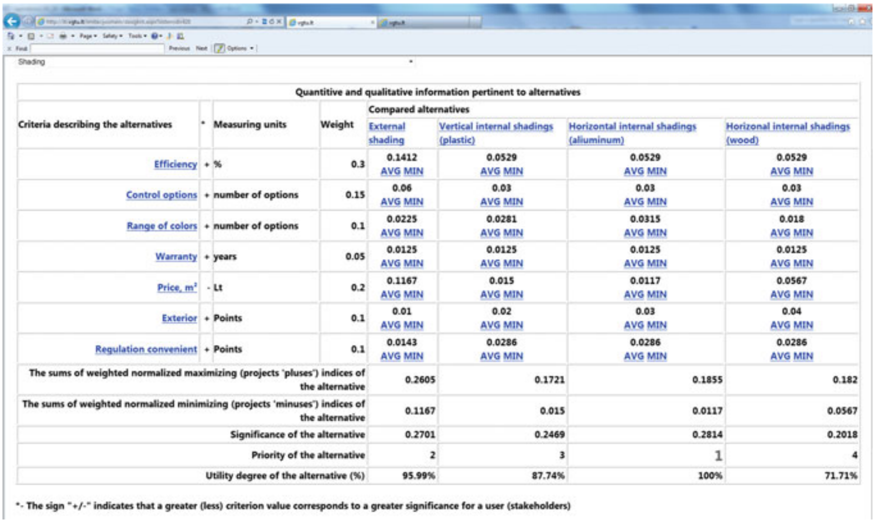
| Quantitive and qualitative information pertinent to alternatives | | | | | | | |
|---|---|---|---|---|---|---|---|
| Criteria describing the alternatives | * | Measuring units | Weight | Compared alternatives | | | |
| | | | | External shading | Vertical internal shadings (plastic) | Horizontal internal shadings (aliuminum) | Horizonal internal shadings (wood) |
| Efficiency | + | % | 0.3 | 80 | 30 | 30 | 30 |
| Control options | + | number of options | 0.15 | 4 | 2 | 2 | 2 |
| Range of colors | + | number of options | 0.1 | 20 | 25 | 28 | 16 |
| Warranty | + | years | 0.05 | 12 | 12 | 12 | 12 |
| Price, $m^2$ | - | Lt | 0.2 | 350 | 45 | 35 | 170 |
| Exterior | + | Points | 0.1 | 1 | 2 | 3 | 4 |
| Regulation convenient | + | Points | 0.1 | 1 | 2 | 2 | 2 |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

regenerated, their compatibility and possible combinations as well as data on complex multivariant design of built environment.

Since the efficiency of a built environment refurbishment variant is often determined taking into account quantitative and qualitative factors a model-base of the IS-BELCP-CCMA should include models enabling a decision maker to do a comprehensive analysis of the variants available and make a proper choice. The following models of model-base are aimed to perform this function:

**Table 4** Shading alternative's multiple criteria analysis results



Shading

Quantitive and qualitative information pertinent to alternatives

| Criteria describing the alternatives | * | Measuring units | Weight | Compared alternatives | | | |
|---|---|---|---|---|---|---|---|
| | | | | External shading | Vertical internal shadings (plastic) | Horizontal internal shadings (aliuminum) | Horizonal internal shadings (wood) |
| Efficiency | + | % | 0.3 | 0.1412<br>AVG MIN | 0.0529<br>AVG MIN | 0.0529<br>AVG MIN | 0.0529<br>AVG MIN |
| Control options | + | number of options | 0.15 | 0.06<br>AVG MIN | 0.03<br>AVG MIN | 0.03<br>AVG MIN | 0.03<br>AVG MIN |
| Range of colors | + | number of options | 0.1 | 0.0225<br>AVG MIN | 0.0281<br>AVG MIN | 0.0315<br>AVG MIN | 0.018<br>AVG MIN |
| Warranty | + | years | 0.05 | 0.0125<br>AVG MIN | 0.0125<br>AVG MIN | 0.0125<br>AVG MIN | 0.0125<br>AVG MIN |
| Price, m² | - | Lt | 0.2 | 0.1167<br>AVG MIN | 0.015<br>AVG MIN | 0.0117<br>AVG MIN | 0.0567<br>AVG MIN |
| Exterior | + | Points | 0.1 | 0.01<br>AVG MIN | 0.02<br>AVG MIN | 0.03<br>AVG MIN | 0.04<br>AVG MIN |
| Regulation convenient | + | Points | 0.1 | 0.0143<br>AVG MIN | 0.0286<br>AVG MIN | 0.0286<br>AVG MIN | 0.0286<br>AVG MIN |
| The sums of weighted normalized maximizing (projects 'pluses') indices of the alternative | | | | 0.2605 | 0.1721 | 0.1855 | 0.182 |
| The sums of weighted normalized minimizing (projects 'minuses') indices of the alternative | | | | 0.1167 | 0.015 | 0.0117 | 0.0567 |
| Significance of the alternative | | | | 0.2701 | 0.2469 | 0.2814 | 0.2018 |
| Priority of the alternative | | | | 2 | 3 | 1 | 4 |
| Utility degree of the alternative (%) | | | | 95.99% | 87.74% | 100% | 71.71% |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

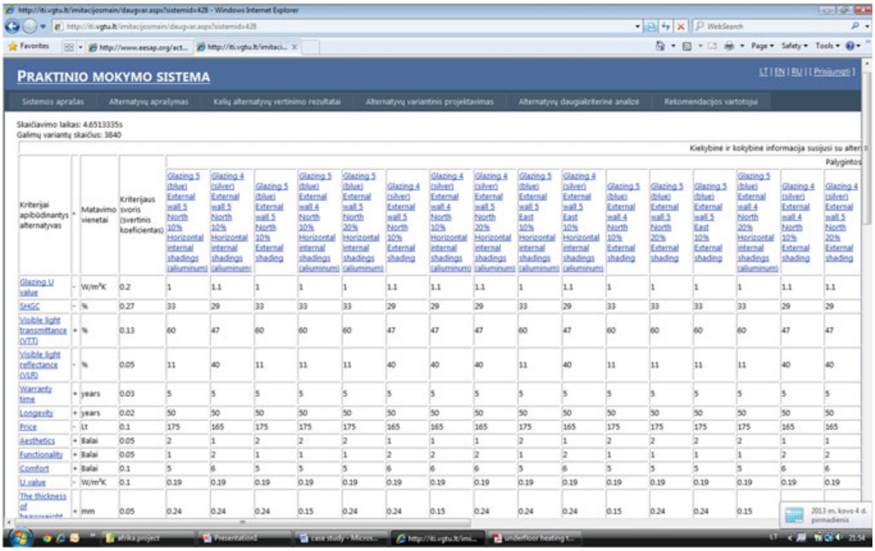
- a model of developing the alternative variants of built environment,
- a model for determining the initial weights of the criteria (with the use of expert methods),
- a model for the criteria weights establishment,
- a model for multiple criteria analysis and setting the priorities (as example see Energy-Efficient House Decision Support Sub-system for Africa (shading: Table 4)),
- a model for multi-variant design of a built environment refurbishment [as example see Energy-Efficient House Decision Support Sub-system for Africa (Table 5)],
- a model for determination of built environment utility degree and market price,
- a model for providing recommendations.

Based on the above models, the IS-BELCP-CCMA system can make until 100 million built environment refurbishment alternative versions, performing their multiple criteria analysis, determining utility degree, market price and selecting most beneficial variant without human interference. Case study of the IS-BELCP-CCMA (Energy-Efficient House Decision Support Sub-system for Africa) is presented below. Energy-Efficient House Decision Support Sub-system for Africa is analysing only microfactors.

**Energy-Efficient House Decision Support Sub-System for Africa**

The Case Study illustrates a part of Stage 5 "A multiple criteria analysis of the composite parts of a climate change mitigation" of the Model of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation.

**Table 5** Multivariant design of energy-efficient house in Africa



Skaičiavimo laikas: 4.6513335s
Galimų variantų skaičius: 3840

Kiekybinė ir kokybinė informacija susijusi su alter

Palygintos

| Kriterijai apibūdinantys alternatyvas | * | Matavimo vienetai | Kriterijaus svoris (svertinis koeficientas) | Glazing 5 (blue) External wall 5 North 10% Horizontal internal shadings (aluminum) | Glazing 4 (silver) External wall 5 North 10% Horizontal internal shadings (aluminum) | Glazing 5 (blue) External wall 5 North 10% External shading | Glazing 5 (blue) External wall 4 North 10% Horizontal internal shadings (aluminum) | Glazing 5 (blue) External wall 5 North 20% Horizontal internal shadings (aluminum) | Glazing 4 (silver) External wall 5 North 10% External shading | Glazing 4 (silver) External wall 4 North 10% Horizontal internal shadings (aluminum) | Glazing 4 (silver) External wall 5 North 20% Horizontal internal shadings (aluminum) | Glazing 5 (blue) External wall 5 East 10% Horizontal internal shadings (aluminum) | Glazing 4 (silver) External wall 5 East 10% Horizontal internal shadings (aluminum) | Glazing 5 (blue) External wall 4 North 10% External shading | Glazing 5 (blue) External wall 5 North 20% External shading | Glazing 5 (blue) External wall 5 East 10% External shading | Glazing 5 (blue) External wall 4 North 20% Horizontal internal shadings (aluminum) | Glazing 4 (silver) External wall 4 North 10% External shading | Glazing 4 (silver) External wall 5 North 20% External shading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glazing U value | - | W/m²K | 0.2 | 1 | 1.1 | 1 | 1 | 1 | 1.1 | 1.1 | 1.1 | 1 | 1.1 | 1 | 1 | 1 | 1 | 1.1 | 1.1 |
| SHGC | - | % | 0.27 | 33 | 29 | 33 | 33 | 33 | 29 | 29 | 29 | 33 | 29 | 33 | 33 | 33 | 33 | 29 | 29 |
| Visible light transmittance (VTT) | + | % | 0.13 | 60 | 47 | 60 | 60 | 60 | 47 | 47 | 47 | 60 | 47 | 60 | 60 | 60 | 60 | 47 | 47 |
| Visible light reflectance (VLR) | - | % | 0.05 | 11 | 40 | 11 | 11 | 11 | 40 | 40 | 40 | 11 | 40 | 11 | 11 | 11 | 11 | 40 | 40 |
| Warranty time | + | years | 0.03 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Longevity | + | years | 0.02 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| Price | - | Lt | 0.1 | 175 | 165 | 175 | 175 | 175 | 165 | 165 | 165 | 175 | 165 | 175 | 175 | 175 | 175 | 165 | 165 |
| Aesthetics | + | Balai | 0.05 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 1 |
| Functionality | + | Balai | 0.05 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 2 |
| Comfort | + | Balai | 0.1 | 5 | 6 | 5 | 5 | 5 | 6 | 6 | 6 | 5 | 6 | 5 | 5 | 5 | 5 | 6 | 6 |
| U value | - | W/m²K | 0.1 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| The thickness of heavyweight | + | mm | 0.05 | 0.24 | 0.24 | 0.24 | 0.15 | 0.24 | 0.24 | 0.15 | 0.24 | 0.24 | 0.24 | 0.15 | 0.24 | 0.24 | 0.15 | [illegible] | [illegible] |

Climate change is both a present and future challenge and represents a key reason to incorporate long-term thinking into the energy design of buildings (Georgiadou et al. 2012).

The building sector contributes up to 30 % of global annual green house gas emissions and consumes up to 40 % of all energy [UNEP], that is why—has the largest potential for significantly reducing greenhouse gas emissions compared to other major emitting sectors. Buildings able to respond to future changes will not become prematurely obsolete; hence, key decisions relating to the energy performance of buildings need to be 'future-proofed' from the early planning and design stages against long-term social, technological, economic, environmental and regulatory changes (Mora et al. 2011).

A building design based on energy-saving criteria reduces economic costs throughout the useful life of the building because of its lower energy consumption, and this more than compensates for the greater initial investment. Since there are also fewer $CO_2$ emissions into the atmosphere throughout the building's life cycle, this benefits society as well (Pacheco et al. 2012). So the building design optimised at the early planning and design stage therefore, make it possible to construct not only energy efficient, but also eco-friendly buildings.

The decision support system (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=428) presented here will facilitate the sustainable building design process and will make it possible to assess any alternatives against a range of criteria. In this particular case, the analysis of building envelope alternatives is adjusted for Johannesburg, a city in South Africa.

During the conceptual design phase of a building, the design team often has to make critical decisions with significant impact on the energy performance and indoor comfort conditions. The design and selection of facades, fenestration systems and their control plays a key role in determining building performance (Tzempelikos et al. 2007).

The presented decision support system covers the following groups of objects: six glazed units, five external-wall constructions, eight different areas of glazing, four orientations of the main façade towards the cardinal directions, and four shading devices. Each of these alternatives makes a considerable impact on a building's energy demands, indoor comfort, aesthetic properties and, naturally, price. Hence, the alternatives will be defined by both quantitative and qualitative criteria. For each criterion, the decision support system sets a measuring unit (qualitative criteria are scored in points) and the weight [e.g. price (0.1)]. Bigger weight means the criterion is more significant. The indicator '±' shows that either higher or lower value of the criterion is better. One by one, each group of objects is considered, its alternatives are analysed against the defined criteria and their weights, and then, the best option is picked out. The utility degree of each alternative is then considered and the alternatives are ranked as a first priority, second priority and so on.

Some indicators were determined theoretically (such as the thermal transmittance coefficient, inertia, etc.), some were obtained from the manufacturers of the materials (such as optical and thermal properties of windows, prices, etc.). Two software applications helped determine the balance of heat gains and the values of quantitative indicators to be used in the assessment of the life cycle of materials:

- Proclim. This application created a reference model of a single-zone building ($7 \times 5 \times 2.6$ m) in Johannesburg (South Africa). By varying wall constructions, optical and thermal properties of glazed units, building's orientation towards the cardinal directions and the glazed area, the software determined typical daily gain balances. Since a universal assessment much depends on the intensity of gain variations, this figure will be included as a quantitative indicator defining the alternatives in question, as it is important in their assessment. The assessment trends of the properties of building's windows and walls correspond to the recommendations laid out in South Africa Fenestration & Insulation Energy Rating Association (SAFIERA).
- SimaPro. It is one of the most popular applications designed to assess the life cycle of building materials. Two methods—IPCC 2007 and Cumulative Energy Demand (CED)—were selected to assess each material used in the construction of walls. IPCC 2007 GWP 100a method lists the climate change factors of IPCC with a timeframe of 100 years. Here, the total amount of carbon dioxide equivalent emissions over the production life cycle (kg $CO_2$-Eq/kg) was determined for each structural material in its production phase.
- The CED represents the direct and indirect energy use in units throughout the life cycle. In our case, CED. Renewable and CED. Non-renewable were determined to assess the external-wall materials in their production phase.

The objective in this analysis was to reach energy efficient, cost-effective, eco-friendly building design, without considering on comfort and aesthetics.

As cooling is dominating in hot climate countries, so here the main intention was to reduce the solar heat gains and cooling demand. The application of life cycle analysis (LCA) lets us compare the alternatives of construction materials in order to find the environmental friendly building design.

Eco-friendly, green building is one of the best strategies for meeting the challenge of climate change. Greenhouse gas emissions from buildings primarily arise from their consumption of fossil-fuel-based energy, both through the direct use of fossil fuels and through the use of electricity that has been generated from fossil fuels. Significant greenhouse gas emissions are also generated through construction materials, in particular insulation materials, and refrigeration and cooling systems [UNEP].

It is fundamental to apply the life cycle vision and take into account both the economic and environmental costs when identifying the most eco-efficient technology. Often, products that are presented as cheap in the medium term can have high maintenance or waste management costs and highly technological products can have very high production costs that are never recouped. Contrarily, it maybe that when we consider the whole life cycle, materials with significant $CO_2$ emissions, such as concrete, can see their emissions reduced by giving them a second life as a filler material in infrastructure, with a double effect: the reduction of emissions compared with obtaining filler materials from quarries and the absorption of $CO_2$ due to the recarbonation processes (Zabalza et al. 2011).

The decision support system has an object group titled ‘External wall’ (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=428), which includes five alternatives of concrete and wooden walls defined by 15 criteria—13 quantitative and two qualitative.

The group of quantitative indicators (with their weights) included the U-value of wall constructions (0.1), the thickness of heavyweight layer (0.05), insulation thickness (0.05), density (0.05), estimated inertia of constructions (0.16) and price (0.1). The application SimaPro and the aforesaid methods assessing the life cycle of materials produced other criteria to define the alternatives: carbon footprint (0.1) and the CED, which comprises non-renewable, fossil (0.05), non-renewable, nuclear (0.05), non-renewable, biomass (0.05), renewable, biomass (0.03), renewable, wind, solar, geothermal (0.03), renewable, water (0.03). The application estimated the values of carbon footprint and CED for each structural material—concrete, timber, thermal insulation materials, etc.—in its manufacturing phase. The qualitative indicators for wall constructions were aesthetic properties (0.1) and maintenance (0.05).

In this instance, the most significant indicator was the inertia of wall constructions with a weight of 0.16. A more massive construction is slower to react to temperature variations, which is a highly important factor in countries with hot climates.

Once the weights of the criteria had been considered, the system produced results indicating ‘External wall 4’ as the best wall construction. The parameters of the alternatives in question show that this construction has the lowest thermal transmittance coefficient, one of the highest inertia values and one of the highest prices. Since the price variation was minor, this criterion was not too determining a factor in the overall assessment.

The group titled ‘Glazing’ (http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=428) comprised six standard, sun protecting, reflecting or tinned glazed units defined by ten criteria—seven quantitative and three qualitative.

Glazed surfaces have an impact on the energy demand for lighting, heating and cooling of buildings (Da Silva et al. 2012), so the optical and thermal properties of glazed units are of particular importance in hot climates. Higher energy demand for cooling, leads to larger emissions, which in turn would exacerbate climate change and global warming.

The alternatives in this group were defined by the following criteria: thermal transmittance (U-value), solar heat gain coefficient (SGHC), visible light reflectance (VLR), price, warranty time, longevity, functionality, comfort and aesthetics. All of the quantitative criteria were available in the specifications produced by manufacturers. The qualitative indicators were scored in points by a group of experts.

In this particular case, the assessment trends of optical and thermal properties correspond to the requirements laid out in SAFIERA: the lower the U-value, the lower the SGHC value and the higher the visible light transmittance (VTT) value. Here, the lower the U-value, the greater a window’s resistance to heat flow and the better its insulating value. The lower the SHGC value, the better glazing is at blocking unwanted heat gain. The higher the VTT value, the more light is transmitted into the room and, in turn, the better is the visual comfort indoors. The biggest weights in this group were, therefore, attributed to SGHC (0.27) and U-value (0.2).

The system’s results indicated ‘Glazing 5’ as the best option among the glazing alternatives. This glazing unit has the best thermal properties with its U-value at 1 W/m$^2$ K., some of the best optical properties with SHGC = 33 %, but the highest price at 175 LTL/m$^2$. Since the optical and thermal properties have far higher weights—SGHC 0.27 and U-value 0.2—than price (0.1), the latter indicator was not the determining one.

Besides the properties of glazed units, other factors that contribute to a building’s energy efficiency—such as glazed area, orientation towards the cardinal directions and shading devices—also play an important role in hot climates. The factors ought to be considered in early designing phases to find an optimal and energy-efficient architectural solution.

Ouedraogo et al. (2012) shown that it is possible to achieve significant a 31 % cooling load reduction by reducing the building total glazing surface area. Shading devices can produce a cooling load reduction of up to 40 % depending on their type and location. For East and West facing facade, the reduction in cooling load is up to 49 % when shading devices are installed.

So our next group of objects is, therefore, eight alternatives of glazed areas [window to wall ratio (WWR %)] (Table 1), four orientations of the main façade towards the cardinal directions (Table 2) and four shading devices (Table 3).

The application ProClim analysed the variation of heat gains for the following groups of alternatives: façade glazing area (WWR %) varying between 10 % and 80 %, and the orientation of the main façade towards either north, south, east or west. Heat gains were used as a quantitative indicator to assess the alternatives.

Naturally, the bigger the glazed area, the higher heat gains, which means higher cooling costs. On the other hand, larger windows may improve a building's aesthetic properties, but may also make the maintenance of transparent surfaces a more difficult task. The biggest weights in the group titled 'Window to wall ratio' (WWR %) were thus attributed to the following criteria: heat gains (0.3) and comfort (0.2). As the glazed area becomes bigger, the area of other wall constructions shrinks, which is why, in terms of a higher price, 'price of glazing' (0.15) has bigger weight than 'price of wall construction' (0.1). The group of qualitative indicators includes such indicators as aesthetics (0.15) and maintenance (0.1). The best option determined by the above weights was the smallest possible glazed area.

Likewise, the façade orientation towards the cardinal directions (Table 2) was assessed against two criteria: heat gains (0.5) and comfort (0.5). Heat gains were estimated by the application ProClim, but it is a relative figure, which, in our case, shows the trends in gain variation determined by different orientation. Comfort was scored in points. In this particular case, the best façade orientation is northward.

Shading devices are one of the simplest ways to block unwanted sun gains.

Shading devices may control solar gains, block direct sunlight and transmit diffuse daylight in the room and eliminate glare and high contrast. Fixed shading devices are usually employed in the building envelope to exclude solar radiation in the summer and admit it during the winter (Tzempelikos et al. 2007).

The decision-making matrix in the group titled 'Shading' (Table 3) analyses four types of blinds: internal vertical plastic blinds, internal horizontal wooden blinds, internal horizontal aluminium blinds and external blinds. At any rate, since blinds are mounted on glazed surfaces, their efficiency to block solar gains, price, control options and the ease of use, the warranty term, are not the only factors, the choice of colour and appearance are also important. All quantitative details were submitted by the manufacturers of shading devices.

In this particular case, the biggest weights were attributed to efficiency (0.3), price (0.2) and control options (0.15).

The best alternative in this group was internal horizontal aluminium blinds. At 30 %, these blinds had the same efficiency as all other options of internal blinds, but the lowest price. The efficiency of external blinds to block solar gains is up to 80 %, but the price had one of the biggest weights in the decision support system and, therefore, it appears to have been the determining criterion in the overall assessment.

Another feature of the system is multivariate design (Table 5). It might prove useful when one needs to make an integrated assessment of all structural and architectural combinations. The method involves the assessment of the alternatives from all groups of objects at once considering all weighted criteria defining each of the alternatives. A possible combination takes one alternative from each group, which are glazing, external wall, orientation, WWR % and shading. The system produces 3,840 possible combinations defined by 40 criteria.

Multivariate design is different from the assessment of individual alternatives by its ability to make an integrated assessment of the entire combination's efficiency. As a result, it may happen that one of the most efficient combinations is not necessarily a combination of the best alternatives from each group of objects. It is a way, then, to pick out a combination of alternatives with maximum efficiency by all possible criteria.

## 5 Conclusion

In the past there has been no intelligent approach to learning from climate change mitigation and adaptation in built environment projects once they are completed. Now, however, the built environment is adapting concepts of tacit and explicit knowledge management to improve the situation. Top managers generally assume that professionals in enterprises already possess tacit and explicit knowledge and experience for specific types of projects. Such knowledge is extremely important to organisations because, once a project is completed, professionals tend to forget it and start something new. Therefore, knowledge multifold utilisation is a key factor in productively executing a climate change mitigation and adaptation in built environment project. The main purpose of this paper is to present the Model and Intelligent System of Built Environment Life Cycle Process for Climate Change Mitigation and Adaptation which the authors of this paper have developed.

## References

Ackerman F, Stanton EA (2008) What we'll pay if global warming continues unchecked. Natural Resources Defense Council, p 42

Akadiri PO, Olomolaiye PO, Chinyio EA (2013) Multi-criteria evaluation model for the selection of sustainable materials for building projects. Autom Constr 30:113–125

Allouche J (2011) The sustainability and resilience of global water and food systems: political analysis of the interplay between security, resource scarcity, political systems and global trade. Food Policy 36(1):3–8

Baucells M, Sarin RK (2007) Does more money buy you more happiness? Available from: http://repositories.cdlib.org/anderson/dotm/RS16. Accessed 12 Apr 2012

Bell ML, Davis DL, Gouveia N, Borja-Aburto VH, Cifuentes LA (2006) The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City. Environ Res 100(3):431–440

Boehmer-Christiansen S (1997) A winning coalition of advocacy: climate research, bureaucracy and 'alternative' fuels: who is driving climate change policy? Energy Policy 25(4):439–444

Bollen J, Zwaan BVD, Brink C, Eerens H (2009) Local air pollution and global climate change: a combined cost-benefit analysis. Resour Energy Econ 31(3):161–181

Carey J (2011) Calculating the true cost of global climate change. Available from: http://e360.yale.edu/feature/calculating_the_true_cost_of_global_climate_change/2357/. Accessed 10 July 2012

Da Silva PC, Leal V, Andersen M (2012) Influence of shading control patterns on the energy assessment of office spaces. Energy Buildings 50:35–48. doi:10.1016/j.enbuild.2012.03.019

Daniels PL (2007) Buddhism and the transformation to sustainable economies. Soc Econ 29(2):155–180

Daniels PL (2010a) Climate change, economics and Buddhism—Part I: an integrated environmental analysis framework. Ecol Econ 69(5):952–961

Daniels PL (2010b) Climate change, economics and Buddhism—Part 2: new views and practices for sustainable world economies. Ecol Econ 69(5):962–972

Easterlin RA (2010) Happiness, growth, and the life cycle. Oxford Univ Press, New York

Easterlin RA, Morgan R, Switek M, Wang F (2012) China's life satisfaction, 1990–2010. Available from: http://www.pnas.org/content/early/2012/05/09/1205672109.full.pdf. Accessed 17 May 2012

Farbotko C, Lazrus H (2012) The first climate refugees? Contesting global narratives of climate change in Tuvalu. Global Environ Change 22(2):382–390

Federal Emergency Management Agency (FEMA) (1998) Homeowner's guide to retrofitting: six ways to protect your house from flooding. Federal Emergency Management Agency, Washington, DC, p 173

Feynman J (2007) Has solar variability caused climate change that affected human culture? Adv Space Res 40(7):1173–1180

Fischer A, Peters V, Vávra J, Neebe M, Megyesi B (2011) Energy use, climate change and folk psychology: does sustainability have a chance? Results from a qualitative study in five European countries. Global Environ Change 21(3):1025–1034

Ford JD, Berrang-Ford L, King M, Furgal C (2010) Vulnerability of Aboriginal health systems in Canada to climate change. Global Environ Change 20(4):668–680

French S (2003) The code of the warrior: exploring warrior values past and present. Rowman & Littlefield, Lanham

French WC (2008) Ecoethics. Encyclopedia of violence, peace and Conflict, 2nd edn. pp 607–662

Gaterell MR, McEvoy ME (2005) The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. Energy Building 37(9):982–995

GCCA (2012) Glossary of climate change acronyms. Available from: http://unfccc.int/essential_background/glossary/items/3666.php. Accessed 12 Apr 2012

Geel BV, Bokovenko NA, Burova ND, Chugunov KV, Dergachev VA, Dirksen VG, Kulkova M, Nagler A, Parzinger H, Plicht JVD, Vasiliev SS, Zaitseva GI (2004) Climate change and the expansion of the Scythian culture after 850 BC: a hypothesis. J Archaeol Sci 31(12):1735–1742

Georgiadou MC, Hacking T, Guthrie P (2012) A conceptual framework for future-proofing the energy performance of buildings. Energy Policy 47:145–155. doi:10.1016/j.enpol.2012.04.039

Hares A, Dickinson J, Wilkes K (2010) Climate change and the air travel decisions of UK tourists. J Transp Geogr 18(3):466–473

Harlan SL, Ruddell DM (2011) Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. Curr Opin Environ Sustain 3(3):126–134

Hekkenberg M, Moll HC, Schoot Uiterkamp AJM (2009) Dynamic temperature dependence patterns in future energy demand model in the context of climate change. Energy 34(11):1797–1806

Hendrix CS, Glaser SM (2007) Trends and triggers: climate, climate change and civil conflict in Sub-Saharan Africa. Polit Geogr 26(6):695–715

IAEA (2008) Climate change and nuclear power. Available from: http://www.iaea.org/OurWork/ST/NE/Pess/assets/08-33461-CCNP-Brochure.pdf. Accessed 22 May 2012

IPCC (2010) Glossary working group III. Glossary. Available from: http://www.commondreams.org/archive/2007/08/18/3255. Accessed 10 July 2012

Kan H, Chen R, Tong S (2012) Ambient air pollution, climate change, and population health in China. Environ Int 42(1):10–19

Li DHW, Yang L, Lam JC (2012) Impact of climate change on energy use in the built environment in different climate zones—a review. Energy 42(1):103–112

Marcott SM (2013) Science, 8 March 2013 339(6124):1198–1201

Marcott SM, Shakun JD, Clark PU, Mix AC (2013) A Reconstruction of regional and global temperature for the past 11,300 Years. Science 339(6124):1198

Mendis P (1993) Buddhist equilibrium: the theory of middle path for sustainable development. Staff Paper Department of Agricultural and Applied Economics, University of Minnesota, St. Paul, pp 93–102

Molina M, Zaelke D, Sarmac KM, Andersen SO, Ramanathane V, Kaniaruf D (2009) Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in $CO_2$ emissions. Proc Natl Acad Sci 106(49):20616–20621

Mora R, Bitsuamlak G, Horvat M (2011) Integrated life-cycle design of building enclosures. Build Environ 46(7):1469–1479. doi:10.1016/j.buildenv.2011.01.018

Ouedraogo BI, Levermore GJ, Parkinson JB (2012) Future energy demand for public buildings in the context of climate change for Burkina Faso. Build Environ 49:270–282. doi:10.1016/j.buildenv.2011.10.003

Pacheco R, Ordóñez J, Martínez G (2012) Energy efficient design of building: a review. Renew Sustain Energy Rev 16(6):3559–3573. doi:10.1016/j.rser.2012.03.045

Pilli-Sihvola K, Aatola P, Ollikainen M, Tuomenvirta H (2010) Climate and electricity consumption—witnessing increasing or decreasing use and costs? Energy Policy 38(5):2409–2419

Radhi H (2009) Evaluating the potential impact of global warming on the UAE residential buildings—a contribution to reduce the $CO_2$ emission. Build Environ 44(12):2451–2462

Raleigh C, Urdal H (2007) Climate change, environmental degradation and armed conflict. Polit Geogr 26(6):674–694

Ramesh T, Prakash R, Shukla KK (2010) Life cycle energy analysis of buildings: An overview. Energy Buildings 42(10):1592–1600

EIA report (2009) Emissions of Greenhouse Gases in the United States

Ruth M, Coelho D, Karetnikov D (2007) The U.S. economic impacts of climate change and the costs of inaction. University of Maryland, p 52

Sakurai R, Jacobson SK, Kobori H, Primack R, Oka K, Komatsu N, Machida R (2011) Culture and climate change: Japanese cherry blossom festivals and stakeholders' knowledge and attitudes about global climate change. Biol Conserv 144(1):654–658

Salick J, Fang Z, Byg A (2009) Eastern Himalayan alpine plant ecology, Tibetan ethnobotany, and climate change. Global Environ Change 19(2):147–155

Schneider SH (2004) Abrupt non-linear climate change, irreversibility and surprise. Global Environ Change 14(3):245–258

Shwom R, Bidwell D, Dan A, Dietz T (2010) Understanding U.S. public support for domestic climate change policies. Global Environ Change 20(3):472–482

SOCCR (2008) The first state of the carbon cycle report: the North American carbon budget and implications national oceanic and atmospheric administration. National Climatic Data Center, Asheville, p 242. Available from: http://www.climatescience.gov/Library/sap/sap2-2/final-report/default.htm

Stern N (2007) Stern review on the economics of climate change: part III: the economics of stabilisation. HM Treasury, London. Available from: http://hm-treasury.gov.uk/sternreview_index.htm. Accessed 12 Apr 2012

Stiglitz JE, Sen A, Fitoussi JP (2008) Report of the commission on the measurement of economic performance and social progress. Available from: www.stiglitz-sen-fitoussi.fr. Accessed 17 May 2012

Thambiran T, Diab RD (2011) Air pollution and climate change co-benefit opportunities in the road transportation sector in Durban, South Africa. Atmos Environ 45(16):2683–2689

The New Scientist (2007) Religious leaders pray for cold weather to combat climate change. New Scientist 195(2621):4

Tideman S (2001) Gross national happiness: towards Buddhist economics. Adapted from paper presented to a forum with leaders and scholars from Bhutan, in the Netherlands

Tzempelikos A, Athienitis AK, Karava P (2007) Simulation of façade and envelope design options for a new institutional building. Sol Energy 81(9):1088–1103. doi:10.1016/j.solener.2007.02.006

Vatican-appointed panel warns of climate change (2011). Available from: http://www.mb.com.ph/node/317748/vaticanappointed-panel-warn. Accessed 10 July 2012

Vodopivec M, Tong MH (2008) China: improving unemployment insurance. World Bank, Washington, DC, p 61

Wardekker JA, Petersen AC, Sluijs JP (2009) Ethics and public perception of climate change: exploring the Christian voices in the US public debate. Global Environ Change 19(4):512–521

Webster D (2005) The philosophy of desire in the Buddhist Pali Canon. Routledge Curzon, London

Willis A (2012) Constructing a story to live by: ethics, emotions and academic practice in the context of climate change. Emot Space Soc 5(1):52–59

Zabalza Bribián I, Valero Capilla A, Aranda Usón A (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 46(5):1133–1140. doi:10.1016/j.buildenv.2010.12.002

# Benefits of Refurbishment

**Marina Mistretta, Marco Beccali, Maurizio Cellura, Francesco Guarino and Sonia Longo**

**Abstract** Energy and environmental performances of buildings strictly depend on many factors related to the choice of construction materials, HVAC plants and equipment, design, installation and use. By definition, a building interacts closely with its environment. The interactions between building and climate, plants and users have to be taken into account. This aspect is evident in new buildings design process, but it is even more important in the design phase of an existing building renovation, during which actions of energy saving are developed. This chapter summarises the results of the energy and environmental assessment of a set of retrofit actions implemented in the framework of the EU Project 'BRITA in PuBs'. The main goals were to improve building energy and environmental performances following a life-cycle approach and to support the project partners to select the retrofit actions involving the highest energy saving and the lowest environmental impacts. Synthetic indices, as energy and GWP payback times, and energy return ratio, are defined to better describe the energy and environmental performances of the actions. The use of the life-cycle approach was very successful and potentially transferable to other contexts of building retrofit study.

## 1 Introduction

The annual balance for operating energy or carbon emissions has been the goal of different building projects implemented in many European countries. This topic has been adopted by politics to define strategies of energy saving and climate

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change in the building sector (Voss et al. 2011). Such a topic is addressed in the EPBD recast, according to which all new buildings should be built as nearly zero energy buildings within 2020 (Directive 2010/31/EU). A particular focus is given to the refurbishment of existing buildings, for which the EPBD recast prescribes retrofit scenarios addressed to reduce operating energy.

This aspect is a key issue owing to the following topics of the building sector:

1. The turn-over rate of buildings is quite low and does not exceed more than 3 % yearly (Eicker 2012)
2. Buildings are the largest consumers of energy and account for about 40 % of the total EU final energy consumption (Ardente et al. 2010)
3. Environmental performances (climate change, resource depletion, toxicity, etc.) are the most relevant driving forces for energy saving in buildings.

The goal of undertaking the energy and environmental assessment of building retrofit actions is a complex matter. The energy use during the building operation is influenced by several factors, such as climate, building envelope and other characteristics, building occupancy and use, heating and air conditioning equipment type and schedule (Cellura et al. 2010). When a building undergoes a retrofit project, the quantification of the related energy savings should include the following steps:

1. the assessment of the energy consumption of the technical equipment;
2. the assessment of the influence of significant variables (e.g. climate, building occupancy, operation hours) on energy consumption;
3. the assessment of the energy consumption of the technical equipment after retrofit, through post-retrofit monitoring or building energy simulations;
4. the calculation of achieved energy savings through a balance between the post-retrofit energy uses and the pre-retrofit ones.

This approach is limited to the assessment of operation energy balances and is not capable to deal with global energy and environmental benefits related to the designed retrofit (Dixit et al. 2010). The improvement of energy performances in building operation still must be the primary goal of the design step to reduce the operating energy demand, improving the thermal insulation of the building envelope and the efficiency of energy devices, installing alternative energy using systems and renewable energy technologies for heating, domestic hot water and electricity generation (Beccali et al. 2011; Lo Mastro and Mistretta 2004). Nevertheless, such measures could lead to an increase in embodied energy of buildings, which is embedded in building materials, transportation and construction processes, and in the energy needed for demolition (disposal/recycling) (Beccali et al. 2001). Some studies show that 40–60 % of the life-cycle energy is used in the production and construction phases (Ardente et al. 2008).

The above considerations highlight the role of the life-cycle approach to perform a reliable and complete building energy and environmental assessment. Designing an effective building retrofit requires an exhaustive study of all solutions involving planimetric and volumetric changes and exclusion of the obsolete building elements. Housing renovation should reduce the environmental impact (e.g. energy and resource consumption, emission of air and water pollutants, waste generation, and noise), increase the indoor comfort and improve the architectural appearance of the building facades.

## 2 Literature Review

Energy use in building operation accounts for 70–90 % of energy used during its life cycle (Chen et al. 2001; Zimmermann et al. 2005; Cole and Kernan 1996; Fay et al. 2000; Suzuki et al. 1998; Nemry et al. 2008; Ortiz et al. 2009). Some literature studies on LCA carried out on low-energy houses focused on minimising the final energy use or the purchased energy in the operation phase, while the energy consumption in other phases is often neglected.

All of the cited studies reach the conclusions that moving toward low-energy building and to nearly Net ZEBs involves a decrease in the relative share of energy use related to building operation.

An interesting Swiss study, based on a life-cycle approach, estimated that the construction sector is responsible for about 50 % of the life-cycle primary energy consumption in Switzerland (Zimmermann et al. 2005). Such consumption is mostly due the single-family dwellings, followed by the multi-family dwellings. The highest contributions are given by the energy use for heating and hot water supply (50–70 % of the global consumption), while embodied energy of the building materials accounts for 10–20 %.

Another life-cycle study was carried out within the EU Building Project ‘Environmental Improvement Potentials of Residential Buildings’. It assessed the environmental improvement potentials of residential buildings, including all relevant types of existing and new buildings used as household dwellings in the EU-25 (Nemry et al. 2008). Such a study took into account the residential building stock in the EU 25, divided in single-family houses, multi-family houses and high-rise buildings. The operation and the end-of-life phases were included in the existing building analyses, and the construction phase was added in the new ones. The results showed a common trend both for new buildings and existing buildings: the high-rise buildings involved the lowest life-cycle impacts, while, on average, single-family houses have the highest impacts (i.e. a primary energy requirement of 1,000–1,500 MJ/($m^2$y), and a GWP of about 70–80 kg$CO_{2eq}$/($m^2$y)). This trend depends on the effects of the climatic conditions, the building shape and the shell insulation on the internal thermal loads. For new buildings, the use phase dominates the total environmental impacts at EU level, but the construction phase also accounts for a large rate of the impacts (8.3–34.3 % of the environmental impacts).

Another interesting comparative study among different residential buildings was presented in (Ortiz et al. 2009). Six semi-detached house typologies, common in the central Europe, with living surfaces ranging from 176 $m^2$ to 185 $m^2$ and an average useful life of 80 years were analysed. The houses differed in the energy efficiency of the heating system as well as in building materials. The reference house had an energy demand for heating of 353 MJ/($m^2$y). The other houses showed values of energy consumption between 122 and 187 MJ/($m^2$y), typical for low-energy houses. The houses only differed slightly in their sizes and layouts. The study showed that the adoption of high-efficiency design solutions (higher insulation, high-efficiency plants, low-energy materials, etc.) sensibly decreased the global energy demands with respect to a common reference building. Worse performances of the examined buildings were generally to be related to inadequate insulation or to the use of electricity for the building heating.

An Italian case study (Blengini and Di Carlo 2010) compared a standard house and a low-energy house, clearly showing the different role of embodied energy in relative terms. The primary energy used for construction and maintenance increased by 20 % when taking the step from the standard house to a low-energy house. The analysis was performed by collecting and estimating data from each phase of the building, including the design phase, production of construction materials and components, energy and water supply, construction and installation of plants, use, maintenance and management of the building end-life. The results showed that the use phase involved the most significant energy consumption, accounting for 75 % of the total primary energy demand. The construction phase required 19 % of the total energy demand, while the maintenance and end of life phases accounted for 6 % of the total primary energy demand. A more detailed analysis of the use phase showed that the electricity consumption was dominant, followed by the use of LPG for house heating, hot water demand and cooking. A large part of the consumptions were related to the use of household appliances and other electrical equipment.

All the above case studies show that the embodied energy has decreased slightly over time, indicating that the construction of buildings and technical systems in general has become more effective over time. However, the relative share of embodied energy in the life-cycle energy assessment is increasing and the most relevant efforts that should be made are to choose insulation materials with low embodied energy instead of increasing the amount of insulation and to increase the share of renewable energy use.

Scientific literature shows few studies specifically focused on building refurbishment actions. The EU Project ‘BRiTA in PuBs’ (Bringing Retrofit Innovation to Application in Public Buildings was aimed at: (1) increasing the market penetration of innovative and effective retrofit solutions; (2) improving energy efficiency of public buildings; and (3) promoting renewable energy technologies in public buildings all over Europe.

The following sections summarise the results of energy and environmental assessment of a set of retrofit actions implemented in the framework of the above-mentioned project (Ardente et al. 2011). In detail, following a life-cycle approach, the authors present a balance between energy and environmental benefits and drawbacks concerning exemplary building retrofit actions, such as the introduction of insulation and windows with high thermal efficiency, installation of renewable energy plants and efficient HVAC and lighting (UNI EN ISO 2006). The use of such an approach was very successful and potentially transferable to other contexts of building retrofit study.

The energy and environmental assessment allowed the partners to select the retrofit actions which could involve the highest energy saving and the lowest environmental impacts to the eco-profile of refurbished buildings.

The environmental burdens of retrofits were assessed to estimate the order of magnitude of the impacts and to identify environmental ‘hot spots’ of retrofits, i.e., materials and components with the highest environmental burdens.

## 3 Description of the Retrofit Actions in the Assessed Buildings

The following six European buildings are the selected case studies; each one underwent proper sets of retrofit actions:

1. Old Brewery, Brno (Total floor area after the intervention: 2,660 $m^2$). The retrofit was applied to the old ‘Brewery’ located in the historical centre. The former brewery has been transformed into a modern social and cultural centre for students and academics, including a structural renovation of the building and an energy retrofit by installing several innovative components, such as new thermal insulation of the surfaces, high-efficiency windows, high-efficiency HVAC systems, condensing gas boilers and PV panels.
2. Hol Church, Gol (Total floor area after the intervention: 555 $m^2$). The retrofit was performed on an ancient Norwegian timber church. The actions included removing rotted timber, installing rock wool insulation, introducing an innovative solar-assisted heating system, and installing PV panels and energy-efficient light bulbs.
3. College, Plymouth (Total floor area after the intervention: 5,794 $m^2$). The retrofit was performed in the existing city college in Plymouth and included specific energy-saving actions. The existing building was erected using a simple cavity wall construction and single glazed windows, all of which results in very low insulation values. The existing walling is typical of its time with an outer façade of imperial-sized bricks and a 50-mm dry cavity with no insulation. Existing window units are single panes in metal frames. The external façades, as in most buildings of the same kind and age, are now in a poor state of repair, and suffer particularly because of their close proximity and exposure to the South West coast line weather. Available data on wind exposure and prevailing wind direction in addition to the outlook of the site suggested that it would be appropriate to install wind turbines. Thus, two wind turbines (with a nominal power of 6 kW each) were installed on the roof of the building, 21 m above ground level. Other modifications for heating, cooling and lighting

control, solar glare control, and thermal gains reduction were designed but not realised during the project.

4. Prøvehallen, Copenhagen (Total floor area after the intervention: 2,300 $m^2$). The site was an old industrial area that was completely reshaped and turned into a modern low-energy and multifunctional cultural centre. The retrofit was essentially characterised by the installation of thermal insulation of the external walls of the buildings, low-energy windows and a 'demand controlled' system of mechanical and natural ventilation. Two PV plants were installed: an array of PV cells on the south gable wall, and an innovative photovoltaic/thermal (PV/T) solar collector cooled by a heat pump to increase the efficiency of the PVs. The produced electricity is used in the building or sold to the electricity grid.
5. Nursing home, Stuttgart (Total floor area after the intervention: 2,131 $m^2$). The heating system had an old measurement control system. The boiler system was not efficient because of the falling insulation and the missing control system. Opening the windows was the only ventilation source, as no mechanical ventilation system was installed. A cooling system in this habitation-like building in Germany is not necessary. The lighting system consists of energy-saving fluorescent tubes and bulbs in the rooms and traffic areas. It was controlled by manual on/off switches. The lighting system did not work efficiently. The power of the installed lighting system ran up to 12.5 $W/m^2$ for 300 lx. The retrofit project included many integrated renovation actions, including energy retrofit of structures, wall insulation with mineral-fibre wool, integration in the façades of high-performance windows, and installation of high-performance heating and ventilation systems. Furthermore, a thermal solar plant was installed to provide 32 % of the domestic hot water demand. Moreover, a PV system with a yearly production of 12.6 kWh/y was installed.
6. Vilnius Gediminas Technical University (VGTU) main building, Vilnius (Total floor area after the intervention: 8,484 $m^2$). The thermal transmittance of the walls was 1.07 $W/(m^2K)$. After 30 years of exposure, both the sun and rainfall impacted the partitioned external sectors. Somewhere, connection junctures of three-layer panels were already partly crumbled and pervious to moisture. The juncture in damaged places of the external sectors partitioned off was sealed with warm sealing material and stopped up with a sealant. The renovation of the VGTU case study mainly involved: (1) the renovation of old façades and of the roof; (2) the substitution of old wall insulation with higher thermal performance materials; (3) the installation of high-efficiency windows with selective glasses and low thermal transmittance; (4) the renovation of the heating system; (5) the replacement of the old heating and ventilation systems with fully automated ones.

The environmental assessment of the case studies was performed by coupling field data with referenced eco-profiles of the main building products and processes applied in the project. Information about retrofit actions arose from:

- Designs, including the description of construction materials, plants, energy-efficient components and technologies to exploit renewable energy sources.
- Checklists and questionnaires for a data survey during the construction and implementation of the retrofits, including also data regarding waste production and energy consumption of construction machinery.
- Monitoring data on the energy consumption of buildings and the energy production energy systems.

Retrofit actions are likely to be conceptually complex, because they include other concepts, such as economic and aesthetic considerations, besides the energy and environmental aspects. The final choices depend on a variety of environmental technological and economic mechanisms. Therefore, a preliminary list of the foreseeable consequences that are potentially important for the energy and environment, due to the retrofit actions, was prepared. Afterwards, the potential key-issues enclosed in the list were discussed with a network of experts involved in the project. A combination of experts was selected from the group of participants to complete questionnaires on numerical data and qualitative judgements. Questionnaires were provided to the project participants to collect data regarding both the design stage and the implementation of the retrofit actions.

In particular, the requested information concerned the following categories:

- building materials used for the retrofit work, with particular attention to their thermal properties
- window typologies and characteristics,
- lighting equipment,
- innovative and traditional heating systems,
- PV and solar thermal collectors,
- ventilation systems,
- pipes and ducts,
- energy consumption of machinery used during retrofit work,
- waste produced during construction.

Table 1 shows the direct energy consumption in the case studies, before the retrofit actions, and the direct energy savings by renovating the building components, materials and technologies; these data were collected among the project partners by means of questionnaires. The greatest difficulties concerned the availability of inventory data. Because a detailed analysis of each construction component was beyond the goals of the project, national and international environmental databases were investigated to select representative eco-profiles of products and systems [23, 24, 25, 26, 27]. Data were deduced from references and adapted to the specific retrofit context when not available.

A relevant issue was the service life of each retrofit component, which were taken from the technical reports of the suppliers (Table 2).

**Table 1** Energy consumption in the case studies, before the retrofit actions

| Case study | Energy use before retrofit (GJ/y) |
|---|---|
| *Brno* | |
| Space heating | 2,376 |
| Electricity | 588 |
| *Gol* | |
| Space heating | 440 |
| Electricity | 74 |
| *Plymouth* | |
| Space heating | 4,320 |
| Electricity | 2,336 |
| *Copenhagen* | |
| Space heating | No data |
| Electricity | No data |
| *Stuttgart* | |
| Space heating | 2,446 |
| Electricity | 472 |
| *Vilnius* | |
| Space heating | 5,437 |
| Electricity | 1,101 |

**Table 2** Energy savings after the retrofit in each case study

| Case study | Total heating energy saving [GJ/year] | Total electricity saving [GJ/year] |
|---|---|---|
| Brno | 1,243 | 133 |
| Gol | 205 | 36 |
| Plymouth | 693 | 41.4 |
| Prøvehallen | 693 | 192 |
| Stuttgart | 1,482 | 433 |
| Vilnius | 1,546 | 1,101 |

## *3.1 Energy and Environmental Analysis of The Retrofit Actions: Benefits and Drawbacks*

Energy and environmental analysis was carried out by means of suitable and meaningful indicators, which were assessed and presented at the level of mid-point indicators according to the data format of the environmental product declaration (EPD) scheme and recommended by ISO 14040 (EPD 2008; UNI EN ISO 14040 2006). Therefore, the following indicators were taken into account:

In particular, the requested information concerned the following categories:

- Gross energy requirement (GER).
- Global warming potential (GWP).
- Ozone depletion potential (ODP).
- Acidification potential (AP).

- Eutrophication potential (EP).
- Photochemical ozone creation potential (POCP).

Furthermore, the following payback indices were added to the above EPD set for a deeper description of the energy performance of the retrofit actions and to compare different alternatives:

- Energy Payback Time ($E_{\mathrm{PT}}$) of a building retrofit action, which indicates the time needed to save as much energy (valued as primary) as that consumed during all the life-cycle phases of each retrofit component/material/technology,
- Emission Payback Time ($\mathrm{Em}_{\mathrm{PT,GWP}}$), which indicates the time during which the avoided GWP by the application of the retrofit actions is balanced by that one derived from the life-cycle of each retrofit component (PRè 2010),
- Energy return ratio ($E_R$), which shows how many times energy saving exceeds global energy consumption. It includes GER and the primary energy saving induced by the retrofit actions during the whole building life cycle.

In detail, $E_{\mathrm{PT}}$ was assessed for each action as:

$$E_{\mathrm{PT}} = \mathrm{GER}/E_{s,y} \tag{1}$$

where

- GER is calculated with regard to the life cycle of the retrofit action (GJ).
- $E_{s,y}$ is the yearly saving of primary energy due to the retrofit action (GJ/y).

The yearly direct saving of electricity and heat was estimated at the design stage of the retrofit actions or measured after the retrofit was completed (Table 3). Such data were converted into primary energy based on the energy mix for the production of electricity and other energy sources for each considered country (Frischknecht et al. 2007). $\mathrm{Em}_{\mathrm{PT,GWP}}$ was defined as:

$$\mathrm{Em}_{\mathrm{PT,GWP}} = \mathrm{GWP}/\mathrm{GWP}_{a,y} \tag{2}$$

where

- GWP is calculated with regard to the life cycle of the retrofit action ($\mathrm{kgCO_2eq}$).
- $\mathrm{GWP}_{a,y}$ is the GWP avoided yearly after the retrofit ($\mathrm{kgCO_2eq/y}$). It also represents the GWP, which arises from the building if no retrofit action performed.

**Table 3** Service life of each retrofit component

| Component | Lifetime (years) |
|---|---|
| Lighting equipments | 3 |
| Small wind turbines | 15 |
| HVAC systems | 15 |
| Solar thermal plants | 15 |
| PV plants | 20 |
| Building components | 35 |

Then, it depends on the typology and efficiency of the used plants. For each action, it is assessed on the basis of $E_{s,y}$ and of the reference emission factor of each electricity mix and national gas-fired heating plants.

$E_R$ was defined as follows:

$$E_R = E_s/\mathrm{GER} \tag{3}$$

where $E_s$ is the total saving of primary energy during the lifetime of each retrofit action (GJ).

## 3.2 Results

### 3.2.1 Case Study: Brno

The retrofit of the Brewery building (Brno) included the following actions:

- refurbishment of the building envelope with new thermal insulation and high-efficiency windows to reduce the thermal losses and the lighting need,
- installation of PV panels and of high-efficiency technology for heating and ventilation.

Figure 1 compares GER to total energy saving, while Fig. 2 shows the contribution to GER of each retrofit phase. The construction phase required the use of electricity and diesel oil to operate the machinery. The disposal scenario included the transportation of wastes coming from the building site and their disposal to local landfills. It is observed that the highest GER is due to the PV plants, while insulation and window replacement represent 4 % and 3 % of GER, respectively. The construction phase represents 19 % of GER, while the contribution due to wastes disposal is 4 % of GER. The retrofit of the building envelope provides yearly primary energy savings of 586 GJ/y. In particular, the building insulation that was improved with mineral wool boards of 100 mm for the facade and the

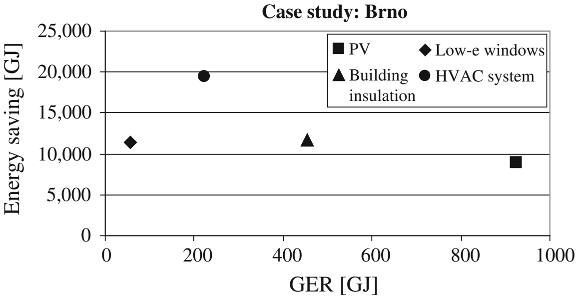


**Fig. 1** GER compared to the total energy saving in Brno case study (brewery)

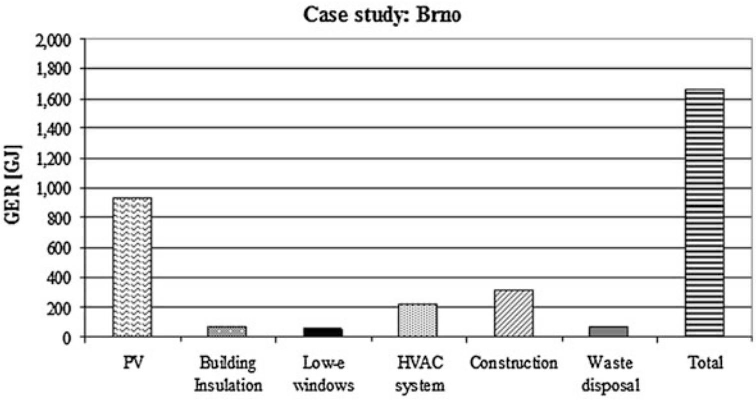


**Fig. 2** Contribution of each retrofit actions to the GER in brno case study (brewery)

roof, and with 60 mm polystyrene boards for the ground floor, involved a primary energy saving of 126 MJ/($m^2$y). The introduction of low-e windows saves 123 MJ/($m^2$y). As indicated in Table 3, the PV panels provided a yearly electricity production of 119 GJ/y. The related primary energy saving was 443 GJ/y (156.5 MJ/($m^2$y)). The high-efficiency HVAC system involved a yearly electricity saving of 14 GJ/y and a yearly heat saving of 772 GJ/y. The related primary energy saving was 1,292 GJ/y (486 MJ/($m^2$y) for a total floor area of 2660 $m^2$).

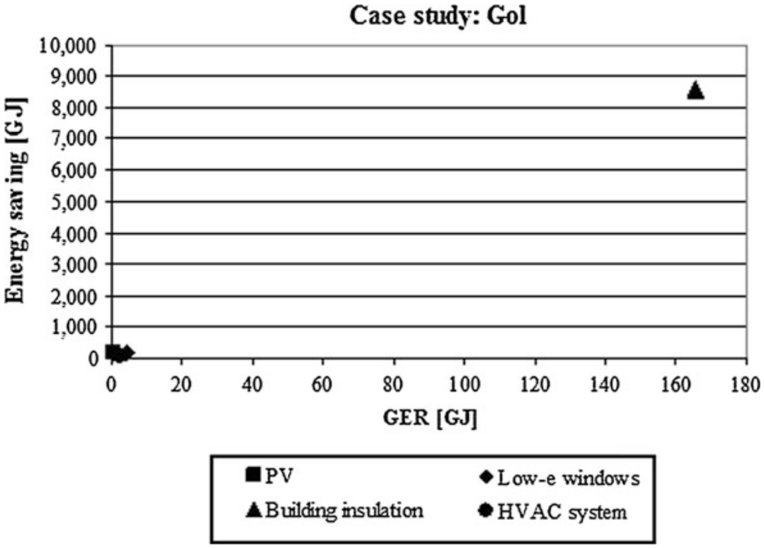


**Fig. 3** GER compared to the total energy saving in Gol case study (Hol Church)

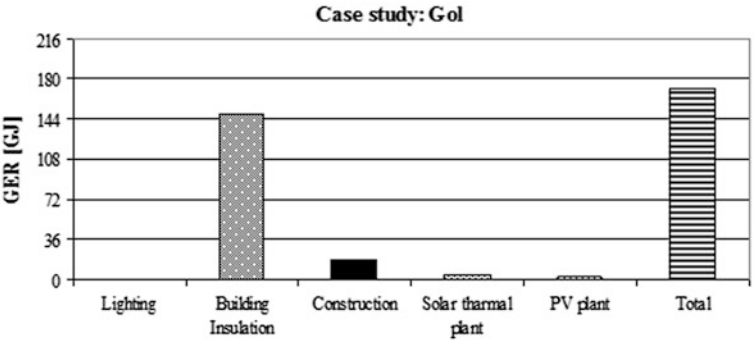


**Fig. 4** Contribution of each retrofit actions to the GER in Gol case study (Hol Church)

### 3.2.2 Case Study: Gol

The retrofit of Hol Church (Gol) included the following actions:

- refurbishment of the building roof and the ground floor, by means of new thermal insulation and high-efficiency windows to reduce the thermal losses and the lighting need,
- installation of PV panels and of a solar thermal system,
- introduction of efficient lighting.

Figure 3 compares GER to total energy saving, and Fig. 4 shows a contribution to GER of each retrofit action. It is observed that the highest GER is due to the building insulation, while the lighting system contribution is negligible. The refurbishment of the building envelope is also the retrofit action that involves the highest energy saving (8,612 GJ).

The refurbishment of the building roof and floor provides a yearly saving of primary energy of 246 GJ/y (443 MJ/($m^2$y) for a total floor area of 555 $m^2$). The installation of the PV panels provided a yearly saving of 1 GJ/y of electricity. The related primary energy saving is 1.5 GJ/y (3 MJ/($m^2$y)). The solar thermal system involved a primary energy saving of about 9 GJ/y (16.2 MJ/($m^2$y)). Concerning the introduction of efficient lighting, the yearly saved electricity was 35 GJ/y and the related primary energy saving was 50 GJ/y, with a primary energy saving per unit of floor area of 90 MJ/($m^2$y).

### 3.2.3 Case Study: Plymouth

The retrofit of Plymouth College included the installation of two 6-kW wind turbines to reduce the electricity demand of the site.

The yearly saving of electricity provided by the retrofit action is 41.4 GJ/y with a primary energy saving of 143 GJ/y. The total floor area is 5,794 $m^2$, and the specific primary energy saving is 24.6 MJ/($m^2$y).No intervention for heat saving was performed.

### 3.2.4 Case Study: Provehallen

The retrofit of Provehallen (Copenhagen) included the following actions:

- refurbishment of the building envelope components to decrease the U-value, by means of the facade and roof insulation, and the installation of high-efficiency windows,
- installation of a PV plant and a PV/T solar collector, which is cooled by a heat pump to increase the efficiency of the PVs,
- installation of a high-efficiency HVAC system.

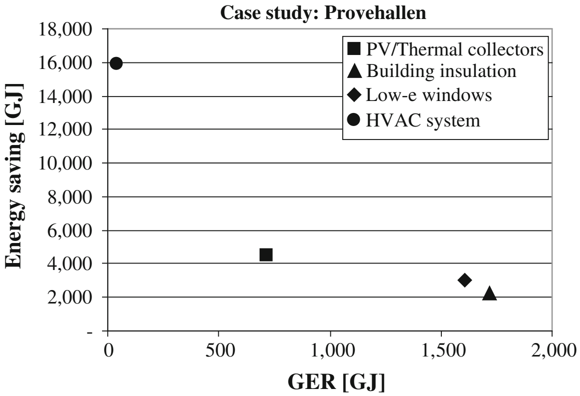
Figure 5 compares GER to total energy saving, while Fig. 6 shows the contribution to GER of each retrofit phase. The building insulation and the low-e windows have the highest contribution to GER and the lowest energy saving, compared to the other retrofit actions. The efficient HVAC system provides the lowest GER (1 %) and the highest energy saving. Based on the results of the energy and environmental analyses of the case study, the retrofit of the building envelope provides a yearly saving of primary energy of 151 GJ/y and a direct heat saving of 126 GJ/y. In particular, the insulation of the building envelope, made with mineral wool boards, led to a primary energy savings of 65 GJ/y, while the introduction of low-e windows involves a primary energy saving of 86 GJ/y. Taken into account a total floor area of 2,300 $m^2$, the primary energy saving was 28 MJ/($m^2$y) and 37.5 MJ/($m^2$y), respectively. Installation of the PV/T solar collector saved 302 GJ/y (131 MJ/($m^2$y)). The high-efficiency HVAC system provided a primary energy saving of 2,113 GJ/y (919 MJ/($m^2$y)).

### 3.2.5 Case Study: Stuttgart

Renovation of the Nursery Home (Stuttgart) involved the following actions:

- insulation of the envelope opaque elements and high-efficiency windows (low-e glasses) to reduce the thermal losses,

**Fig. 5** GER compared to the total energy saving in Provehallen case study



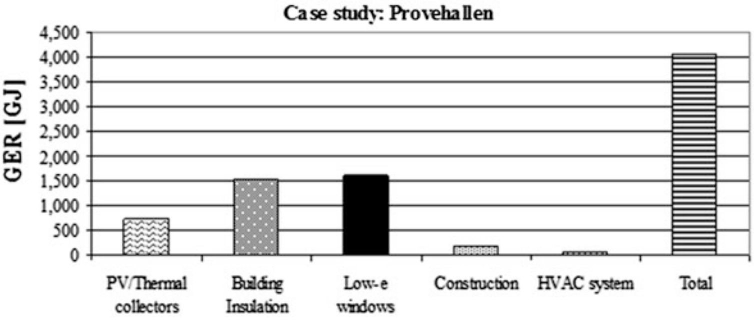
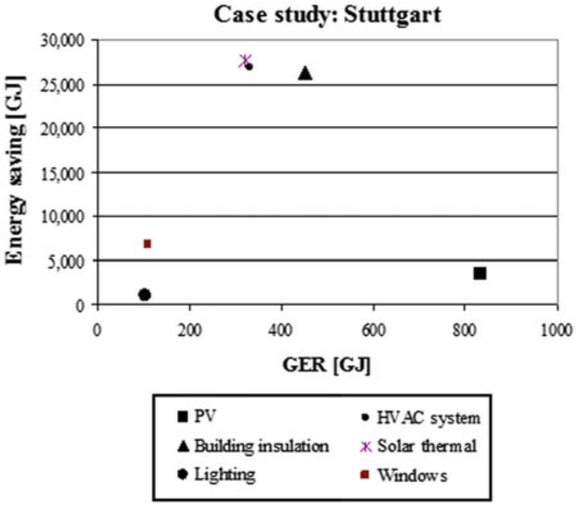


**Fig. 6** Contribution of each retrofit actions to the GER in Provehallen case study

**Fig. 7** GER compared to the total energy saving in Stuttgart case study



- installation of a solar heating system and a PV plant,
- installation of high-efficiency technology for heating and ventilation (HVAC),
- installation of efficient lighting.

Figure 7 compares GER to total energy saving, and Fig. 8 shows the contribution of each retrofit action to GER.

The heat saving due to the retrofit of the building envelope (756 GJ/y) involved a primary energy saving of 1,021 GJ/y, of which 352 MJ/($m^2$y) were provided by the insulation of the envelope opaque elements, and 127 MJ/($m^2$y) derived from the introduction of low-e windows. The total floor area was 2,131 $m^2$.

The primary energy saving related to the PV production (49 GJ/y) was 81 MJ/($m^2$y). The solar thermal plant provides heat savings of 84 GJ/y, with and a primary energy saving of 866 MJ/($m^2$y). The high-efficiency HVAC system saved 284 GJ/y (642 GJ/y), involving a primary energy saving of 841 MJ/($m^2$y).

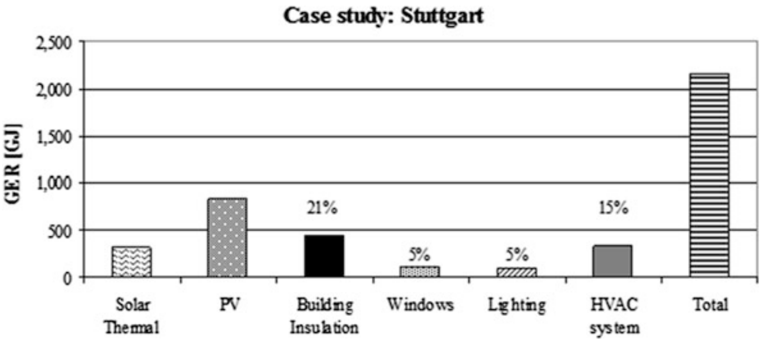


**Fig. 8** Contribution of each retrofit actions to the GER in Stuttgart case study

With regard to the lighting, the efficient system and the improvement of the daylight transfer together brought an electricity saving of 100 GJ/y and a related saving of primary energy of 349 GJ/y (163.6 MJ/($m^2$y)).

### 3.2.6 Case study: Vilnius

The retrofit of the VGTU main building (Vilnius) included the following actions:

- replacement of the existing thermal insulation of the external walls and installation of high thermal performance materials,
- replacement of the existing windows with high-efficiency ones (low-e glasses and low U-value),
- refurbishment of the roof with the introduction of a waterproof layer.

The assessed final energy saving was 794 GJ/y from the high-efficient windows, and 852 GJ/y due to insulation and renovation of roofs and facades. The related primary energy saving due to the high-efficient windows was 116 MJ/($m^2$y), while the insulation of the building envelope provided a primary energy saving of 125 MJ/($m^2$y). The total floor area of the studied building is 8,484 $m^2$.

Figure 9 compares GER to total energy saving, and Fig. 10 shows the contribution to GER of each retrofit action. The manufacturing of materials provided the highest impacts. In particular, insulation and window replacement are each responsible for about half of the GER.

The construction phase represents about 5 % of GER, while the contribution from wastes disposal is almost negligible. The construction phase required the use of electricity and diesel oil to operate the building machineries.

The disposal scenario included the transportation of wastes coming from the building site and their disposal to local landfills. GJ/y (919 MJ/($m^2$y)).

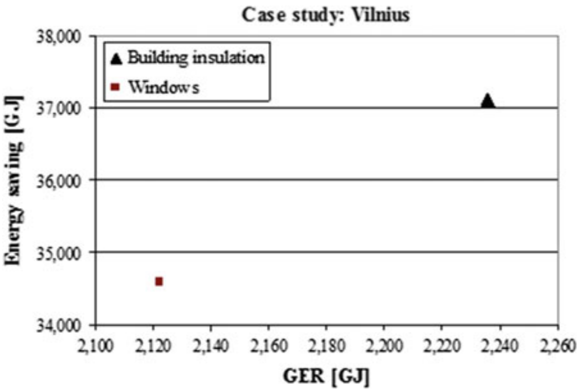


**Fig. 9** GER compared to the total energy saving in Vilnius case study

## 4 Discussion of the Results and Conclusions

Looking at the assessment outcomes, the most significant benefits (energy saving and avoided GWP) are related to the improvement of the quality of envelope thermal insulation (high-efficiency windows and thermal insulating boards). Substitution of insulation, lighting and glazing components were the most efficient solutions.

In all the case studies, renovation of HVAC plants and lighting systems provides significant energy benefits. Both for solar and wind plants, a generally overestimated energy production at the design stage was observed with regards to the monitored one. This involved lower energy savings and higher payback indices than the predicted ones.

In detail, the following key considerations can be traced. For each case study, the retrofit actions involve about 50 % of energy saving for heating, except for

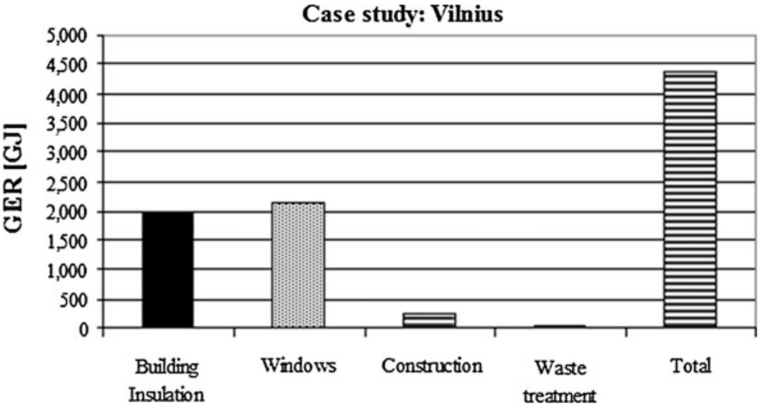


**Fig. 10** Contribution of each retrofit actions to the GER in Vilnius case study

**Table 4** Environmental indices for each case study

| Building | Index | Benefits | Impacts | Net benefits |
|---|---|---|---|---|
| *Brewery–Brno* | GER [GJ] | 51,382 | 1,657 | 49,725 |
| | GWP [$10^3$ kg $CO_2$-eq] | 3,087 | 82 | 3,005 |
| | ODP [kg CFC11 eq] | 0.28 | 0.03 | 0.25 |
| | AP [kg $SO_2$eq] | 4,847 | 598 | 4,249 |
| | EP [kg $PO_4^{3-}$eq] | 394 | 59 | 335 |
| *Hol Church–Gol* | GER [GJ] | 8,927 | 172 | 8,755 |
| | GWP [$10^3$ kg $CO_2$-eq] | 499.5 | 10.5 | 489 |
| | ODP [kg CFC11 eq] | 0.06 | 0 | 0.06 |
| | AP [kg $SO_2$eq] | 377 | 60 | 317 |
| | EP [kg $PO_4^{3-}$eq] | 41 | 7.6 | 33.4 |
| *College–Plymouth* | GER [GJ] | 2,142 | 97 | 2,045 |
| | GWP [$10^3$ kg $CO_2$-eq] | 117 | 7 | 110 |
| | ODP [kg CFC11 eq] | 0.003 | 0 | 0.003 |
| | AP [kg $SO_2$eq] | 415 | 32 | 383 |
| | EP [kg $PO_4^{3-}$eq] | 30 | 2.4 | 27.6 |
| *Prøvehallen* | GER [GJ] | 25,748 | 4,078 | 21,670 |
| | GWP [$10^3$ kg $CO_2$-eq] | 2,697 | 216 | 2,481 |
| | ODP [kg CFC11 eq] | 0.15 | 0.05 | 0.1 |
| | AP [kg $SO_2$eq] | 2,494 | 987 | 1,507 |
| | EP [kg $PO_4^{3-}$eq] | 205 | 118 | 87 |
| *Stuttgart* | GER [GJ] | 91,983 | 2,151 | 89,833 |
| | GWP [$10^3$ kg $CO_2$-eq.] | 5,230 | 115 | 5,115 |
| | ODP [kg CFC11eq] | 0.37 | 0.04 | 0.33 |
| | AP [kg $SO_2$eq] | 3,852 | 753 | 3,099 |
| | EP [kg $PO_4^{3-}$eq] | 401 | 56 | 345 |
| *Vilnius* | GER [GJ] | 71,717 | 4,358 | 67,359 |
| | GWP [$10^3$ kg $CO_2$-eq.] | 4,077 | 218 | 3,859 |
| | ODP [kg CFC11eq] | 0.4 | 0.16 | 0.24 |
| | AP [kg $SO_2$eq] | 3,206 | 1,253 | 1,953 |
| | EP [kg $PO_4^{3-}$eq] | 334 | 111 | 223 |

Plymouth, where no intervention for heat saving is performed, and for Vilnius, where the energy saving is lower (about 30 %).

With regard to the electricity use, the highest saving is reached in the Stuttgart case study (90 %), while at Plymouth College, the wind turbine installation involved just 2 % of the yearly consumption, reaching unsatisfactory results (see Table 3).

Table 4 shows the outcomes of the environmental indices for each case study. The results are not numerically comparable because of the different complexity and scale of interventions. With regard to GER and GWP, two sets of building retrofits with different and extended interventions can be identified:

- Stuttgart, Vilnius, Proevehallen and Brno case studies, which involve high values of GER and GWP.

**Table 5** Environmental indices for each case study

| Case study | Retrofit actions | GER | Primary energy saving | $E_{PT}$ | GWP | Avoided GWP | $Em_{PT,}$ GWP |
|---|---|---|---|---|---|---|---|
| *Brno* | PV | 926 | 8,859 | 2.1 | 42 | 608 | 1.4 |
| | Building insulation | 454 | 11,724 | 1.4 | 26 | 666 | 1.5 |
| | Low-e windows | 55 | 11,414 | 0.2 | 2 | 680 | 0.1 |
| | HVAC system | 222 | 19,385 | 0.2 | 11 | 1,133 | 0.2 |
| | Total | 1,657 | 51,382 | 0.7 | 82 | 3,087 | 0.6 |
| *Gol* | Lighting | 0.3 | 150 | 0.01 | 0.02 | 2 | 0.03 |
| | Insulation | 165.5 | 8,612 | 0.7 | 10.15 | 490 | 0.73 |
| | Solar thermal plant | 4.1 | 134 | 0.5 | 0.22 | 7.5 | 0.44 |
| | PV plant | 2.1 | 31 | 1.5 | 0.1 | 0 | 6.1 |
| | Total | 172 | 8,927 | 0.6 | 10.49 | 499.5 | 0.7 |
| *Plymouth* | Wind Turbines | 97 | 2,142 | 0.68 | 7 | 117 | 0.9 |
| *Prøvehallen* | PV/Thermal plant | 716 | 4,533 | 2.4 | 37 | 390 | 1.9 |
| | Building Insulation | 1,716 | 2,262 | 26.5 | 117 | 129 | 31.9 |
| | Low-e windows | 1,604 | 3,016 | 18.6 | 58 | 172 | 11.8 |
| | HVAC system | 42 | 15,937 | 0.04 | 3 | 2007 | 0.03 |
| | Total | 4,078 | 25,748 | 2.7 | 216 | 2697 | 1.3 |
| *Stuttgart* | Solar thermal plants | 323 | 27,680 | 0.2 | 18.5 | 1,574 | 0.2 |
| | PV | 833 | 3,449 | 4.8 | 37.7 | 196 | 3.8 |
| | Building Insulation | 452 | 26,255 | 0.6 | 32.7 | 1,493 | 0.8 |
| | Windows | 110 | 6,681 | 0.6 | 0.1 | 380 | 0.01 |
| | Lighting | 104 | 1,046 | 0.3 | 6.7 | 59 | 0.3 |
| | HVAC system | 330 | 26,871 | 0.2 | 19.5 | 1,528 | 0.2 |
| | Total | 2,151 | 91,983 | 0.4 | 115.1 | 5230 | 0.4 |
| *Vilnius* | Insulation | 2,236 | 37,120 | 0.5 | 85 | 2,110 | 1.4 |
| | Windows | 2,122 | 34,597 | 0.5 | 133 | 1,967 | 2.4 |
| | Total | 4,358 | 71,717 | 2.1 | 218 | 4,077 | 1.9 |

- Gol and Plymouth case studies, with smaller and more focused actions that involve lower GWP and GER values.
- The other environmental indices, such as AP, EP, and POCP, follow a similar trend to the GER and GWP.

Table 5 shows the results of $E_{PT}$ and $Em_{PT,GWP}$ indices calculated for each action.

The highest payback time results are connected to the PV plants for each case study, except for Provehallen, where the renovation of the building envelope involves high values for $E_{PT}$ and $Em_{PT,GWP}$. Such action provides the highest GER and the highest GWP with the lowest energy saving and the lowest environmental benefit (avoided GWP). With regard to the $E_R$, all implemented actions are characterised by relevant energy benefits. The energy saving overcomes the total energy consumption a minimum of 6 times (Proevehallen case study) to a maximum of 52 times (Gol case study).

## References

Ardente F, Beccali M, Cellura M, Mistretta M (2008) Building energy performance: a LCA case study of kenaf fibres insulation board. Energy Build 40:1–10

Ardente F, Cellura M, Lo Brano V, Mistretta M (2010) LCA-driven selection of industrial ecologicy strategies. Integr Environ Assess Manage 6:52–60

Ardente F, Beccali M, Cellura M, Mistretta M (2011) Energy and environmental benefits in public buildings as a result of retrofit actions. Renew Energy Sustain Rev 15:460–470

Beccali G, Cellura M, Mistretta M (2001) Managing municipal solid waste: energetic and environmental comparison among different management options. Int J Life Cycle Assess 6(4):243–249

Beccali M, Cellura M, Longo S, Nocke B, Finocchiaro P (2011) LCA of a solar heating and cooling system equipped with a small water–ammonia absorption chiller. Sol Energy 86:1491–1503

Blengini GA, Di Carlo T (2010) The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy Build 42:869–880

Cellura M, Lo Brano V, Mistretta M, Orioli A, (2010) To assess the validity of the transfer function method: a neural model for the optimal choice of conduction transfer function. ASHRAE Trans Part 2:585–596

Chen TY, Burnett J, Chau CK (2001) Analysis of embodied energy use in the residential building of Hong Kong. Energy 26:323–340

Cole RJ, Kernan PC (1996) Life cycle energy use in office buildings. Build Environ 31:307–317

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)

Dixit MN, Fernández-Solís JL, Lavy S, Culp CH (2010) Identification of parameters for embodied energy measurement: a literature review. Energy Build 42:1238–1247

Eicker U (2012) Policity–energy networks in sustainable cities. Stuttgart, ISBN 978-3-7828-4051-4

Fay R, Treolar G, Iyer-Raniga U (2000) Life-cycle energy analysis of buildings: a case study. Build Res Inf 28:31–41

Frischknecht R, Jungbluth N, Althaus HJ, Doka G,. Dones R, Heck T, Hellweg S, Hischier R, Nemecek T,. Rebitzer G, Spielmann M, 2007. Overview and methodology. ecoinvent Report No. 1, ver.2.0, Swiss Centre for Life Cycle Inventories. Dübendorf (CH)

Lo Mastro F, Mistretta M. (2004) Cogeneration from thermal treatment of selected municipal solid wastes. A stechiometric model building for the case study on Palermo. Waste Manage 24(3):309–317

Nemry F, Uihlein A (2008) Environmental improvement potentials of residential buildings. European Commission Joint Research Centre, Institute for Prospective Technological Studies

Ortiz O, Bonnet C, Bruno JC, Castells F (2009) Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain. Build Environ 44:584–594

PRè-Product Ecology Consultants. SimaPro7.2, Environmental Database 2010. Amersfoort, The Netherlands

Suzuki M, Oka T (1998) Estimation of life cycle energy consumption and $CO_2$ emission in office buildings in Japan. Energy Build 28:33–41

The International EPD Cooperation (2008) General programme instructions for environmental product declarations, EPD. Version 1.0

UNI EN ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework, International organisation for standardisation, July.Brown B, Aaron M (2001)

Voss K, Musall E, Lichtmeß M (2011) From low energy to net zero energy building: status and perspecives. J Green Build 6:46–57

Zimmermann M, Althaus HJ, Haas A, (2005) Benchmarks for sustainable construction. A contribution to develop a standard. Energy Build 35:1147–1157

# Modelling the Occupant Behaviour Impact on Buildings Energy Prediction

João Virote and Rui Neves-Silva

**Abstract** Building retrofitting projects represent great opportunities to include new energy efficient technologies, already available on the market. However, for many of these technologies, the occupants' behaviour within the building can weaken the expected return on investment. This is special true in intelligent technologies that try to compensate the lack of user awareness of energy consumption problems. This chapter describes a model for occupant behaviour within the building in relation to energy consumption, along with a building energy consumption model (ECM) is proposed based on stochastic Markov models. The ECM is used to predict possible energy saving gains from building retrofitting projects. The obtained results demonstrate that the proposed ECM learns occupant behavioural patterns from the building. Additionally, it reliably reproduces them, predicts the building energy consumption and identifies potential areas of energy waste. The ultimate objective of the proposed models is the integration in Decision Support Tools to advise the investor on the selection of technologies and evaluate the merits of the investment.

## 1 Introduction

This chapter is derived after the results first presented by Virote et al. (Virote and Neves-Silva 2012).

According to Hoes et al. (2009), 'Energy use in buildings is closely linked to their operational and space utilisation characteristics and the behaviour of their occupants'. User behaviour and lifestyle choices are closely linked to the use of

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F. Pacheco Torgal et al. (eds.), *Nearly Zero Energy Building Refurbishment*,
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energy (Oikonomou et al. 2009). In particular, most of the energy waste in a building occurs during non-occupancy hours (Masoso and Grobler 2010).

Usually, building retrofitting projects are associated with high costs and large payback periods. These projects rely on intelligent building technologies or energy-efficient technologies to achieve sustainable consumer behaviour (Midden et al. 2008). The outcome of building retrofitting projects is often unpredictable due to the uncertainty surrounding occupant behaviour as studied in (Murray 2009). Therefore, it is crucial to take into account the interactions between the occupants and the building when investing in energy efficient technologies. These investments could be sustained through a model that reliably reproduces the building's usage patterns and predicts the building energy consumption while analysing potential energy saving areas.

Technology can help raising awareness of energy use and reduce the level of consumption and waste (Ockwell 2008; Midden et al. 2007). Retrofitting of existing buildings has many challenges and opportunities, and a major issue is the effectiveness in the adopted technologies and measures (Ma et al. 2012). As a result, a framework to support the decision-making process in order to ensure the outcome of investments in energy efficiency is mandatory (Masini and Menichetti 2012).

To summarise, retrofitting projects should be adapted to each specific building and not through a generic or systematic approach to the building stock. Moreover, being able to conveniently adapt a building to its occupants ensures a better indoors working and living environment (Frontczak and Wargocki 2011).

## 1.1 Research Problem

The behaviour of building occupants are often based on assumptions rather than based on measured observations or resulting predicting models. These assumptions lead to limitations in current simulation tools and provide a poor instrument to predict the outcome of energy efficiency measures in a building. This results in a gap between the estimated energy savings and the actual energy savings from retrofitting projects (Yalcintas 2008). Hence, current simulation tools must be provided with prediction models that reliably predict the energy consumption of a specific building according to its actual utilisation patterns.

The objective is to develop an *energy consumption model* (ECM) for predicting the energy consumption of a building based on actual measured performance and usage data. Furthermore, this ECM is an added value when applied to the creation of alternative scenarios implementing energy-efficient technologies.

This research work explores the applicability of stochastic models to represent the space occupancy and the occupant's behaviour. The research question is as follows: *Can stochastic models be used to model the space occupancy patterns and occupant's behaviour in order to predict the energy consumption of the building and its waste under different conditions?* The adopted solution approach is

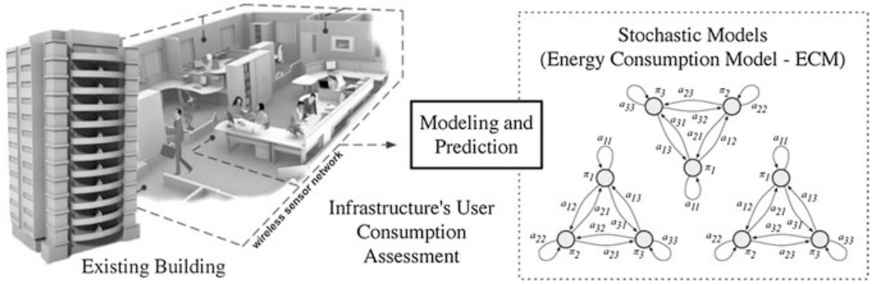

**Fig. 1** ECM concept reflecting the building and occupants consumption assessment

represented in Fig. 1. The ultimate goal is to improve the success of investments of energy-saving solutions in buildings.

## 1.2 Methodology

For proof of concept, our approach focuses on the utilisation of the lighting system within the building. Although the lighting system is usually not the system that consumes the most energy, such as HVAC systems for example, it provides the greatest opportunity for energy savings.

It should be noted that example of HVAC systems is not structurally very different from the case developed here. Although occupants can directly control lighting, it is not expected that they will adjust for example airflow characteristics. This is usually done by some type of Building Automation Systems controlling the local variables from a collection of desired set-point values (local or global). Nevertheless, building occupants do many things that directly affect the overall energy demand although not necessarily with energy efficiency in mind. In that case, the events of interest for the proposed approach would be actions such as, opening and closing windows and blinds, or leaving the heating controls on high demand when absent from the space.

The building performance and usage auditing could be achieved through an installed wireless sensor network (WSN) (Jang and Healy 2010; Menzel et al. 2008; Spinar et al. 2008). In our context, the user occupancy assessment is a repository of events, which represents user actions in the building environment under regular usage conditions.

In the first approach, the ECM should approximate the energy consumption prediction $P_{\mathrm{ECM}}$ to the real building energy consumption

$$\int_0^T P_{\mathrm{ECM}}(t)\,\mathrm{d}t = \int_0^T P_{\mathrm{B}}(t)\,\mathrm{d}t + \varepsilon \tag{1}$$

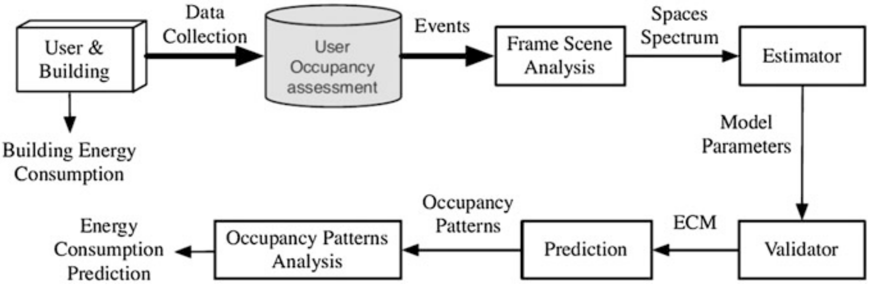

**Fig. 2** Block diagram representing the proposed approach steps

The residuals $\varepsilon$ are estimates of experimental error obtained by subtracting the observed data from the predicted responses, and $T$ represents the observation period.

The predicted response is calculated from the ECM, after the entire unknown model parameters have been estimated from the observed data. Examining the residuals is a key part of stochastic modelling. This tells us whether our assumptions are reasonable, and the choice of model is appropriated. The methodology is composed of a set of steps, which are depicted in Fig. 2.

## 2 Related Work

### *2.1 Building Simulation*

A large number of studies have been conducted over the past decades to understand how building occupants interact with building environmental systems and how to simulate the building performance and environment. This is usually referred to in the literature as building simulation or building performance simulation and is a research area examining building life cycle in all their aspects.

The tools in the building energy field are the building energy simulation programs that provide users with performance indexes. In addition, most current building simulation programs do not deal with activities performed by building occupants and with the resulting utilisation of space. These tools rely on assumptions referring to human behaviour (Robinson 2006).

A number of approaches have been proposed to simulate the energy consumption of a building. In (Crawley et al. 2008), a comparison of twenty major building energy simulation programs is performed. These programs are as follows: BLAST, BSim, DeST, DOE-2, ECOTECT, Energy-10, Energy Express, EnerWin, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES < VE > , HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS. From these, EnergyPlus (Team 2010) is considered to be the state of the art with regard to building energy simulation software and is widely used by simulation experts and beginners alike. The reason for this is that EnergyPlus is based on the most popular features and capabilities of BLAST and DOE-2 and because it is only a calculation engine without any graphical user interface. An example is the DesignBuilder (Tindale 2010), which is acknowledged as the most comprehensive interface for EnergyPlus.

Building performance simulation has become an accepted method of assessment during the building design process (Hoes et al. 2009). Furthermore, due to an increasing complexity of building design and higher demand for performance requirements on sustainability, use of building simulations will become inevitable.

Mahdavi suggests that user interactions are difficult to predict at the level of the individual (Mahdavi and Pröglhöf 2009) although, behavioural patterns for building occupants could be extracted from long-term observational data. Since this data are the outcome of actual observations in a building, they are more reliable than the currently applied simulation assumptions (Mahdavi and Pröglhöf 2009). In this way, patterns obtained for one building cannot be transported to other different buildings, because the occupancy models would be different. Therefore, it is assumed that user behaviour is one of the most important parameters influencing the results of building performance simulations. Unreliable assumptions regarding user behaviour may have large implications for such assessments. Moreover, this effect will become crucial when the design under investigation contains improved passive and active energy efficiency measures.

In current building performance simulation tools, user behaviour is mirrored in a very rigid way. In recent years, some models have been developed to include the interaction of the user behaviour in building simulation. Models for the simulation of occupant interactions with windows have been addressed in the Humphreys algorithm for window opening that was derived from analysis of extensive survey data and was implemented in the ESP-r software (Rijal et al. 2007). More work related to window usage can be found in Herkel et al. (2008), Frederic and Darren (2009). In (Borgeson and Brager 2008), a methodology for predicting occupant window control is presented. Reinhart developed LIGHTSWITCH-2002 using a dynamic stochastic algorithm (Reinhart 2004). Based on an occupancy model and a dynamic daylight simulation application, it predicted manual lighting and blind control actions providing the basis for the calculation of annual energy demand for electrical lighting. Page hypothesised that the probability of occupancy at a given time step depends only on the states of occupancy at the previous step (Page et al. 2008). In this way, he proposed the application of Markov chains towards occupancy prediction.

As a continuation of the work by Reinhart and Nicol (Nicol 2001), Bourgeois attempted to bridge the gap between energy simulation and empirically based information on occupant behaviour via a module called SHOCC that was also integrated in ESP-r application (Bourgeois et al. 2006). The SHOCC module is applied in Hoes et al. (2009); however, this module requires several assumptions with respect to the degree of occupation and the behaviour of users. That is, when the number of occupants is relatively high and they operate with less strict schedules, the predictions are less reliable. For these, and more complex situations, the USSU module can be applied (Tabak and Vries 2010).

The ECM proposed in this chapter is constructed with generated data, simulating a building, and highlights from current simulation tools that rely on assumptions or simulation methods. The applicability of the results is limited to supporting or accurately predicting the effectiveness of energy efficiency measures in a building. The purpose of the ECM is to fill that gap. Furthermore, the ECM can be used to predict the outcome of the installation of energy efficient technologies by exploring alternative scenarios.

## *2.2 User Behaviour Modelling*

The study of human behaviour has been the focus of many fields of research and has been extensively investigated in business process modelling, cognitive modelling, distributed artificial intelligence, computational organisational theory and educational psychology (Atallah and Yang 2009). The main challenge is related to the modelling of complex human behaviour using realistic yet adaptable models. One of the most popular models is that of a *hidden Markov model* (HMM) (Rabiner 1989), which is a stochastic model. Due to their ability to model spatial–temporal information in a natural way, a significant amount of work in the area of behaviour recognition is based on HMMs.

The concept of energy behaviours is explored in Lopes et al. (2012) where the interactions between energy behaviours and energy efficiency in buildings are reviewed from an interdisciplinary to multidisciplinary end-use energy efficiency in buildings and modelling energy behaviour trends. A survey in behaviour modelling is performed by Atallah and Yang (2009). Because little is known about user activity in buildings, several experiments observe motions of real users with cameras and other means of locating people (Tabak 2009). In other experiments, user activities regarding light control have been monitored providing useful statistics to improve lighting control (Mahdavi and Pröglhöf 2009). Although such experiments provide realistic user patterns, it is not easy to extract the reasons for activities and thus derive abstract dynamic models. The study performed in Borgeson and Brager (2008) classifies human behaviour as not deterministic. In (Zimmerman 2007), agent models are addressed as suitable for behaviour modelling, and multiple-agents simulation studies are performed. Other agent-based model, which takes into account, the building occupant's decision-making regarding energy usage is performed in Chen et al. (2012).

Another important modelling technique is applying pattern recognition analysis (Abreu et al. 2012) in order to identify common behaviours, which could provide valuable feedback about dominant behaviours (affect building energy consumption directly) and thus improving the effectiveness of energy-efficient technologies. In order to isolate the effects of occupant behaviour on building energy consumption from other factors influencing the building energy consumption, a technique based on cluster analysis proposed in (Yu et al. 2011) is used.

An occupant behavioural model based on HMMs is proposed by Virote and Neves-Silva (2010). The objective was to capture the user dynamics and model the user actions in a building regarding the interaction with the lighting system. In this chapter, these models are improved and extended to the simulation process. The novelty of this model is that it behaves as a generator and not as a behaviour recognition model. That is, the model does not intend to explain, infer or recognise the occupant behaviour based on external constraints. In its place, it generates a similar occupancy behaviour pattern as the occupant generates.

# 3 Proposed Methodology

## 3.1 *Stochastic Occupant Behavioural Model*

The objective of developing a behavioural model for the building occupant, represented in Fig. 3 is to be able to predict the impact of the occupants' decisions in the overall energy consumption. Taking a simple example in lighting, how often will the occupants switch off the lights when exiting a single office room and what is the impact on energy consumption? The model reflects the behaviour of an aggregate population expressed by the probability of performing an action.

Of course, occupants' actions are the result of a complex behaviour characteristics related with education, environmental awareness, involvement with the economic impact, among other factors. Thus, it is possible to characterise occupant behaviour as a composition of *observable states* representing actions; and *hidden*

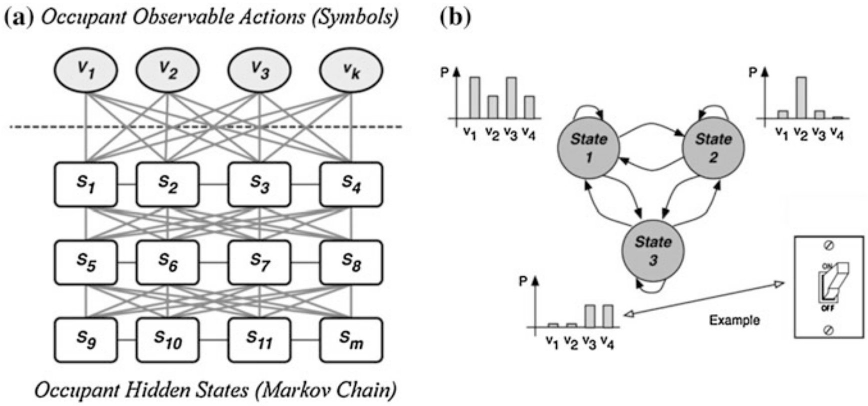

**Fig. 3** **a** Generic structure of a Hidden Markov Model and **b** concretization of the generic hidden Markov model with example of emission symbols

*states* representing the complex behaviour that have influenced the observed actions. Nonetheless, the motivations for the actions are often difficult to access or see, for example, someone's personal values, economics or even emotional condition. So when building the behavioural model, the non-observable (hidden) states model these factors.

An HMM is a probabilistic model composed by observable and hidden states, as represented in Fig. 3a. The observable states represent the symbols that the model can output associated with the actions performed by the occupants, e.g., turning on or off the air-conditioning; or switching the lighting system, Fig. 3b.

## 3.2 Building Markov Model Approach

Each building has its own use patterns according to the building purpose and its occupants. As a result, each building will lead to a different model. Uncertainty is always present when modelling, predicting and simulating real systems and buildings are no exception. Many factors affect building performance that cannot be known with certainty when the building is planned, designed, built, managed and operated. But uncertainty also arrives due to the complex and unpredictable nature of human behaviour. The ECM here proposed accounts for this stochastic nature. The issue being on developing the ECM.

In an abstract way, and with no loss of generality, let us consider the building illustrated in Fig. 4. The building is considered as a set of spaces. Consequently, the building energy consumption is the sum the energy consumption of all spaces. Likewise, the building configuration is the combination of each space's configuration.

The spaces are strongly influenced by the stochastic (not deterministic) nature of occupant behaviour. Therefore, it can be assumed that the state of these spaces will also have a stochastic nature. Stochastic modelling can take several forms. Some can be simple functions that produce the probability of an action given a set of environmental conditions as inputs, while others like *Markov chains* (MC) can

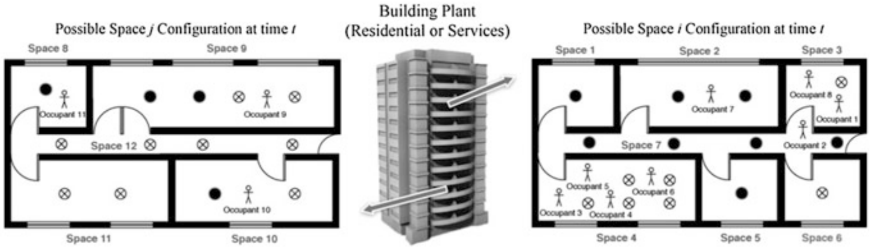

**Fig. 4** Decomposition of the building in a set of spaces in a lighting example. A *white circle* represents the lighting system turned off and a *shaded circle* represents it turned on

use the current state or other time-variant factors to influence the outcome. When considering a first-order chain this defines the Markov condition that: the next state is solely dependent on the current state, or

$$P\{X_{k+1}\} = P\{X_{k+1} = j | X_k = i\} = p_{i,j} \tag{2}$$

The values $X_k$ from the countable set $S$ are called *states*. If the model parameters are constant over time, the MC is denominated *time-homogeneous Markov chain* or *stationary Markov chain*. That is, the model transition matrix is a constant time-invariant matrix independent of the time instant $k$

$$P = \begin{pmatrix} p_{1,1} & \cdots & p_{1,n} \\ \vdots & \ddots & \vdots \\ p_{m,1} & \cdots & p_{m,n} \end{pmatrix}, \; p_{i,j} \geq 0, \; \forall_{i,j \in S} \wedge \sum_{j \in S} p_{i,j} = 1 \, \forall_{i \in S} \tag{3}$$

This mathematical model describes a system that undergoes transitions between states with a certain probability. Likewise, there exists a probability of observing a space in a state and an additional probability of switching from that state (Fig. 5).

If considering that the spaces' states are based on the observations over time, the spaces are modelled using a state-space approach. A possible state decomposition is illustrated in Fig. 6. The spaces can either be occupied or empty, and the lighting system can either be turned on or off. The result is a discrete state space with four states $S = S_0, S_1, S_2, S_3$ which represent: *empty space with energy consumption*; *empty space with no energy consumption*; *occupied space with energy consumption* and *occupied space with no energy consumption*, respectively. The stochastic nature is related to the transitions between these states.

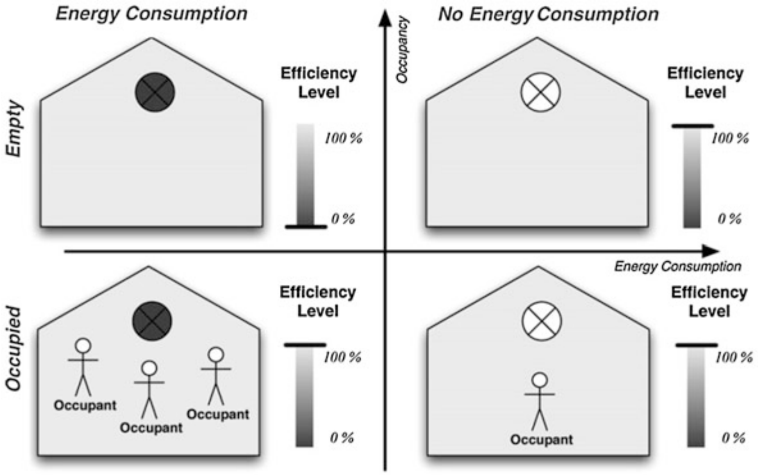

**Fig. 5** Graphical interpretation of 4 possible states regarding the lighting system for a space

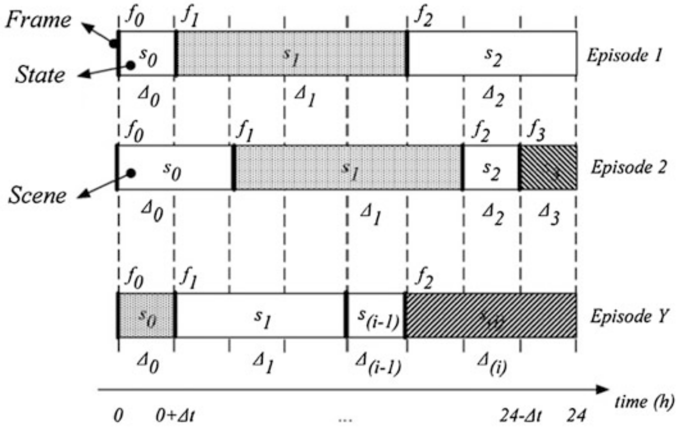

**Fig. 6** Introduction to the concept of frame, state, scene and spectrum

Given this description, the ECM is a cluster of $n$ different MC, where $n$ represents the number of spaces in the building, as represented in Fig. 4. Accordingly, the ECM can be written as

$$\mathrm{ECM} = \bigcup_{i=1}^{n} \mathrm{MC}_i(k),\ \forall \mathrm{MC}_i(k) = \begin{cases} X_i(k+1) = AX(k) \\ Y_i(k) = CX_i(k) \end{cases} \tag{4}$$

The next step consists of estimating the ECM parameters based on acquired measurements. That is, estimate the probability transition matrix $P$ for each $\mathrm{MC}_i$ of the ECM. To solve this problem, an algorithm is proposed named Frame-Scene Analysis.

### 3.3 Frame-Scene Analysis

A strong assumption for the MC is that system states being modelled are observable. So in order to obtain the model parameters, it is fundamental to have access to the spaces' states, since they must be observable. However, the measurements are a collection of visible events and not directly the states. To estimate the MC parameters, it is necessary to reconstruct the spaces' states based on the available events.

The developed algorithm was inspired by the work of Wada and Matsuyama (2000) regarding behaviour recognition in a video sequence. The concept is that during the observation period the spaces suffer changes to their configuration due to the presence of the occupants and their actions. As a result, the space's states evolution is analogous to a video sequence in which there exists a history evolving over time.

The frame-scene analysis algorithm depicted in Fig. 6 transforms the events into a *spectrum* for each space. The spectrum is the range of observed states that the space underwent during the observation period. At a specific time instant, we have a snapshot of that space configuration, that is, a frame. A frame $f_i$ is a description of the space configuration at the time instant $t_i$. Since a frame may be valid for a period of time $\Delta t$, it is extended to a *state* $s_i$.

The day period is discretised into *time slots*. At each time slot $t_k$, the space is observed and between $t_k$ and $t_{k+1}$, it is assumed that the space remains equal. This time interval $\Delta t$ is the time slot. For example, if considering 240 time slots per day, each one will have 6 min. Nevertheless, consecutive time slots may experience the same state. This raised the creation of a scene, which represents a state remaining over one or more time slots. Finally, the sequence of all scenes over the observation period provides the spectrum for each space.

## 3.4 Model Parameter Estimator

With the frame-scene analysis, it is straightforward to construct the model for each space. As illustrated in Fig. 7, the estimation process is responsible for determining the model parameters $a_{ij} = p_{ij}$ as follows:

$$F = \begin{bmatrix} f_{1,1} & \cdots & f_{1,n} \\ \vdots & \ddots & \vdots \\ f_{m,1} & \cdots & f_{m,n} \end{bmatrix} \to P : p_{i,j} = \begin{cases} \frac{f_{i,j}}{\sum_{i=1}^{m} f_{ij}}, & \sum_{i=1}^{m} f_{ij} > 0 \\ 0, & \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{5}$$

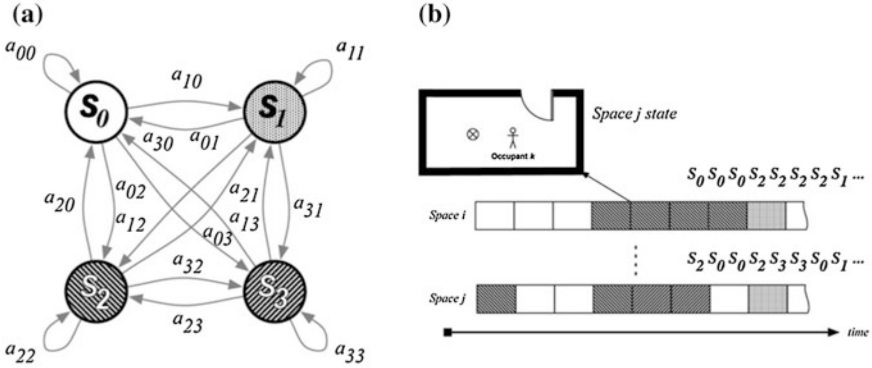

**Fig. 7** Markov model for a space. **a** Example of a MC with four states modelling a space, and **b** example of a state sequence generated by the MC

In (5), $f_{ij}$ is the frequency of being in state $i$ and transit to state $j$. The transition matrix $P$ is computed just by counting each state frequency and dividing that by the total amount of transitions (Ching and Ng 2005).

## 3.5 Model Validation

The validation process takes advantage of the stationarity of the ECM stochastic model. This implies that its statistical characteristics do not change over time. That is, the provided time series varies over time; however, its characteristics such as mean and variance converge to constant values. The cumulative state distribution over a finite horizon for a MC similar to the one in Fig. 7a is depicted in Fig. 8. Since the model is stochastic, the generated sequences in Fig. 7b, also referred as time series or paths, are different. However, with this model structure, the state probability distribution converges to a stationary distribution also referred as steady state distribution (Pollard 1984). The steady-state distribution is a characteristic of the model and not of the generated sequence. Generally, there are two ways of determining the steady-state distribution, either by simulation or by analytically. The simulation method consists in generating a sequence with the model over a sufficient large period. Next, the generated sequence is analysed, and the state distribution is computed. The problem is to define how large should the period be for the different models. The analytical method uses the time-homogeneous property of the MC as follows:

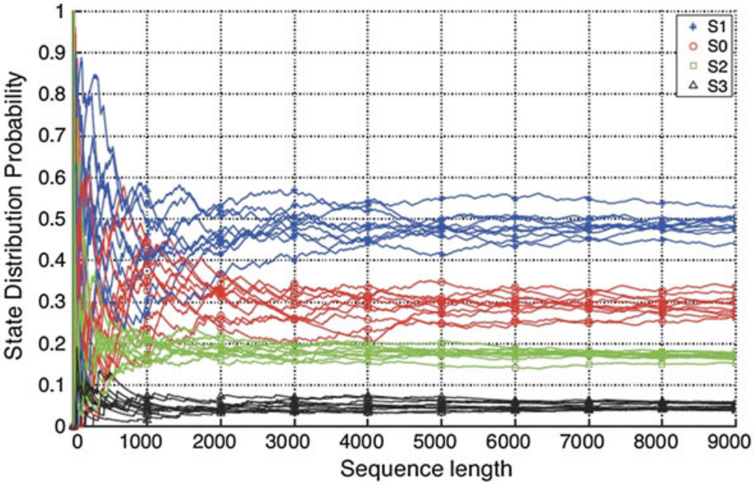

**Fig. 8** Simulation of a Markov chain with 4 states over different initial conditions

$$XP = IX \Leftrightarrow (P - I)X = 0 \Leftrightarrow RX = 0 \Leftrightarrow \Pi = \frac{R}{\|R\|} \tag{6}$$

where $R$ represents the null space basis of $X$ and the steady-state vector $\Pi$ is the result of the normalisation of $R$.

The measurements are divided into two clusters, one for estimation and the other for validation. This process consists of dividing the spectrum of each space and using half of the observation period data for the model parameters estimation and the other half for parameters optimising by finding one optimal path. That is, which time series best describes the space? Since ECM is a stochastic model, every time the ECM is simulated a different state sequence is produced, and consequently, different occupancy patterns and energy consumptions are predicted. This property could be interesting for some applications, although it is not suitable for prediction and decision support. To overcome this limitation, a method to start the model sequence is applied.

One important aspect of computation is that, usually, for dealing with random numbers, a *pseudo-random number generator* (PNGR) is used. This applies an algorithm for generating a sequence of numbers that approximates the properties of random numbers. A characteristic of this algorithm is that a PNGR can be started from an arbitrary starting number called *seed*, and it will always produce the same sequence as long as initialised with the same value. So to achieve a random number generator, the key is to use different seed values. As a final remark, this allows a stochastic model to behave like a deterministic process. Each time the stochastic model is simulated with the same seed, and it will always behave likewise. To account for this, the method of selecting a seed is important.

To select a seed for the ECM state sequence generation, two algorithms have been developed: static and dynamic algorithm. The block structure of these algorithms is depicted in Fig. 9. The first algorithm attributes a seed to each MC in the ECM based on the model parameters

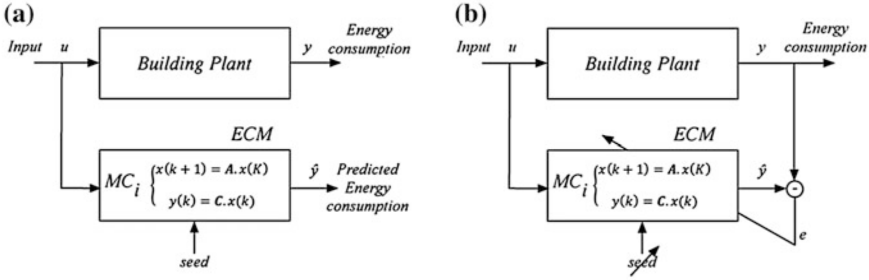

**Fig. 9** Block diagrams illustrating the seed discover algorithms. **a** Static algorithm, and **b** dynamic algorithm

$$\text{seed}_k = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(10^3 \times p_{i,j}\right),\ \forall \text{MC}_k \in \text{ECM} \tag{7}$$

This process is illustrated in Fig. 9a, and it is referred to as open loop seed discovery. A property of (7) is that the seed becomes a property of the model, since it is derived from its parameters. The upside of this method is the simple computational calculation; however, it does not provide any feedback about the generated sequence. The sequence can be the worst-case prediction. In order to account for the generated sequence, another algorithm was implemented – the close-loop seed discover (Fig. 9b). In this method, the performance of the model is evaluated by a residual analysis and the model prediction error. The following residual is applied

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_1)^2} \tag{8}$$

$$\text{RMSRE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_1)^2}}{\bar{y}} \tag{9}$$

In the above definitions, RMSE is the *Root Mean Square Error* and RMSPE is the *Root Mean Square Relative Error*. There, $x_i$ is measured data, $y_i$ is ECM prediction, $\bar{y}$ is the measured data mean value and $n$ is the number of data points.

The objective is to select the best seed within an interval that minimises the RMSE or RMSRE in order to select an optimal state sequence. To accomplish this, it is necessary to introduce two new metrics. The *state distribution error* (SDE) and the *prediction error* (PE). Considering that the two data sets (estimation and validation) are two time series, the SDE is the quadratic error between both the steady-state distributions

$$\text{SDE} = \sum_{k=1}^{\#states}\left(P(\bar{s}_k) - P(\hat{v}_k)\right)^2 \tag{10}$$

The PE represents the quadratic error between the model and the building

$$\text{PE} = (\hat{y}_{\text{ECM}} - y_{\text{B}})^2 \tag{11}$$

The optimal state metric is calculated by minimising the previous metrics

$$\text{seed}_k^* = \text{argmin}_{\text{seed}_k}\{\text{RMSE}, \text{SDE}, \text{PE}\} \tag{12}$$

### 3.6 Occupancy Patterns Prediction

After the learning process is complete, the final step is simulate the ECM and analyse the predicted states sequences for the building, accordingly to

$$\mathrm{PEC} = \sum_{i=1}^{\#\mathrm{spaces}} \left( \sum_{k=0}^{\#\mathrm{states}} \frac{P_{\mathrm{si,k}}}{1,000} \times \Delta P_{\mathrm{si,k}} \right)^2 \tag{13}$$

where $P_{\mathrm{si,k}}$ represents the power used in state $k$ of space $i$, $\Delta P_{\mathrm{si,k}}$ represents the time duration of the state $k$, and PEC is the predicted energy consumption of the building.

### 3.7 Algorithms

After the methodology description, the modelling and estimation algorithms are described in Algorithms 1 and 2, respectively.

**Algorithm 1** (Modelling process).

```
Require: Collection of events
    for space $s = 1 : total$ do
        for day $d = 1 : analysis\ period$ do
            Create frames and states
            Create scenes
        end for
        Create spectrum
        Create estimation and validation data
        Build Markov model structure
        Calculate state transitions probabilities
        Calculate stationary state distribution
        if static seed == true then
            Calculate static seed
        else{dynamic}
            for iteration $i = 1 : \max$ do
                Select model seed
                Generate state sequence
                Residual analysis
            end for
        end if
    end for
Create ECM with all MC and associated seeds
```

**Algorithm2** (Prediction process).

```
Require: ECM
    for space $s = 1 : total$ do
        Generate a state sequence for space s
        Analyze state sequence
        for day $d = 1 : prediction\ period$ do
            for state $e = 1 : end\ of\ day$ do
                Calculate state energy consumption
            end for
            Calculate space $s$ day $d$ energy consumption
        end for
        Add generated predictions to building predictions
    end for
    Building predictions results
```

## 4 Simulation Results

The described methodologies and algorithms have been implemented for simulation in a Java application developed by the authors and described in Virote and Neves-Silva (2010), Virote (2010). Compared with approach described in Fig. 7, the building has been replaced by a simulator based on multi-agent system approach and a rule-based reasoning engine (Virote 2010). The objective is to use this simulator as a data generator capable of reproducing the same occupancy patterns as a real building. This is achieved by controlling the behaviour of the occupants with the occupant behavioural model described in Sect. 1. The occupants are implemented in each software agent in which the occupant behavioural model is integrated.

The objective of the simulations is to predict the building energy consumption and analyse the spaces occupancy patterns. Furthermore, the opportunity of improving the energy consumption is discussed. Changing the occupant behavioural model parameters within the building simulation is expected to have a direct impact in the overall building energy consumption resulting in more or less wasted energy. This must be reflected in the ECM predictions.

The purpose of the ECM is to capture the space occupancy patterns in order to reproduce them. This result is verified in the simulation depicted in Fig. 10, which was performed in *building A* composed by 10 spaces. The ECM predictions are achieved by the calculation of the stationary state distribution as they are only dependent on the model parameters. The outcome is that the model can reliably capture and reproduce the space occupancy patterns.

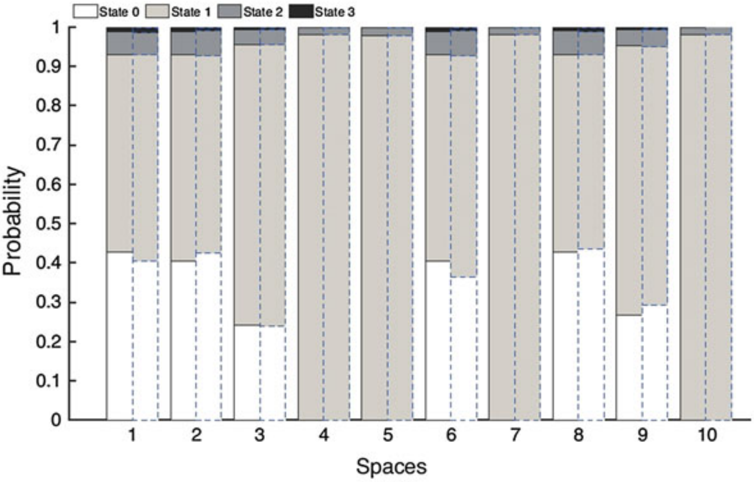

**Fig. 10** Simulation results in *building A* with 10 spaces. Building data (*right columns*) and the estimated ECM (*left columns*)

The case when the building size increases is analysed in Fig. 11. This simulation is performed in *building B* with 50 spaces, again the result shows that the performance of the ECM is not significantly affected. This is a consequence of the ECM structure in which the number of Markov chains represents the size of the building and they are not strictly dependent on each other. Moreover, Fig. 11 also illustrates the ability of the ECM to capture and to reliably predict the building occupancy patterns, even for a building with five times more spaces.

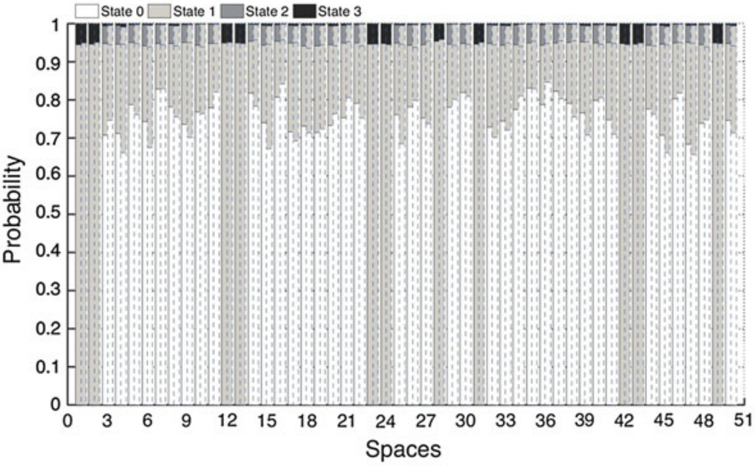

**Fig. 11** Simulation results in *building B* with 50 spaces. Building data (*right columns*) and the estimated ECM (*left columns*)

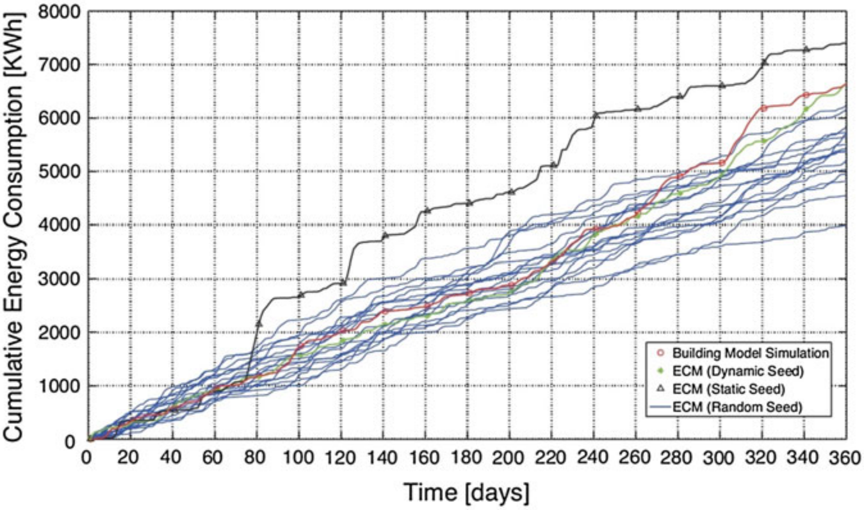

**Fig. 12** Building A ECM simulations with random seeds and comparison with the building energy consumption

The stochastic nature of the ECM is illustrated in Fig. 12. This figure represents the ECM simulations obtained in building A. In the absence of a systematic method of generating a sequence and, at the same time guaranteeing a lower prediction error, the sequences are randomly generated. Each time the ECM is simulated a new, and often different, sequence is produced. This sequence is the combination of each Markov chain predicted sequence. As illustrated in Fig. 12, some predictions poorly represent the building, for example, the prediction using the static algorithm (line with triangles) is completely degraded.

In order to analyse and validate the effect of different occupant behavioural models on the building energy consumption, Figs. 13, 14 and 15 illustrate the results for simulations performed in building A. Figure 13 represents an energy efficient scenario, in which no energy savings are predicted. This is the outcome of a conservative behaviour, where the occupants are simulated to be concerned with the energy consumption within the building. In contrast, we have an energy inefficient scenario represented in Fig. 14. In this case, the occupants are simulated to have a wasteful behaviour, with no respect for the energy use in the building. In the between, we have a more common scenario (Fig. 15). This scenario is characterised by a combination of the previously described behaviours. By comparing these figures, the dynamic algorithm provides better predictions than with the static algorithm. Moreover, although the daily energy consumption predictions differ from the building, the ECM reliable predicts the building's total energy consumption.

A residual analysis between the previous simulations is illustrated in Fig. 16. The simulations 1–17 are performed applying a random seed. The simulations 18

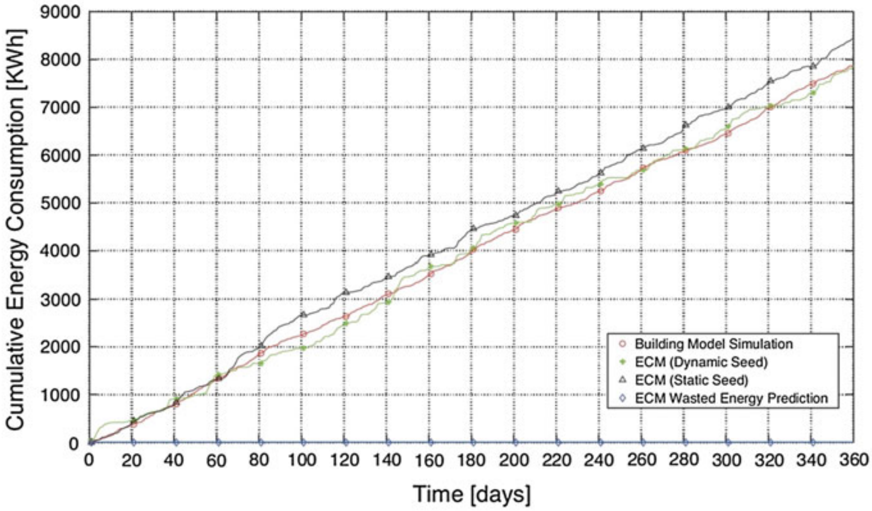

Fig. 13 Simulation A.1 illustrating an energy efficient behavioural scenario

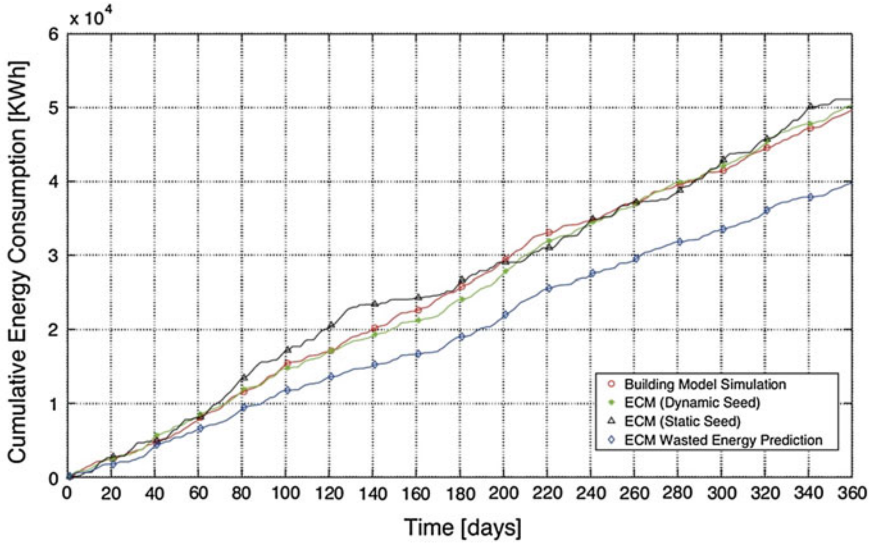

Fig. 14 Simulation A.2 illustrating an energy inefficient behavioural scenario

and 19 are performed when applying the static and dynamic algorithm, respectively. It is possible to verify that the dynamic algorithm does not guarantee the best residual; however, it is always better than the static algorithm. Moreover, it provides a predication error of less than 2 % for these simulations. These residuals are the absolute value of the difference between the building energy consumption and the ECM prediction in percentage relatively to the building.

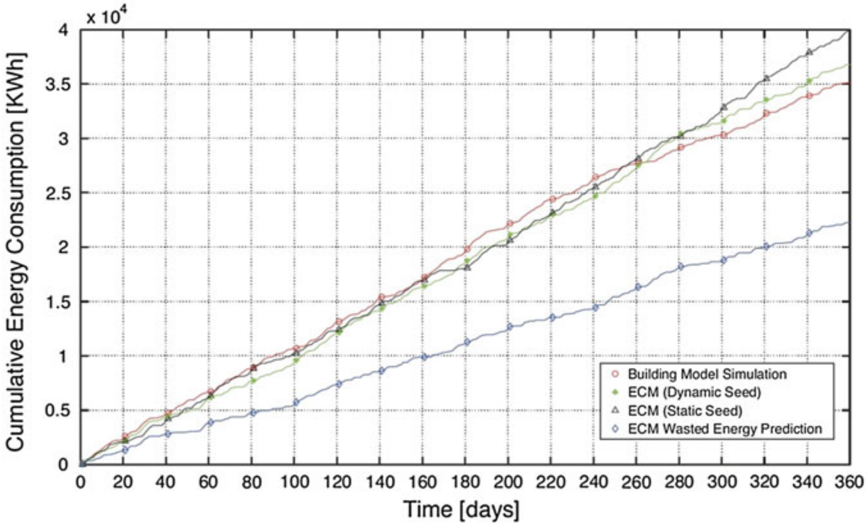

**Fig. 15** Simulation A.3 illustrating a common behavioural scenario

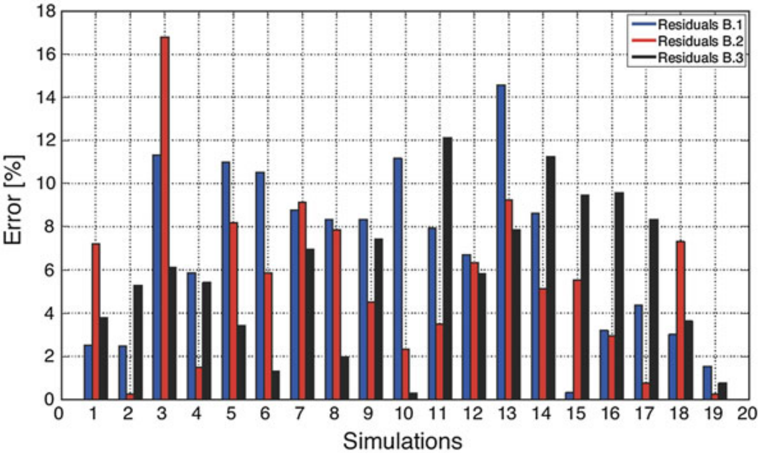

**Fig. 16** A residual analysis between the simulations performed

## 5 Conclusions

As building standards improve, so will the relative impact of occupants on resource use increase. Thus, it seems inevitable that better models of occupation presence and interaction are necessary. The set of models here discussed is a contribution to predict the impact of occupants' behaviour on a building in terms of energy consumption, utilisation and waste. The output of these models provides valuable information for the simulation of a single building. Central to this set is the stochastic model of occupant presence. The stochastic models of occupant behaviour regarding the use of the lighting system imposes no loss of generality as it can always be defined to other type of devices, represent the variety of occupant behaviours and their randomness over time.

The obtained results demonstrate that it is important to consider the behaviour analysis of occupants within the building, as different occupancy patterns result in different patterns of energy consumption. Moreover, the obtained results are aligned to hypothesis of applying stochastic models to represent either building occupant behaviour or the space occupancy patterns.

The proposed ECM for predicting building energy consumption produces reliable predictions. Additionally, it can accurately capture space utilisation and predict different scenarios and support reliable decision making for investing in potential areas for energy savings. An important aspect being refined in further developments is the ECM simulation. The simulation results show better results with the dynamic approach. However, this algorithm is based on a search method and it does not guarantee the best prediction. Additionally, as the size of the building increases, the dynamic algorithm becomes computationally complex. Another important improvement is extending this ECM to account for multiple devices in the building's spaces.

Although the proposed methodology seeks to improve and support retrofitting projects in existing buildings, the results can be extrapolated to support new building, e.g., buildings in a design or project stage. That is, buildings with the same activities, in the same geographic area and occupied by people that share the same cultural background are expected to have similar energy usage patterns. In this case, previous obtained retrofitting project results can be used at an early stage to promote the installation of energy efficient technology and improving the energy efficiency of new buildings.

**Acknowledgments** The presented work has been partly supported by the European Commission through ICT Project EnPROVE: Energy consumption prediction with building usage measurements for software-based decision support (G. A. FP7-248061).

## References

Abreu JM, Ferrão P, Pereira FC (2012) Using pattern recognition to identify habitual behavior in residential electricity consumption. Energy Buildings 49:479–487

Spinar R et al (2008) Efficient building management with ip-based wireless sensor network. Cork

Atallah L, Yang G (2009) The use of pervasive sensing for behaviour profiling—a survey. Pervasive Mobile Comput 5:447–464

Borgeson S, Brager G (2008) Occupant control of windows: accounting for human behaviour in building simulation. University of California, Berkeley

Bourgeois D, Reinhart C, Macdonald I (2006) Adding advanced behavioural models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control. Energy Buildings 38:814–823 (special issue on daylighting buildings)

Chen J, Taylor JE, Wei H–H (2012) Modeling building occupant network energy consumption decision-making: the interplay between network structure and conservation. Energy Buildings 47:515–524

Ching W, Ng M (2005) Markov Chains: models, algorithms and applications, 1st edn. Springer

Crawley D, Hand J, Kummert M, Griffith B (2008) Contrasting the capabilities of building energy performance simulation programs. Build Environ 43:661–673 (building performance simulation)

Frederic H, Darren R (2009) A comprehensive stochastic model of window usage: theory and validation. Glasgow, pp 545–552

Frontczak M, Wargocki P (2011) Literature survey on how different factors influence human comfort in indoor environments. Build Environ 46:922–937

Herkel S, Knapp U, Pfafferott J (2008) Towards a model of user behaviour regarding the manual control of windows in office buildings. Build Environ 43:588–600

Hoes P et al (2009) User behaviour in whole building simulation. Energy Buildings 41:295–302

Jang W, Healy W (2010) Wireless sensor network performance metrics for building applications. Energy Buildings 42:862–868

Lopes M, Antunes CH, Martins N (2012) Energy behaviours as promoters of energy efficiency: a 21st century review. Renew Sustain Energy Rev 16:4095–4104

Ma Z, Cooper P, Daly D, Ledo L (2012) Existing building retrofits: Methodology and state-of-the-art. Energy Buildings 55:889–902

Mahdavi A, Pröglhöf C (2009) User behaviour and energy performance in buildings

Masini A, Menichetti E (2012) The impact of behavioural factors in the renewable energy investment decision making process: conceptual framework and empirical findings. Energy Policy 40:28–38

Masoso O, Grobler L (2010) The dark side of occupants' behaviour on building energy use. Energy Buildings 42:173–177

Menzel K et al (2008) Towards a wire-less sensor platform for energy efficient building operation. Tsinghua Sci Technol 13:381–386

Midden C, Kaiser F, McCalley LT (2007) Technology's four roles in understanding individuals' conservation of natural resources. J Soc Issues 63:155–174

Midden C, Ham T, Zaalberg R (2008) Pervasive persuasive technology and environmental sustainability. Sydney

Murray C (2009) New insights into rebound effects: theory and empirical evidence. Master's Thesis, School of Economics and Finance

Nicol J (2001) Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans

Ockwell D (2008) Energy and economic growth: grounding our understanding in physical reality. Energy Policy 36:4600–4604

Oikonomou V, Becchis F, Steg L, Russolillo D (2009) Energy saving and energy efficiency concepts for policy making. Energy Policy 37:4787–4796

Page J, Robinson D, Morel N, Scartezzini J (2008) A generalised stochastic model for the simulation of occupant presence. Energy Buildings 40:83–98

Pollard D (1984) Convergence of stochastic processes. Springer, New York

Rabiner L (1989) A tutorial on hidden Markov models and selected applications in speech recognition, pp 257–286

Reinhart C (2004) Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. Sol Energy 77:15–28

Rijal H et al (2007) Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy Buildings 39:823–836

Robinson D (2006) Some trends and research needs in energy and comfort prediction. Windsor

Tabak V (2009) User simulation of space utilization. Eindhoven

Tabak V, Vries B (2010) Methods for the prediction of intermediate activities by office occupants. Build Environ 45:1366–1372

Team E (2010) Tips & tricks for using EnergyPlus: insider secrets to using Energy-Plus. U.S. DOE Energy Efficiency and Renewable Energy (EERE)

Tindale A (2010) Designbuilder and energyplus. Designbuilder software ltd. Building Simulation User News 25

Virote J (2010) Algorithms and methodologies for decision support in energy efficiency on buildings. Universidade Nova de Lisboa, Lisboa

Virote J, Neves-Silva R (2010) User behaviour modeling of buildings energy consumption using hidden Markov models. Coimbra

Virote J, Neves-Silva R (2012) Stochastic models for building energy prediction based on occupant behaviour assessment. Energy Buildings 53:183–193

Wada T, Matsuyama T (2000) Multiobject behaviour recognition by event driven selective attention method. IEEE Trans Pattern Anal Mach Intell 22:873–887

Yalcintas M (2008) Energy-savings predictions for building-equipment retrofits. Energy Buildings 40:2111–2120

Yu Z et al (2011) A systematic procedure to study the influence of occupant behavior on building energy consumption. Energy Buildings 43(6):1409–1417

Zimmerman G (2007) Modeling and simulation of individual user behaviour for building performance predictions. San Diego, pp 913–920

# Uncertainty in Refurbishment Investment

### Carol C. Menassa and Wilson Ortiz-Vega

**Abstract** Nearly zero-energy refurbishments provide many of the benefits of nearly zero-energy buildings to the aging building stock and offer an opportunity to make them more resource-efficient and environmentally friendly, with an increased social and financial value. However, high initial costs and uncertainties about the expected benefits characterize this type of investment and affect the building stakeholders' decision on whether to go ahead with such a project or not. Given the special case of existing buildings and associated challenges to refurbish them to nearly zero energy, this chapter identifies and classifies uncertainties that characterize and make this type of investment a highly uncertain endeavor over the project life cycle. It also provides recommendations about managing these uncertainties during the project evaluation phase. Finally, a new approach to project evaluation based on the option pricing theory is presented along with a case study example.

## 1 Introduction

The existing building sector is responsible for over 70 % of the world delivered energy consumption (US EIA 2011). In addition, over 80 % of the energy consumption in the life cycle of a building occurs during its operation (United Nations Environment Program 2007). High energy-consuming countries, such as the United States of America (USA), estimate that in the next 25 years, approximately three-quarters of their built environment will be either new or refurbished (US EIA 2012).

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DOI: 10.1007/978-1-4471-5523-2_6,

Refurbishing the existing building stock to become energy-efficient will result in a reduction in the material throughput and improve the functional quality and the durability of these buildings at one-half to one-third the cost of demolition and reconstruction of a new building (Poel et al. 2007; Kohler 1999). One approach to achieve energy efficiency while refurbishing buildings would be to adopt nearly zero-energy refurbishments (NZER). In general, a nearly zero-energy building (NZEB) is a high-energy-performance building that balances the energy consumed by the building through onsite or offsite renewable sources (NIST 2011). If properly implemented, NZER provide many of the benefits of NZEB to the aging building stock and offer an opportunity to make them more resource efficient and environmentally friendly, with an increased social and financial value (Gohardani and Björk 2012). However, high initial costs and uncertainties about the expected benefits characterize the NZER investment and should be taken into account by the building stakeholders when making a decision on whether to go ahead with such a project or not.

A major challenge to the adoption of this type of buildings by the industry is the availability of reasonable financing opportunities. In a recent analysis of 2011 proxy voting patterns, 35 % of mutual fund companies, with almost $12 trillion of managed assets in the USA, indicated that they still do not see the business value of energy efficiency. This significantly limits the amount of capital available to unlock the full potential of NZER and other energy efficiency investments (Kropp 2012). In addition, the three largest US mutual fund companies (i.e., American Funds, Fidelity, and Vanguard), which manage a total of $1.6 trillion in US securities, did not vote in favor of a single resolution addressing climate change in 2011 (Kropp 2012). This indicates that investment in energy efficiency in general, and NZER in particular, is perceived as too uncertain due to different technical challenges like demonstrating the achievement of energy efficiency while respecting budgets. Other conditions of uncertainties such as those related to the increase in value of the building, increase in demand for green space, fluctuation costs of energy, the perceived savings in the building operation and maintenance costs, and tenant/occupant resistance to change impose additional limitations that make building stakeholders reluctant to move forward with the NZER investments.

The above is exacerbated by lack of information and benchmarks about the actual performance of NZER after the design and construction phases. Currently, only 129 projects are registered in the US Department of Energy High Performance Buildings Database (US DOE 2012), and only 280 buildings have claimed net zero-energy balance in the past two decades worldwide (Musall et al. 2010). Most of this knowledge is for new construction of NZEB, with very limited information about NZER. All of the above increase the uncertainty surrounding the expected costs and benefits from any investment in refurbishments and force building stakeholders to postpone investment until more proven returns are demonstrated (Mckinsey and Company 2008). This is further complicated by the 2008–2009 global recession where investors became careful about their investment portfolios, thus limiting the investment and debt capital necessary to refurbish the buildings to achieve NZER.

Given the special case of existing buildings and associated challenges to refurbish them to NZER, this chapter identifies and classifies uncertainties that characterize and make NZER a highly uncertain endeavor. It also provides recommendations about managing these uncertainties especially during the project evaluation phase. It concludes by recommending a new approach to evaluate projects under uncertainty using the option pricing theory. A case study example illustrates the potential benefits of this approach.

## 2 Characteristics of Investments in NZEB Refurbishments

NZER are sustainable refurbishments that improve the existing building stock in order to achieve energy balance through onsite or offsite renewable sources. In general, refurbishments reset the building life, improve the energy performance, and provide many economic, environmental, and social benefits. However, achieving NZER requires high initial costs, compared to regular refurbishments that must be justified by the expected additional benefits (Danfoss 2010). Given the uncertainties that characterize the costs and benefits of NZER, decision to finance these projects presents a great challenge to building stakeholders and financial institutions.

The additional costs of NZER result from different design requirements to achieve a higher energy performance and provide the required energy balance while having to deal with existing conditions. For example, the site location and current layout of the building can limit the ability of the building to have the required sun exposure to generate the required solar energy for the balance. In this case, designers might need to select more expensive insulation material with greater thermal resistance in order to reduce the energy required in heating and cooling of the building, or procure renewable energy offsite at higher rates. Other examples of typical costs in a NZER project are the use of energy-efficient heating, ventilating, and air-conditioning (HVAC) system, changes required to the building facade, improvements to the building interiors to achieve better occupant satisfaction and comfort, installation of solar water-heating system, and the use of high thermal resistant construction materials to improve thermal insulation. These highly efficient systems are often more expensive than the less efficient versions (Fuller 2008). Moreover, integrating all of these systems with existing building systems might also raise the cost even more.

Thus, the building could achieve the energy balance requirement but not be economically feasible. The implementation of these systems in existing buildings without proven record of performance and guaranteed returns (i.e., higher rent and energy savings) needs to be justified to all building stakeholders. The expected high initial cost may prevent the investment, either because the stakeholder does not have access to capital or has other high-priority investments (Fuller 2008). Government tax incentives have been offered by a number of European Union (EU) countries and the USA to help with the high upfront costs of constructing new or refurbishing buildings to achieve energy efficiency and achieve reduction in emissions (Baden et al. 2006). This could be achieved and financed by using market-based approaches to control pollution. One example of this was the Acid Rain Program initiated in 1995 by the US Environmental Protection Agency in an effort to reduce overall atmospheric levels of sulfur dioxide and nitrogen oxides, which cause acid rain (EPA 2009). The program was an implementation of emissions trading that targeted coal-burning power plants, allowing them to buy and sell emission permits according to individual needs and costs. The program allowed companies the flexibility to adapt and update their compliance strategy based on their individual circumstances (EPA 2009). This program could be a prototype for undertaking emerging environmental issues and financing NZER where building stakeholders can offset some of the technology cost required to achieve the net zero balance. This approach will monetize the pollution savings of the refurbishment. However, such a system is not completely risk free especially if emissions targets are not put in place as part of the policy. A similar emissions trading program in Europe has faced some major problems that discouraged investors from pursuing it further. In the 1 year, the number of permits topped the amount of pollution, sending the price of carbon crashing to almost nothing (Milner 2008). This resulted in banks pulling out of the carbon-offsetting market after failures to reach agreement on emissions targets. The lack of activity and the drop-off in investment demand made some investors pull out of large planned clean-energy projects because of the expected fall in emissions credits after 2012.

A lack of regulatory certainty post 2012 affected the market's view of what carbon credits from clean-energy projects will be worth and subsequently constrained financing for projects (Webb 2010). European permits have lost 80 % of their value since mid-2008 and 50 % in the last 12 months, due to claims that the carbon market is becoming irrelevant in the EU's efforts to cut emissions (Chen and Reklev 2012). Volatility is just one of the many challenges the emissions market has faced since its launch in 2005. Tax evasion, theft of permits, and re-usage of credits have also damaged the reputation of the world's biggest carbon market (Chen and Reklev 2012).

Because of this, a local or regional approach might be the best option for NZER. The location of the building greatly affects the performance of the NZER, and local and regional officials can have a better knowledge of what challenges a building stakeholder faces when they aim for NZER in their building portfolio. This is one of the many ways the financing problem for NZER could be solved. The above discussion indicates that government incentives are subject to the capability of the government to sponsor these tax credits. Furthermore, studies have shown that compulsory performance upgrades in buildings might not be cost-effective unless they are subsidized which in turn increases the burden on governments to finance (Desogus et al. 2013). These incentives can help in the near term but a long-term privately financed mechanism must also be found to provide access to financing capital and be able to achieve the long-term goal of NZEB (Baden et al. 2006).

As is typically the case, building stakeholders are more interested in an investment with benefits that exceed the initial costs over the facility life cycle and has an acceptable payback period. Uncertainty in the benefits of NZER occurs because they are obtained over a long-term period and come from different sources. Direct and monetary benefits such as the reduction in energy costs and the increase in the value of the building are easy to quantify using energy simulation models and other approaches; however, the inputs used to calculate these benefits are highly uncertain and dependent on user input and experience (Turner Construction 2010). The reduction in energy costs depends on two highly uncertain inputs such as the fluctuating energy costs and forecasting building performance. The future value of the building depends on uncertain inputs such as the real estate market conditions and the residual value of the building equipment; as well as, demand for space. In the case of indirect benefits, it is even harder to quantify benefits such as the improvement in occupant productivity and health, which are highly subjective measures.

These uncertain costs and benefits of NZER result in high ratio of risk exposure to the return on investment. NZER projects frequently fall short in traditional quantitative capital budgeting analysis like pay-back period, internal rate of return (IRR), and net present value (NPV). They also do not meet the common criteria typically used to factor in risk in the evaluation of a project. For example, speculators or hedge fund managers are willing to take on risky investments with proven returns, but energy-efficient investments in individual buildings are not large enough to attract speculators and are perceived as too risky for commercial bankers (Detserclaes 2007). Bankers might rank NZER projects lower in their agenda due to the long payback time that these projects tend to have in comparison with other investments. Using payback period for analysis could reduce the attractiveness of the investments due to the length of a building's lifetime, and therefore, payback period should not be used alone to determine the attractiveness of NZER investments (BPIE 2010). However, lack of financier's awareness and training on energy efficiency issues could hinder the ability of building stakeholders to obtain qualified advice and proper evaluation of their investment in NZER. If a financier uses the associated risk exposure, the payback time, and the rate of the return on investment to evaluate the project, then the final decision could be biased to not finance NZER due to high uncertainties in costs and benefits. The lack of standardization in the measurement and verification procedure, the relatively small size of NZER projects, and the high risk associated with these projects, contribute to higher transaction costs for the projects compared to other traditional investments (BPIE 2010).

It is clear that the financing incentives are still modest because of the uncertainty associated with the costs and benefits of NZER. Thus, there is a need to classify and understand what the uncertainties are and their sources. In the next section of the chapter, a life cycle perspective of the uncertainties associated with NZER are discussed in detail.

# 3 Life Cycle Uncertainties in NZEB Refurbishments

NZER buildings are exposed to uncertainties in costs and benefits throughout their life cycle. Thus, a life cycle perspective is appropriate to identify and classify the uncertainties that characterize NZER during the design, construction, operation, and maintenance phases of the building. In addition, these uncertainties can be classified into two categories according to their sources and the possible control that building stakeholders have over them. Internal uncertainties are internal to the NZER project and are within the control/decision of the building stakeholders. On the other hand, external uncertainties are those beyond the control of the building stakeholders. Whether internal or external uncertainties, building stakeholders are required to use appropriate risk management approaches to manage these uncertainties in order to ensure reliable evaluation results for investment decision-making.

## *3.1 Life Cycle Uncertainties: Design Phase*

During the design phase of NZER, architects and engineers need to decide how they are going to refurbish their building (e.g., what construction materials they will use; how they are going to achieve the energy balance through onsite and offsite use of renewables; and how to integrate with existing building systems). These decisions need to be made using assumptions about occupant behavior, fluctuating energy costs, economic benefits, and others. All of these assumptions affect the success of a NZER project and impact the long-term benefits. Lack of information about most of these things makes these assumptions a major cause of uncertainty in NZER design. The internal and external uncertainties associated with the design phase are listed in Table 1 below along with descriptions of each.

All the uncertainties listed in Table 1 should be evaluated by building stakeholders during NZER evaluation phase and can be proven to significantly impact the decision. For example, over 30 % of the energy consumption in high-performance buildings is related to occupant behavior (Glover 2011). However, currently, there is no proven approach to account for occupancy behavior during the design phase and its impact on the predicted energy savings and building performance (Marszal et al. 2011). In a NZER, the occupant energy consumption cannot be ignored since it can affect the required renewables to balance the demand, thus increasing the cost of the refurbishment. If the design team in a NZER project is too optimistic about the occupants' behavior and their acceptance of new systems and technology (e.g., occupancy sensors), the refurbished building might not achieve the expected savings, and the required renewable energy balance might increase (Pless and Torcellini 2009). In addition, the building-related energy usage is constantly decreasing due to advances in technology; therefore, impact of occupants on total building energy demand will become increasingly important (Sisson et al. 2007).

Another uncertainty that affects NZER during design is fluctuating energy costs. High energy prices will make the refurbishment investment more attractive

**Table 1** Design-phase uncertainties

| Design uncertainties | Classification | Characteristics |
|---|---|---|
| Forecasting weather conditions | Internal | NZEB performance is estimated using historical weather data, which might change or fluctuate significantly during building operation, resulting in a change in the actual energy use profile and the required energy balance from renewables (Robert and Kummert 2012) |
| Predicting energy savings | | Energy use and savings are typically estimated using building simulation models where several assumptions about existing building conditions and future use are made (Verbruggen et al. 2011; Hirsch et al. 2009; Wang et al. 2009; and De Wit and Augenbroe 2002). However, these assumptions often result in significant differences between predicted and actual energy use in the building (Yudelson 2010; Dell'lsola and Kirk 2003; Soebarto and Williamson 2001). For example, the design engineer might estimate that a commercial building will be operated 60 h per week, but that might increase or decrease depending on the tenants of the building and their energy use behavior. In addition, several studies indicate that buildings use more energy afterhours that during regular operation time (Sanchez et al. 2007; Webber et al. 2007), making the assumption of ideal schedule for building operation a major source of uncertainty when calculating energy savings |
| Predicting equipment performance and costs | | The building equipment installed in the NZER could be unreliable in its operation (Stadler et al. 2009). In addition, facilities managers often lack time, necessary skills, and experience required to ensure that equipment is running as designed. Another important aspect is that technology innovations might make the expensive equipment installed today in the building outdated in a few years. This might reduce the resale value of NZER, making the initial investment less desirable (Brown 2008) |
| Offsite generation prices of renewable energy | External | The price of offsite-generated renewable energy could be as uncertain as fossil fuel prices due to the unreliability in their efficiency and operation (Mavrotas et al. 2003) |
| Predicting occupancy energy use characteristics | | A substantial amount of a building performance is related to occupants' behavior and how they use energy. Considerable differences in energy use are associated with the high uncertainty of occupant behavior (Azar and Menassa 2012a) |
| Fluctuating energy costs | | High uncertainties associated with the fluctuating energy costs have a strong influence on the expected economic benefits from energy savings in NZER. In addition, the use of expensive offsite renewable energy sources might not make economical sense when traditional energy costs are low (Marszal et al. 2012 and Elkinton et al. 2009) |

(continued)

**Table 1** (continued)

| Design uncertainties | Classification | Characteristics |
|---|---|---|
| Availability of space | | A source of uncertainty is the future availability of space for the installation of NZER equipment. Energy-renewable installations such as solar panels and wind turbines are critically affected by the space available for their accommodation, current location of the building, and site layout as discussed below (Fong and Lee 2012) |
| Building location and layout | | The existing building location will highly affect the performance of equipment such as solar panels and other sustainable options. The building location might force building stakeholders to seek off-site expensive renewable energy sources, which might not always be available through local utilities (Marszal et al. 2012; Leckner and Zmeureanu 2011) |

to building stakeholders due to the possibility of higher monetary savings during the life of the building. On the other hand, low energy prices will reduce the possible monetary benefits that a building stakeholder can obtain from a NZER (Leckner and Zmeureanu 2011). Therefore, energy planning is increasingly important to manage the uncertainty associated with fluctuating energy costs. Designers can select between off-site and on-site options to achieve the energy balance keeping in mind that each has its associated uncertainties and risks (Pless and Torcellini 2009). For example, off-site sources are uncertain because the purchasing price of green power could fluctuate significantly due to possible large demand of green power in the future.

On-site sources are also uncertain because the building stakeholders need to manage the uncertainties and costs associated with the operation and maintenance of renewable energy systems. For example, the performance of wind turbines and PV systems is very dependent on uncertain conditions such as weather and sun exposure. Moreover, adopting these technologies of high upfront costs could become difficult because the market for these technologies is constantly changing from the technological and economic standpoints. Furthermore, reliance on this type of equipment is affected by the availability of space for their installation. Energy-renewable installations such as solar panels and wind turbines require large open spaces for their installation and might not be the best source of renewable energy for a NZER due to the limiting conditions the project location might impose (Fong and Lee 2012; Marszal et al. 2012; Leckner and Zmeureanu 2011).

The location of the building will not only affect the availability of sustainable options, but it will also have a considerable impact on the amount of energy required for the operation of the building. A building may be designed to achieve energy balance, but in reality, it may not achieve a net zero-energy balance every year due to extreme weather conditions. The total energy use variation can be relatively small, but the energy excess or shortage in relation to the net zero targets could become significant when the design is performed using historical data (Robert and Kummert 2012). Abnormal weather years that have above-average heating and cooling loads, with below-average solar and wind resources could greatly affect the performance of the NZER and whether it achieves the energy balance for any particular year.

All of the above and the lack of information of the past performance of NZEB make it difficult to design NZER projects and to obtain a clear estimate of the future costs and benefits.

### *3.2 Life Cycle Uncertainties: Construction Phase*

During the construction phase, a NZER project faces many challenges such as uncertainty in scheduling, financing, budget management, and unknown preexisting conditions among others. All of these directly affect the cost of finalizing the project within budget and on schedule during the construction phase. The internal

**Table 2** Construction-phase uncertainties

| Construction uncertainties | Classification | Characteristics |
|---|---|---|
| Scheduling uncertainty | Internal | Activities during the construction process are subject to considerable uncertainty due to preexisting conditions (Cattano et al. 2012). For example, resources may become unavailable or new activities may have to be incorporated due to changes in the refurbishment scope. In addition, contractors might need to work around tenants who are not fully evacuated; thus, all construction activities need to be scheduled taking that into account. All of these will affect the schedule and time of completion of the project |
| Budget and financing decisions | | Availability of continuous funding and the duration and availably of tax rebates and incentives to support construction activities might change over the duration of the project (Baden et al. 2006). In addition, unforeseen conditions in the existing building may force stakeholders to reduce the scope of the project when the cost to refurbish exceeds the allocated budget, and additional financing cannot be secured (Menassa 2011) |
| Preexisting conditions | External | Unforeseen site conditions are among the largest contributing factors of uncertainty during the construction phase because it impacts both the project schedule and allocated budget (Cattano et al. 2012). Hidden preexisting conditions might cause budget overrun and construction delays |
| Material functional characteristics | | The long-term reliability and performance of the construction materials used for the refurbishment have a high impact on the expected benefits of the NZER (Kadam 2001) |
| Integration of new and old building systems | | The compatibility issues between new and existing building systems might result in unforeseen difficulties and force building stakeholders to modify design with adverse impact on both cost and schedule of the project as well as the expected benefits (Cattano et al. 2012) |

and external uncertainties associated with the construction phase of NZER are listed in Table 2.

During project execution of the NZER, construction activities are subject to considerable uncertainty that may lead to schedule disruptions. This uncertainty may arise from a number of possible sources, such as integrating some of the new systems to achieve NZER with existing building systems may take more or less time than originally estimated, renewable energy systems may become unavailable due to supply constraints, construction materials may arrive behind schedule, new activities may have to be incorporated or activities may have to be dropped due to unforeseen site conditions, and finally unforeseen weather conditions may cause severe delays (Herroelen and Leus 2005). A disrupted schedule will incur higher costs due to missed due dates and deadlines as well as the need for frequent rescheduling. More importantly, this might result in conflicts and disputes between the building stakeholders (e.g., owner and contractor) when they cannot agree on the extent and cost of the resulting changes. NZER have a higher possibility of facing these challenges since the stakeholders might not have full knowledge of the existing building to be refurbished due to misplaced and often non-existent original building plans as well as several un-documented changes that might have been incorporated in the building over its lifetime (Cattano et al. 2012).

Attempting to realistically consider the uncertainty in the construction schedule poses several challenges. For example, there is a lack of accessible information documenting the construction challenges during NZER. This is intensified by other budget-related sources of uncertainty such as the availability of continuous funding and the duration and availably of tax rebates and incentives (Baden et al. 2006). Uncertainty due to the existing conditions may reduce the scope of the NZER endeavor when the cost of the refurbishment exceeds the allocated budget (Cattano et al. 2012). Furthermore, other sources of uncertainty that affect the construction phase are the refurbishment material functional characteristics and the integration of new and old building systems. These will affect how well the construction process goes according to the design and will determine the final building performance. For example, if the installed thermal insulation selected during design does not perform as required, the building might not achieve the expected energy savings and affect the amount of renewable energy required to achieve a balance. Furthermore, the integration of outdated mechanical equipment with the new renewable systems could pose a greater challenge. All of the above can increase the uncertainty surrounding the NZER, the actual final cost of construction, and duration of the project. This poses big challenges especially in existing buildings where operations cannot be delayed and tenants expect minimum disruption to their everyday activities and businesses.

### *3.3 Life Cycle Uncertainties: Operation and Maintenance Phase*

The design and construction phases uncertainties discussed above will directly contribute to additional uncertainties during the operation and maintenance phase of a NZER. These include the following: uncertainty in perceived benefits of the refurbishment, non-energy cost savings or benefits, future supply, and demand of energy among others listed in Table 3. All of these uncertainties directly affect the success of the NZER project especially the expected benefits from the initial high level of investment incurred during the design and construction phases.

During the operation and maintenance phase of a NZER, stakeholders will start to realize many of the expected benefits resulting from the initial investment

**Table 3** Operation and maintenance-phase uncertainties

| Operations and maintenance uncertainties | Classification | Characteristics |
|---|---|---|
| Actual benefits of the refurbishment | Internal | The actual benefits in energy savings of the refurbishment can be uncertain due occupancy behavior, equipment performance, and changes in weather conditions (Azar and Menassa 2012b; Masoso and Grobler 2010; and Pless and Torcellini 2009) |
| Non-energy cost savings or benefits | | There is uncertainty in the non-energy cost savings or benefits due to the difficulty and subjectivity in quantifying these benefits (e.g., improved occupancy productivity and health) (Turner Construction 2010) |
| Whole-building performance | | There is uncertainty in optimizing and quantifying energy efficiency, durability, and occupant productivity; therefore, it is hard to determine the future whole-building performance. This will impact the returns from the building and the resale value (Brown 2008 and Sisson et al. 2007) |
| Revenue from building operation | | The revenue from building operation can be uncertain due to the difficulty to quantify benefits of the NZER and the willingness of tenants to pay the extra premium for NZER (McCabe 2011) |
| Operation and maintenance costs | | Sources of uncertainty are the operation and maintenance costs of the NZER due to the limited available information to stakeholders of how often and when maintenance will be required as well as the timing of this maintenance (US DOE 2012) |
| Performance of renewable energy systems | | Renewable energy system's performance depends on the building location and available space. For example, the performance of wind turbines and solar panel systems is very dependent on uncertain conditions such as weather and sun exposure (Marszal et al. 2012 and Leckner and Zmeureanu 2011) |
| Real estate market fluctuations | External | Changes in regulation of real estate and the future demand for sustainable buildings are sources of uncertainty for NZER (Parker 2009) |

(continued)

**Table 3** (continued)

| Operations and maintenance uncertainties | Classification | Characteristics |
|---|---|---|
| Electrical and thermal demands of building occupants | | Considerable differences in electrical and thermal demands are expected due to the uncertain occupant behavior (Masoso and Grobler 2010) |
| Public policy | | Sources of uncertainty are the availability of governmental policy initiatives that promote NZER and the future regulation of emissions (Baden et al. 2006) |
| Future value of the building | | It is uncertain how the NZER refurbishments are capitalized into the resale value of the building (Brown 2008) |
| Future supply and demand of energy | | The future supply and demand of delivered energy are highly uncertain because it depends on many unknown factors such as the future world population, cost of fossil fuel and renewable energy, and energy supply technologies (US EIA 2012) |

during the design and construction phases. Many of these benefits were assumed during the design phase, and now, the stakeholder can compare the predicted benefits with the actual performance. However, these benefits will be perceived differently by the occupants and by the building stakeholders. There is high uncertainty in the non-energy cost savings and benefits due to the difficulty in quantifying their return. Not only are the non-energy savings and benefits difficult to quantify, but also the scale of their impact and success will depend upon whose perspective is being considered. Occupants might not notice improvement in building performance but will notice the improvement of the working environment in the refurbished building. However, they might still be concerned about the premium they are paying for these improvements and if it is balanced by the perceived benefits of improved health and productivity. On the other hand, a building owner might think the refurbishment was not successful because they did not obtain the expected energy performance even though occupant satisfaction was greatly increased. Quantifying the benefits of a NZER is another barrier. While some benefits are easy to quantify (e.g., expected energy use), other benefits are less tangible and more difficult to quantify, such as increased employee productivity, improved employee satisfaction, and the positive impact on the community (Turner Construction 2010; Menassa 2011).

Furthermore, other uncertainties affecting the NZER operation and maintenance are the future supply and demand of energy. The supply and demand of energy may strongly affect the power quality at feeder level of an electricity distribution network. As such, large-scale integration of NZER in particular and renewable electricity generation in general will require well-developed solutions in the form of energy storage, demand-side management, or both (Baetens et al. 2012). In addition to this, the available power for the NZEB could be limited in the future due to energy supply constraints. Therefore, careful planning should be done during the design phase so the building stakeholders do not face these challenges during the operation phase. Another source of uncertainty during the operation and maintenance phase is the revenue from building operation. Other sources of uncertainty are the operation and maintenance costs of the NZER. There is limited information about the actual performance of NZER, and therefore, a clear base of proven returns and costs are not available to building stakeholders for benchmarking and comparison. Studies have shown that the uncertainty due to operational factors can overshadow the impact of design features; thus, operating and maintaining the building efficiently are a top priority for building stakeholders (Wang et al. 2012).

Changes in regulation of real estate and the future demand of sustainable buildings are sources of uncertainty for NZER. Today, there is an increasing demand for this type of buildings, which might not be the case in the future especially as sustainable and green design and construction become the norm. Thus, the additional premiums that building owners can claim for improved building performance will be offset by increase in supply of green buildings (McCabe 2011).

One final uncertainty and probably one of the most influential is how the NZER are capitalized into the resale value of the building. Very limited information exists on this topic thus it will be challenging to obtain an accurate estimate (Brown 2008).

## 4 Risk Management Approaches

After identifying and classifying uncertainties, it is important for building stakeholders to determine the most appropriate framework to manage these uncertainties to properly evaluate NZER investments. Figure 1 presents a general risk management process that can be used in NZER. After identifying and classifying uncertainties, it is important for building stakeholders to determine the most appropriate framework to manage these uncertainties to properly evaluate NZER investments. Figure 1 presents a general risk management process that can be used in NZER. The first step in the risk management process is to identify and classify the NZER risks and uncertainties. As mentioned before, in this chapter, these uncertainties and risks can be internal and external according to their sources and the possible control that building stakeholders have over them. In the following steps, the stakeholders need to evaluate the uncertainties and risks with an appropriate framework to determine whether they will accept or manage the risks. Afterward, if risk management is chosen, then the stakeholders should use an appropriate management tool. An example of a framework to manage the risks and uncertainties in NZER will be presented later in this chapter. Finally, these risks should be monitored constantly during the life of the NZER. As with the case of uncertainties, the risk management framework can also be divided over the project life cycle.

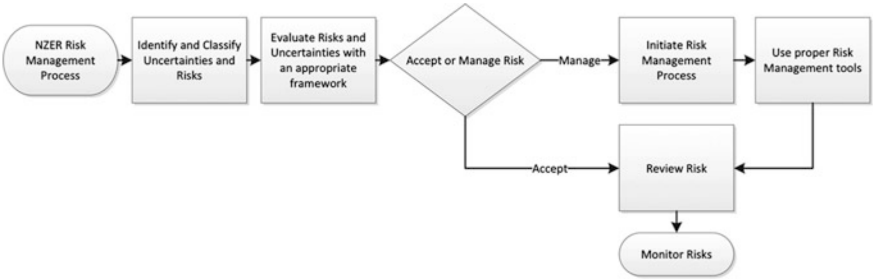


**Fig. 1** NZER risk management process

### 4.1 Risk Management During Design Phase

Risk management is a constant process of decision-making that reduces to an acceptable level the uncertainties associated with an investment (Condamin et al. 2006). Different risk management options are available to manage the challenges during the design phase. For example, it is known that occupants are a source of high uncertainty, and there is a great potential for reducing energy consumption by motivating energy-efficient behavior. Studies have determined that occupant behavior and operational aspects of energy use may be more effective than technological solutions (Gray and Zarnikau 2011). Therefore, costs of NZER could be significantly reduced if the design engineer considers conservation as part of the energy balance equation for NZER. This can be achieved by designing intervention strategies that focus on appropriate involvement of the building occupants (Fong and Lee 2012). An example would be developing a plan that enables occupants to compare their electricity use to others (Peschiera et al. 2010).

Another approach to manage risk during design phase is using statistical models to predict future energy prices and climate. This allows building stakeholders to reduce the risk associated with the energy savings (Robert and Kummert 2012). Other tools such as energy modeling software can be integrated with the statistical models to obtain the most economical renewable equipment to achieve the energy balance. For example, off-site generation energy prices that take into consideration market volatility can be modeled so they are compared with on-site generation system costs. Furthermore, designers can develop statistical models to predict climate conditions to reduce the risk associated with renewable systems and building performance.

### 4.2 Risk Management During Construction Phase

During the construction phase of a NZER project, some risks can be easily identified and controlled. For example, the building stakeholders might know that they will be refurbishing a building that can have many unknown preexisting conditions, and therefore, the construction schedule should have some time reserved to address these problems as they arise in the project (Herroelen and Leus 2005). In addition, the integration of new and old building systems might impact the construction schedule and costs (Cattano et al. 2012). This is also highly affected by the selection of construction materials. Using a specific thermal insulation material that is not accessible to suppliers could pose a risk to costs or project duration; a similar less-performing material that is more accessible should be selected to prevent problems during the construction and reduce the associated risks. That is why it is important that stakeholders develop a detailed plan to manage the impact and implement solutions if such problem arises during construction.

Another important consideration during the construction phase is that the building to be refurbished is typically occupied. This is another situation where all building stakeholders need to have a good plan to relocate the occupants while the building is being refurbished. This plan should minimize the disruption in the occupants' daily operations and productivity. In large NZER building projects, this can become complex and having a good occupant mobilization plan can significantly reduce the costs and duration of the refurbishment.

### *4.3 Risk Management During Operation and Maintenance Phase*

Finally, there are several ways to manage the risks that stakeholders will face during the operations and maintenance phase of NZER. For example, proper maintenance programs will reduce the probability of major breakdowns and improve the reliability of the systems' performance. In addition, the maintenance personnel should be properly trained to be able to service the building systems. As more technology is implemented in buildings, complexity and risks of severe problems due to errors and lack of training of maintenance personnel increase (Danfoss 2010). Facility managers should have well-established plans to operate and service the building systems to maintain an optimal performance.

To account for risks associated with the expected revenue from the building operation, building stakeholders should develop models of real estate market conditions to determine the best price that they could rent the available space. The goal is to reduce the risks of vacancy while ensuring that tenants are willing to pay the extra premium for NZER (LaSalle 2011). One last example is to promote the participation of occupants in the building operation. Occupants might not know how the building operates and could become too dependent on technology. This could lead to careless behavior toward reducing their energy consumption because they think that the building is well equipped to be energy efficient without any effort on their part.

This chapter provided the first step to manage the associated risks of NZER given a life cycle perspective of these uncertainties. Identification of these risks occurs by looking at the limited historical data of NZER. Not only is the nature of the NZER risks important, but also proper consideration must be given to all the associated uncertainties. The stakeholder should have at his disposal ample and adequate resources to ensure that the refurbishment objectives are completed even in the most difficult circumstances. Furthermore, uncertainties affect the evaluation of NZER, and thus, we need to have a way to account for them. A method other than the traditional NPV approach is required to accommodate the uncertainties in the investment decision of NZER. Because of this, an approach to project evaluation based on the option pricing theory was proposed by Menassa (2011) to account for these uncertainties in existing building investments. This approach is summarized in the next section along with a case study example to illustrate its applicability.

## 5 NZER Evaluation Under Uncertainty

Different approaches to project evaluation other than traditional quantitative capital budgeting techniques like pay-back period, IRR, and NPV are required to accommodate the uncertainties in the investment decision of NZER. Among these methods, NPV is the only technique that ensures the stakeholder objectives of maximizing return on investment (Copland and Tufano 2004; Trigeorgis 1996). However, the NPV method alone has several limitations. For example, it requires a discount rate, which cannot be easily determined and is often the decision-maker's choice to establish this rate (Rushing and Lippiatt 2009; Dell'lsola and Kirk 2003; and Fuller and Petersen 1995). The discount rate has two components: the risk-free component and the risk premium. The risk-free component is usually set by the lender and can be easily determined. The risk premium, in this particular case, will account for the uncertainties associated with NZER expected costs and returns. The value of the risk premium affects the final discount rate used to perform the NPV analysis (Ye and Tiong 2000; Dowd 1998). In addition, the NPV assumes that all future cash flows for a given investment are known in advance (Copland and Tufano 2004; Luehrman 1998). This is considered a limitation when performing an investment evaluation for NZER when it is impossible to predict accurately the future benefits and costs given the uncertainties discussed in the previous section.

Thus, from an investor perspective, a highly risky and unacceptable investment can be easily adjusted to look favorable with a positive NPV by just changing the risk premium component of the discount rate. Similarly, an investment with a negative NPV could also be simply adjusted to look less unfavorable by just changing the risk premium component of the discount rate. Another way to adjust the NPV results is to use the NPV-at-risk method where the primary variables underlying a project's NPV are simulated to obtain distribution and confidence intervals (Ye and Tiong 2000; Dowd 1998). However, there are several objections to adjusting both the discount rate and the variables in the NPV method because this amounts to double counting the risk (Myers 1976). Finally, the NPV technique does not allow the decision-maker to account for the indirect and strategic values of an investment that might create future growth opportunities to the existing building stakeholders either through follow-up NZER on other buildings in their portfolio, or acquiring new buildings and sustainably NZER them (Menassa 2011). Therefore, an investment valuation method that overcomes the limitations of the traditional NPV method will allow the decision-maker to effectively quantify the economic value of any NZER and suggest optimal investment strategies when the future is uncertain.

To achieve this objective, principles from modern option pricing theory in finance can be used to augment the traditional NPV method and develop a framework for single or multiphase investment evaluation of NZER (Menassa 2011). This framework allows building stakeholders to account for different scenarios when they encounter a NZER and properly manage the associated uncertainties. Optimal investment strategies can be developed with this framework that allow the stakeholders to postpone investment until the uncertainty is resolved. Table 4 shows the different examples of strategies for NZER investment evaluation.

The recommended strategies can help existing building stakeholders in evaluating investment in NZER and develop optimal investment strategies. In the single-stage investment, the building stakeholders can decide to postpone the investment until uncertainty is resolved. This will result in a higher NPV for the investment even when initially the traditional NPV is positive. For a multistage investment, the staging with the option to abandon provides a better opportunity as opposed to the case where the whole project is dependent on the completion of all stages. Thus, the framework provides a good alternative to the traditional NPV approach when uncertainty is high, and the building stakeholders want to incorporate more strategic investment opportunities in their analysis. Applying this approach, however, requires significant data collection and availability of historical information related to similar NZER. In the subsequent section, option pricing in financial market is presented as a basis to develop an improved framework for single or multiphase investments in NZER and illustrate the benefits of this evaluation approach over the traditional NPV approach for NZER and other similar projects characterized by high and varying uncertainty levels.

## 6 Framework to Evaluate Refurbishment Investments

The suggested strategies in the previous section can help existing building stakeholders in evaluating investments in NZER. This section presents a new approach to project evaluation based on the option pricing theory. This is illustrated in the context of a case study example.

**Table 4** Examples of strategic value to NZER (Adapted from Menassa 2011)

| Option category | Definitions | Application to investments in NZER |
|---|---|---|
| Option to stage | The refurbishment project is divided into stages. At the end of each completed stage, the costs/benefits are evaluated to determine whether subsequent stages can be pursued or not | The refurbishment is divided into stages depending on available budget. First stage might involve installation of PV systems to achieve energy balance. And the second stage could involve major renovations of HVAC equipment |
| Option to abandon | Terminate the refurbishment before completion and dedicate resources to other projects | An exhaustive feasibility study of the existing building condition might indicate that the associated incremental costs to NZER are too high. In this case, the building stakeholders might abandon the project |
| Option to defer | Postpone the refurbishment without jeopardizing the potential benefits | The decision to invest in NZER can be deferred until debt financing becomes available at attractive rates to the owner, or until the tenants can arrange to lease alternative space for the duration of the refurbishment project |
| Option to grow | Provides an initial baseline that allows the stakeholder to pursue follow-on opportunities | The owner of several existing buildings nationwide can decide to invest in one NZER as a pilot project and decide to expand refurbishment work to the remaining of his/her existing building stock once perceived benefits from NZER the pilot project outweigh the costs incurred |
| Option to reduce | Reduce the magnitude of the refurbishment and save costs | Reduce the scope of the NZER endeavor when the costs of the refurbishment exceed the allocated budget. For example, replacing the existing HVAC system might exceed the allocated costs due to lack of information about the existing system and how it is distributed throughout the building. In this case, other scheduled energy-efficient replacements or updates for the building will need to be postponed or forgone all together |
| Option to switch | Developed assets can be switched or redeployed to serve another purpose | Stakeholders of a commercial building might decide to switch the tenant occupancy of certain floors from three to four tenants per floor to only one tenant per floor to be able to satisfy the market needs |

## 6.1 Introduction to Option Pricing Theory

Options on traded assets like stocks give the holder the right (or option) to buy (i.e., call options) or sell (i.e., put options) assets at a prefixed price referred to as the exercise price ($K$) on or before a specified expiration date (Hull 2000; Black and Scholes 1973). The investor has the flexibility to postpone buying or selling the underlying asset (e.g., stock with value $S$) until information about future market conditions become available. In this case, the investor benefits from an increase in the upside potential of the investment whereby he/she commits to buying/selling the stock only if positive payoffs are realized. On the other hand, the downside losses are truncated at the cost of the option (i.e., no negative payoffs) (Fichman et al. 2005; Trigeorgis 1993).

The cost of an option involves taking a position in a replicating portfolio where the investor buys a certain number of shares in the underlying stock and borrows against them the exercise price amount at the risk-free interest rate (Hull 2000; Black and Scholes 1973). The basic assumption underlying this solution is that the change in the stock price follows the geometric Brownian motion (GBM) $\mathrm{d}S/S = (\mu_s - \delta)\mathrm{d}t + \sigma_s \mathrm{d}z$ (Wilmott et al. 2005; Hull 2000). The $(\mu_s - \delta)\mathrm{d}t$ component is the deterministic value of the change in the stock price as a function of the instantaneous growth rate in the price of the stock over time $\mu_s$ and the dividend $\delta$ which is a portion of a company's earnings given to the shareholders (i.e., actual owners of the stock but not the option holders) (Wilmott et al. 2005; McDonald 2005; Trigeorgis 1996). The $\sigma_s \mathrm{d}z$ component represents the stochastic change in the value of the stock as a function of the standard deviation (i.e., volatility) $\sigma_s$, and the increment in the standard Wiener process $\mathrm{d}z$ which is normally distributed with a mean of 0 and a variance that increases linearly with the time interval $\mathrm{d}t$.

A European option can be exercised on the expiration date only, while American options can be exercised any time before expiration. Black and Scholes (Black and Scholes 1973) and (Cox et al. 1979) pioneered the two most used techniques to value European options, namely the analytical method and the numerical binomial tree distribution, respectively. The latter method is a more general approach that can also be used to solve American options (McDonald 2005). This method is illustrated in Fig. 2. Given a specific distribution of the stock price, the binomial tree is constructed with each node of the tree (shown on the left of Fig. 2) representing a possible future realization of the stock price at each time interval. At each period, the stock price can either go up or down with probabilities $p$ and $(1 - p)$, respectively. For example, $S_{\mathrm{uud}}$ shows that $S$ goes up in the first and the second time periods and then down in the third time period. The most important aspect of this method is that the probabilities $p$ and $(1 - p)$ are not the stock's actual probabilities but risk-neural probabilities which remain constant throughout the analysis period. The tree on the right-hand side of Fig. 2 shows how the option value changes with the change in the underlying asset value (i.e., stock). The value of the European option ($F$) is obtained by solving this tree backward starting at the last period and using the risk-free interest rate ($r$) to

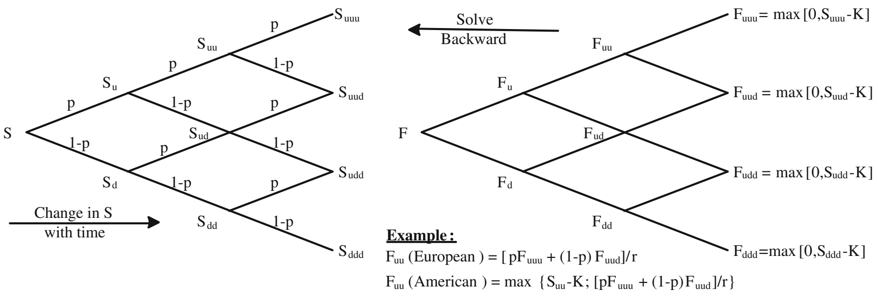


**Fig. 2** Binomial trees for solving European and American call options (Menassa 2011)

discount cash flows to present time. For an American option, this solution needs to be repeated at each time period to determine whether it is optimal to exercise the option earlier or wait until expiration. The option is exercised earlier (say at time period 2) if the exercise payoff ($S_2 - K$) is greater than the option value $F_2$. There is an optimal stock price $S^*$ below which exercising an American option is not optimal, and the value of waiting to exercise that option is higher (McDonald 2005; Dixit and Pindyck 1994).

Perpetual American options are a special case of an American option where the option does not have an expiration date and lives infinitely (McDonald and Siegel 1986). Thus, the investor is continuously evaluating early exercise versus option value at a given period in time and would only exercise when $S$ is greater than $S^*$. Several analytical and numerical solutions are available to evaluate perpetual American options. These solutions form the basis for the framework to evaluate investments in sustainable refurbishment of existing buildings as discussed in the subsequent sections.

## *6.2 Model Assumptions and Parameters*

As discussed earlier, evaluating investments in NZER presents a number of challenges to the decision-maker particularly related to the unexpected future benefits of such an investment. In this framework, these benefits are therefore assumed to represent the underlying asset of the investment which will be denoted by $V$.

These benefits vary with time due to the uncertainties discussed above. For capital or real projects (i.e., not traded in financial markets), a number of researchers have consistently assumed that the change in the value of the underlying asset under uncertainty follows the same lognormal or GBM distribution as that of financial market stocks (Menassa et al. 2009, 2010; Ho and Liu 2003; Schwartz et al. 2000; Trigeorgis 1996; Dixit and Pindyck 1994; and Majd and Pindyck 1987). Therefore, the change in value of the expected benefits $V$ from

NZER is assumed to follow the GBM process given in Eq. (1); $(\mu_v - \delta_v)$ and $\sigma_v$ represent the deterministic and stochastic change in the value of the benefits from the NZER project over time, respectively.

$$\mathrm{d}V/V = (\mu_v - \delta_v)\mathrm{d}t + \sigma_v \mathrm{d}z \tag{1}$$

where $\mu_v$ is the market equilibrium rate of return of the completed NZER project; $\delta_v$ is the rate of return shortfall or opportunity cost of delaying the refurbishment; and $\sigma_v$ is the volatility of future benefits from the NZER project.

The main advantage of this assumption is that it allows the decision-maker the flexibility to align the dynamics of $V$, a non-market traded security, with those of securities traded in the capital market. This assumption simply means that there exists a traded financial asset (e.g., a stock) that has the same risk characteristics (i.e., $\sigma_v \mathrm{d}z$) as $V$. Thus, $\mu_v$ can be obtained similar to that of the traded financial asset by using the capital asset pricing model (CAPM) (French 2003; Mossin 1966; Lintner 1965; Sharpe 1964), which states that that the expected return of an asset equals the risk-free rate of return, $r$, plus a risk premium required by investors due to the correlation of the asset with the market, and accounts for the systematic non-diversifiable risk (Brealey et al. 2010).

Finally, $\delta_v$ is obtained as the difference between $\mu_v$ (i.e., rate of return on traded financial asset) and $\mu_v r$, the rate of return for the real non-financial traded asset. In this case, the non-traded asset is $V$ if the NZER program is implemented (Ho and Liu 2003 and Dixit and Pindyck 1994). Since $V$ is realized only if the NZER is undertaken in the future, then $\delta_v$ represents the opportunity cost of delaying the investment (Dixit and Pindyck 1994).

Given this assumption about $V$, the subsequent section will present a case study example using a new approach to project evaluation based on the option pricing theory.

## 6.3 Case Study

Suppose that an existing building requires $10 million in energy upgrades investment. This includes installing new PV panels, installing high-performance windows and replacing all light fixtures with more efficient LED lights. Preliminary energy analysis for the building indicates that these changes will result in an expected $1.65 million reduction in annual costs ($A$) of operating and maintaining the building for the next 20 years. If the minimum attractive rate of return (MARR) for the building owner is 15 %, then the NPV for this investment will be ($10.33–$10) $0.33 million. Therefore, the building owner should invest immediately in NZER to reduce the costs of operation.

However, if the expected annual operation cost reduction slightly fluctuates to $1.60 million or less due to changes in energy prices and inability to accurately evaluate building performance when the new systems are installed, then the NPV becomes zero or less. Thus, a slight uncertainty about the annual cost savings will change the decision from invest to do not invest even when there are other strategic benefits for having a NZER. If the uncertainty is represented by $\sigma_v$ [see Eq. (1)], and we assume that $r = 0.05$ and $\delta_v = 0.15$ (i.e., corresponds to the building owner's MARR), then the investment decision can be analyzed for the three scenarios in the next sections.

### 6.3.1 Single-Stage Investment: Option to Defer

In the single-stage NZER, the building stakeholders want to commit a fixed-amount $I$ to cover the costs of the sustainable refurbishment. An important aspect of a single-stage investment in NZER for existing buildings is that once the money is committed, the decision cannot be reversed regardless of how the building performs in the future. This presents a challenge to the building stakeholders especially when uncertainty about future benefits $V$ is very high. Simply relying on a positive NPV analysis might be misleading because of the irreversibility of the investment which means that the selected NZER measures (e.g., new renewable energy sources/high-performance mechanical systems) placed inside of the building cannot be simply dismantled and moved to another building if the required energy efficiency and building performance are not achieved. In this type of investment, postponing the decision to invest in NZER effort is beneficial (i.e., can invest at anytime in the future) to allow for some of the uncertainty about NZER benefits to unfold. For example, testing of a given technology at another building might result in more accurate information about its effect on the building refurbishment. Thus, the building stakeholders should evaluate the investment with the time to wait to determine whether this alternative adds value to their investment. This is analogous to the perpetual American option case where the investor decides to wait and exercises the option only when market conditions are favorable. Using this analogy, the exercise price $K$ and stock price $S$ correspond to the total cost of investment $I$ and expected benefits $V$ of the NZER. However, as discussed in the previous section, the option might be more valuable if left unexercised until $S > S*$ even when market conditions are favorable (e.g., $S > K$ for a call option). In this case, the solution of a perpetual American option proposed by McDonald and Siegel (1986) can be used to determine the value and time of the investment in single-stage NZER projects as given in Eq. (2). This value will be the modified NPV for single-refurbishment project, $\mathrm{NPV}_m$. Whenever, $\mathrm{NPV}_m > \mathrm{NPV}$, the building stakeholders should wait.

$$\mathrm{NPV}_m(V,I) = (V^* - I)(V/V^*)^{\beta} \text{when } V \leq V^* \tag{2}$$

$$\mathrm{NPV}_m(V,I) = (V - I) \text{when } V > V^*$$

where $\frac{V^*}{I} = \beta/(\beta - I); \beta = \left(0.5 - \frac{r-\delta_v}{\sigma_v^2}\right) + \sqrt{\left(\frac{\mathrm{r}-\delta_\mathrm{v}}{\sigma_\mathrm{v}^2} - 0.5\right)^2 + 2\mathrm{r}/\sigma_\mathrm{v}^2}$

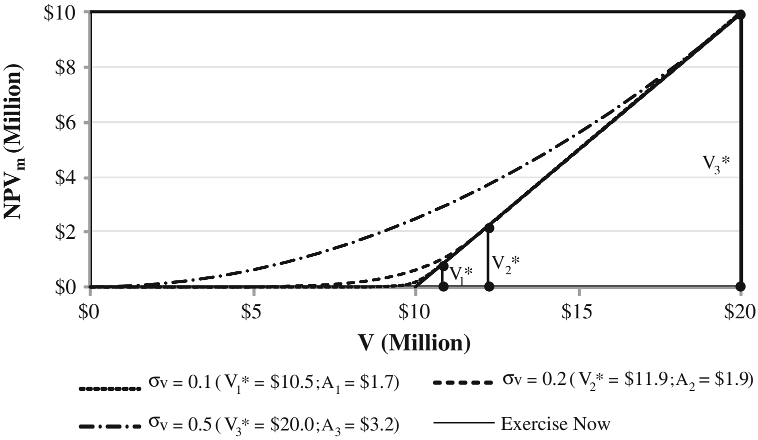


**Fig. 3** Value of single-stage investment under uncertainty (Menassa 2011)

The ratio $V^*/I$ is known as the critical ratio for investment to be undertaken without waiting.

Equation (2) can then be used to determine whether it is optimal to invest at an expected $A = \$1.65$ million when there are different levels of uncertainty. Figure 3 shows the change in value of $\text{NPV}_m$ versus the expected benefits from the investment $V$, for different levels of $\sigma_v$. The results indicate that when the level of uncertainty increases, the value of $V^*$ at which the option to NZER an existing building increases. This in turn implies that investment should only be undertaken in the future when $A$ is greater than initially estimated \$1.65 million even when level of uncertainty is low at $\sigma_v = 0.15$ where the corresponding $A = \$1.7$ million. The solid line indicates the "exercise now" option if all uncertainty is resolved about $V$. It is clear from Fig. 3, than when there is uncertainty, that simply making a decision based on a positive NPV (represented by the "exercise now" line) will ignore additional value of postponing this investment to resolve uncertainty.

### 6.3.2 Multistage Investment with Option to Abandon

In this option, each stage of the investment provides the decision-maker with more information that can be used to decide whether to go ahead with the subsequent stages of the investment or not (McDonald and Siegel 1985). In this case, $I_k$ ($k = 2, 3, \ldots, n$) defines the amount of investment at each stage/time period, $k$, during the NZER process. This provides the decision-makers with strong flexibility to stop or abandon the investment at any stage when it becomes apparent that the expected benefits $V$ are not attainable. If the NPV approach is to be used, then costs incurred at different stages of the investment are discounted to current time and compared to the benefits. This directly assumes that all stages of the NZER will be implemented and does not provide the decision-maker with the flexibility to determine whether to implement the next stage or abandon it. The valuation of this flexibility is similar to that of an exchange option (Villani 2007; McDonald and Siegel 1985; Margrabe 1978). An exchange option, a special case of American option, involves the exchange of one asset, $S_1$ (risky asset), for another asset $S_2$ (can also be risky).

In the case of NZER, at each stage of the investment evaluation, the cost of implementing an additional refurbishment measure, $I_k$, is exchanged for the expected benefits $V$. The decision to invest in the each stage, $k - 1$, is dependent on the present value of exchange option, $\mathrm{NPV}_{\mathrm{mk}}$, at the subsequent stage $k$. If $\mathrm{NPV}_{\mathrm{mk}} \geq I_{k-1}$, then investment in stage $k - 1$ should be undertaken. This will allow for subsequent investments; otherwise, the project should be abandoned, and no further NZER are necessary as their costs exceed the expected additional benefits. This is repeated at each stage to determine whether the investment should be undertaken until all stages are completed or the condition $\mathrm{NPV}_{\mathrm{mk}} < I_{k-1}$ is reached. Using Villani (2007), McDonald and Siegel (1985), and Margrabe (1978), $\mathrm{NPV}_{\mathrm{mk}}$ is calculated using Eq. (3) below by assuming that the investment $I_k$ can alternatively be invested at the risk-free interest rate $r$ between time periods $k - 1$ and $k$:

$$\mathrm{NPV}_{\mathrm{mk}}(V, I_k) = Ve^{-\delta vt}N(d_1) - I_k e^{-rt}N(d_2) \tag{3}$$

where $N(y) = \text{Probability } \{Y \leq \mathrm{y}\} - Y$ is a standard normal random variable;

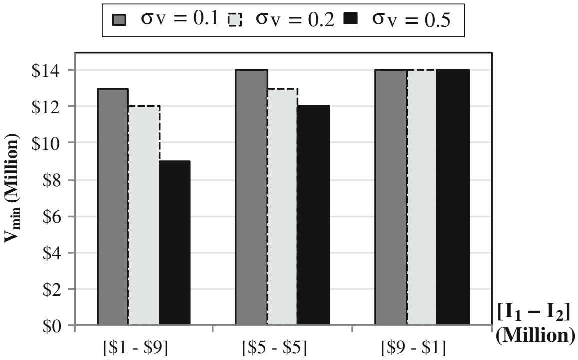
$$d_1 = \left(ln(Ve^{-\delta vt}/I_k e^{-rt}) + \left(r - \delta_v + 0.5\sigma_2^v\right)\right)/\sigma_v\sqrt{t}\,\text{and}\,d_2 = d_1 - \sigma_v\sqrt{t}$$

t is the time period between $k - 1$ and $k$.

This problem is analyzed for the two-stage investment scenario where the \$10 million total investment is divided into two stages. Investment in the first-stage $I_1$ depends on the value of the investment in the subsequent stage $\mathrm{NPV}_{m2}$. Thus, using Eq. (3), the NZER was analyzed to determine the minimum cutoff value of $V$ at which investment should occur for a given initial investment $I_1$. This of course depends on the level of $\sigma_v$. Figure 4 shows the cutoff value $V_{\min}$ for different initial or first-stage investments $I_1$ for three levels of uncertainty $\sigma_v$. Investment $I_2$ will only be undertaken if $V > V_{\min}$.

Two main observations can be made from these results. First, for the same level of initial investment $I_1$, the cutoff value of $V$ decreases with increase in uncertainty $\sigma_v$. This indicates that the higher the uncertainty associated with the investment, the lower the expected value of benefits $V$ at which the NZER should be abandoned. Second, the higher the initial stage investment $I_1$, the higher is the cutoff value $V$ for the same level of uncertainty. This indicates that when the initial investment is high, the expected benefits from subsequent investments should be high because most of the uncertainty surrounding this value would have been resolved during the initial stage of investment. That is a higher initial stage of the investment indicates higher confidence by the decision-maker about the expected value of their project.

**Fig. 4** Two-stage investment with option to abandon $V_{min}$ to implement stage 1 (Menassa 2011)



### 6.3.3 Multistage Investment with Option to Stage

In this scenario, all stages of the investment need to be implemented before the building can be operated and occupied again. However, because of budgeting, financing, and technical constraints, the decision-maker wishes to stage the investment over a period of time. This might be the case where the building requires major refurbishment that forces all the existing tenants of the building to move to an alternative accommodation during the refurbishment process. The total investment expenditure is still $I$; however, the expenditures at any specific stage cannot exceed a preset rate $i$. Thus, if the NZER is to be implemented in $n$ stages, then $I \leq \sum_{k=1}^{n} i_k$ and $i_k \leq i$. This type of the investment allows the decision-maker to stage the investment and stop or abandon the investment at any given stage (Majd and Pindyck 1987) and (Espinoza and Luccioni 2007). However, if the project is abandoned after several stages of investing, then the building owners will not be able to operate the building because not all the refurbishment measures are in place. This is a major difference between this scenario and that presented in the previous section. Majd and Pindyck (1987) developed the partial differential equations along with the boundary conditions for this type of investments assuming a perpetual American option with time to build. A discussion of the numerical solution can be found in both (Dixit and Pindyck 1994) and (Majd and Pindyck 1987). For the purpose of this problem, the approximate solution proposed by Espinoza and Luccioni (2007) is adopted to determine the value of this investment at each stage $NPV_m$. The assumptions underlying this approximate solution are as follows:

1. $I_0$ is the present value of investment cost assuming that investment is continuously made over a period of time $T = I/i$ at a rate that does not exceed $i$. The value of this investment cost at time $k = 0$ and $k = m$ is given in Eqs. (4) and (5), respectively:

$$I_0 = \int_0^T ie^{-\mathrm{rt}}\mathrm{d}t = \left(1 - e^{-\mathrm{rT}}\right)i/r \tag{4}$$

$$I_m = \int_m^T ie^{-\mathrm{rt}}\mathrm{d}t = \left(e^{-\mathrm{rm}} - e^{-\mathrm{rT}}\right)i/r \tag{5}$$

2. $V_0$ is the present value of expected benefits from the investment that is made continuously over $T$ until the whole NZER is completed. The expected value of benefits from this investment at time $k = 0$ and $k = m$ is given in Eqs. (6) and (7), respectively:

$$V_0 = \left(Ve^{\mu\mathrm{vrT}}\right)e^{-\mu\mathrm{vT}} = Ve^{-\delta v}T \tag{6}$$

$$V_m = \left(Ve^{\mu\mathrm{vr}(T-m)}\right)e^{-\mu v(T-m)} = Ve^{-\delta v(T-m)} \tag{7}$$

3. Thus, the value of this multistage investment in NZER of a given building at time $t = 0$ is given in Eq. (8) below:

$$\mathrm{NPV}_m(V,I) = (V^* - I_0)(V_0/V^*)^{\beta}\text{when } \mathrm{V}_0 \leq \mathrm{V}* \tag{8}$$

$$\mathrm{NPV}_m(V,I) = (V_0 - I_0)\,\text{when} V_0 > V^*$$

$$\frac{V^*}{I_0} = \frac{\beta}{\beta - 1};\beta = \left(0.5 - \frac{r - \delta_v}{\sigma_v^2}\right) + \sqrt{\left(\frac{r - \delta_v}{\sigma_v^2} - 0.5\right)^2 + 2r/\sigma_v^2}$$

It is important to note that Eq. (8) has a similar structure to that of Eq. (2) because they are both solutions to a perpetual American option with time to build. The only difference in this case is that the investment expenditure is spread over a period of time $T = I/i$. The project value at each stage of the investment can be assessed based on the remaining investment $I_k$ at that stage by simply replacing $V_0$ and $I_0$ in Eq. (8) by $V_m$ and $I_{\mathrm{m}}$, respectively.

Finally, the investment problem is analyzed for the case where the decision-maker decides to spread the $10-million investment over a period of time $T$ with a maximum investment per time period $i$. The building will only be operational after all of the planned refurbishment are completed over the period of time $T$. Figure 5 shows the cutoff values of $V*$ at each time period for the case where the investment is divided into $T = 2$ years and $T = 5$ years, respectively.

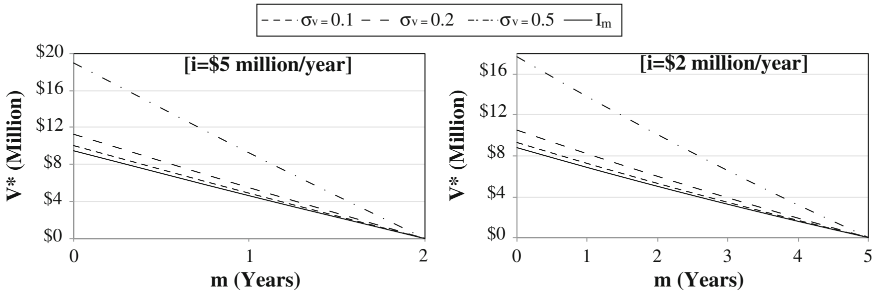


**Fig. 5** Multistage investment without option to abandon (Menassa 2011)

These results indicate that $V^*$ decreases with the decrease in time period for the same level of uncertainty, indicating that most of the project has been completed in prior periods and uncertainty does not affect the value of the refurbishment project toward the end of the investment period. On the other hand, $V^*$ increases with the increase in uncertainty for a specific time period, indicating that investment decision is more stringent with higher uncertainty at a given time period. Finally, $V^*$ in the left-hand side of Fig. 5 is greater than $V_{\min}$ in Fig. 4 for ($5–$5) million cases, indicating that staging the investment with the option to abandon provides more flexibility in terms of the value of expected benefits because the building stakeholders can abandon the NZER project and still benefit from the refurbishments made in the previous stages. The option to stage alone requires a higher expected value of benefits for the investment to be undertaken under uncertainty because the stakeholders will not be able to use the building unless all refurbishments are completed.

## 7 Conclusion

As discussed in this chapter, high uncertainty characterizes the NZER investment and creates financial barriers that affect the investment decisions of the building stakeholders. These uncertainties are obstacles that remain in the way of convincing large institutions to invest in energy efficiency financing projects such as NZEB and NZER. In order to make financing companies and others see the business value of NZEB or NZER, strategies to manage these uncertainties need to be developed. After identifying the uncertainties associated with NZER, the next logical step is to develop a financial model that will help building stakeholders manage these uncertainties. By this way, the technical challenges that characterize NZER will be addressed. Another important challenge to address is improving the benchmarks about the actual performance of NZER and its systems after the design phase. In this chapter, a framework to evaluate NZER investments is developed to account for three main scenarios encountered in refurbishment projects, including single-stage investment, multistage investment with option to abandon, and multistage investment with option to stage. The proposed methodology draws from financial option pricing method and uses the CAPM method to estimate the parameters for the model. An important aspect of this framework is that the building stakeholders do not have to estimate parameters beyond those that are typically known to them, including the MARR and risk-free interest year. In addition, the case study example illustrates the possible cases where this framework could be applied and the benefits to decision-maker beyond the traditional NPV approach that would typically be used to evaluate this type of investment. The proposed framework can help existing building stakeholders in evaluating investment in sustainable building refurbishments and developing optimal investment strategies. In the single-stage investment, the building stakeholders can decide to postpone the investment until uncertainty is resolved. This will result in a higher $\mathrm{NPV}_m$ for the investment even when initially the traditional NPV is positive. For the multistage investment, the staging with the option to abandon provides a better opportunity as opposed to the case where the whole project is contingent on the completion of all stages. Thus, the framework provides a good alternative to the NPV approach when uncertainty is high, and the building stakeholders want to incorporate more strategic investment opportunities in their analysis. This additional knowledge would reduce uncertainty and make access to the investment and debt capital necessary to refurbish the buildings more readily available. If the uncertainties are satisfactorily managed and the benefits outweigh the costs of a NZER building, stakeholders might be more interested in refurbishing their building portfolios. Given the special case NZER and its potential, the industry and research community should work together to be able to unlock the full potential of the NZER around the world.

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## References

Azar E, Menassa CC (2012a) A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. Energ Build 55:841–853. Available at: http://dx.doi.org/10.1016/j.enbuild.2012.10.002. Accessed 23 Nov 2012

Azar E, Menassa CC (2012b) Agent-based modeling of occupants and their impact on energy use in commercial buildings. J Comput Civ Eng 26:506–518

Baden S et al (2006) Hurdling financial barriers to low energy buildings: experiences from the USA and Europe on financial incentives and monetizing building energy savings in private investment decisions. In: Proceedings of 2006 ACEEE summer study on energy efficiency in buildings. American Council for an Energy Efficient Economy, Washington DC. Available at: http://www.fsec.ucf.edu/en/publications/pdf/FSEC-PF-396-06.pdf. Accessed 2 July 2012

Baetens R et al (2012) Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation. Appl Energ 96:74–83. Available at: http://dx.doi.org/10.1016/j.apenergy.2011.12.098. Accessed 3 April 2012

Black F, Scholes M (1973) The pricing of options and corporate liabilities. J Polit Econ 81(3):637–654

Brealey R, Stewart M, Franklin A (2010) Principles of corporate finance + S&P Market Insight, 10th edn. McGraw-Hill/Irwin, New York City

Brown MA (2008) Market failures and barriers as a basis for clean energy policies. Energ Policy 29(2001):1197–1207

Building Performance Institute Europe (BPIE) (2010) Financing Energy Efficiency in Buildings, Brussels

Cattano C, Valdes-Vasquez R, Klotz L (2012) Barriers to the delivery of building renovations for improved energy performance: a literature review and case study. ICSDC 2011 Integrating Sustainability Practices in the Construction Industry ASCE, pp 203–210

Chen K, Reklev S (2012) China keen to avoid CO2 rollercoaster ride. Available at: http://in.reuters.com/article/2012/07/20/us-china-carbon-trade-idINBRE86J0BA20120720. Accessed 22 July 2012

Condamin L, Louisot J-P, Patrick N (2006) Risk quantification: management, diagnosis and hedging. John Wiley, Chichester West Sussex England; Hoboken NJ

Copland T, Tufano P (2004) A real world way to manage real options. Harvard Bus Rev 82(3):1–12

Cox C, Ross S, Rubinstein M (1979) Option pricing: a simplified approach. J Financ Econ 7:229–263

Danfoss (2010) Industry research and report. High-performance buildings, Available at: http://envisioneering.danfoss.com/NR/rdonlyres/DB9475EA-28C4-4684-BEE6-E03901F2BB66/0/HighPerformanceNetZeroReport_October2010.pdf. Accessed 13 Nov 2012

Dell'Isola AJ, Kirk SJ (2003) Life cycle costing for facilities: economic analysis for owners and professionals in planning, programming, and real estate development: designing, specifying, and construction, maintenance, operations, and procurement. Robert s Means Co

Desogus G et al (2013) Economic efficiency of social housing thermal upgrade in Mediterranean climate. Energ Build 57:354–360. Available at: http://linkinghub.elsevier.com/retrieve/pii/S037877881200607X. Accessed 11 Jan 2013

Detserclaes P (2007) Financing energy efficient homes. International Energy Agency, Paris

De Wit S, Augenbroe G (2002) Analysis of uncertainty in building design evaluations and its implications. Energ Build 34(9):951–958. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778802000701. Accessed 10 Oct 2012

Dixit A, Pindyck RS (1994) Investment under uncertainty. Princeton University Press, New Jersey

Dowd K (1998) Value at risk: the new science of risk management. Wiley, New York

Elkinton MR, McGowan JG, Manwell JF (2009) Wind power systems for zero net energy housing in the United States. Renew Energ 34(5):1270–1278. Available at: http://dx.doi.org/10.1016/j.renene.2008.10.007. Accessed 17 April 2012

Environmental Protection Agency (EPA) (2009) Acid rain program. Available at: http://www.epa.gov/airmarkets/progsregs/arp/index.html. Accessed 20 July 2012

Espinoza RD, Luccioni L (2007) An approximate solution for perpetual American option with time to build: the value of environmental remediation investment projects. Int J Bus 12(3):291–300

Fichman R, Keil M, Tiwana A (2005) Beyond valuation: option thinking in IT project management. California Manage Rev 47(2):74–96

Fong KF, Lee CK (2012) Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong. Appl Energ 93:686–694. Available at: http://dx.doi.org/10.1016/j.apenergy.2012.01.006. Accessed 3 April 2012

French CW (2003) The Treynor capital asset pricing model. J Investment Manage 1(2):60–72

Fuller MC (2008) Enabling investments in energy efficiency. California Institute for Energy and Environment, California

Fuller SK, Petersen SR (1995) Life-cycle costing manual for the federal energy management program. US Department of Commerce, Washington, DC

Glover B (2011) Road to net zero (Presentation) (No. NREL/PR-6A42-51124). National Renewable Energy Laboratory (NREL), Golden, CO

Gohardani N, Björk F (2012) Sustainable refurbishment in building technology. Smart Sustain Built Environ 1(3):241–252

Gray M, Zarnikau J (2011) Chapter 9—getting to zero: green building and net zero energy homes, energy, sustainability and the environment, Butterworth-Heinemann, Boston, pp 231–271. Available at: http://dx.doi.org/10.1016/B978-0-12-385136-9.10009-9. Accessed 21 June 2012

Herroelen W, Leus R (2005) Project scheduling under uncertainty: Survey and research potentials. Eur J Oper Res 165(2):289–306. Available at: http://dx.doi.org/10.1016/j.ejor.2004.04.002. Accessed 29 Jan 2013

Hirsch JJ and Associates (2009) EnergyPlus input/output reference: the encyclopedic reference to EnergyPlus Input and Output, Urbana, IL

Ho SP, Liu LY (2003) How to evaluate and invest in emerging A/E/C technologies under uncertainty. J Constr Eng Manage 128(1):16–24

Hull J (2000) Options, futures, and other derivative securities, 4th edn. Prentice Hall, New Jersey

Kadam S (2001) Zero net energy buildings: are they economically feasible? 10.391 J Sustain Energ

Kohler N (1999) The relevance of green building challenge: an observer's perspective. Build Res Inf 27(4–5):309–320

Kropp R (2012) Why are institutional investors ignoring climate change risk? http://www.greenbiz.com/blog/2012/06/14/why-are-institutional-investors-ignoring-climate-change-risk?page=full. Accessed 15 Sept 2012

LaSalle J (2011) A landmark sustainability program for the empire state building, pp 1–12

Leckner M, Zmeureanu R (2011) Life cycle cost and energy analysis of a net zero energy house with solar combisystem. Appl Energ 88(1):232–241. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261910003004. Accessed 8 Mar 2012

Lintner J (1965) The valuation of risk assets and selection of risky investments in stock portfolios and capital budgets. Rev Econ Stat 47(1):13–37

Luehrman T (1998) Strategy as a portfolio of real options. Harvard Bus Rev 76(5):89–99

Majd S, Pindyck RS (1987) Time to build, option value, and investment decisions. J Financ Econ 18:7–27

Margrabe W (1978) The value of an exchange option to exchange one asset for another. J Financ 33(1):177–186

Marszal AJ et al (2011) Zero energy building: a review of definitions and calculation methodologies. Energ Build 43(4):971–979. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810004639. Accessed 1 Mar 2012

Marszal AJ et al (2012) On-site or off-site renewable energy supply options? Life cycle cost analysis of a net zero energy building in Denmark. Renew Energ 44:154–165. Available at: http://dx.doi.org/10.1016/j.renene.2012.01.079. Accessed 12 Mar 2012

Masoso OT, Grobler LJ (2010) The dark side of occupants' behaviour on building energy use. Energ Build 42(2):173–177. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778809001893. Accessed 25 July 2012

Mavrotas G et al (2003) Energy planning in buildings under uncertainty in fuel costs: the case of a hotel unit in Greece. Energ Convers Manage 44(8):1303–1321. Available at: http://dx.doi.org/10.1016/S0196-8904(02)00119-X. Accessed 5 July 2012

McCabe M (2011) High-performance buildings—value, messaging, financial and policy mechanisms, Richland. Available at: http://www.pnl.gov/main/publications/external/technical_reports/pnnl-20176.pdf. Accessed 29 Jan 2013

McDonald R (2005) Derivatives markets, 2nd edn. Addison Wesley, Boston

McDonald R, Siegel D (1985) Investment and valuation of firms when there is an option to shut down. Int Econ Rev 26(2):331–349

McDonald R, Siegel D (1986) The value of waiting to invest. Q J Econ 101(4):707–727

Mckinsey and Company (2008) The case for investing in energy productivity. Available at: http://www.mckinsey.com/mgi/publications. Accessed 1 Aug 2012

Menassa CC (2011) Evaluating sustainable retrofits in existing buildings under uncertainty. Energ Build 43(12):3576–3583. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778811004324. Accessed 9 Mar 2012

Menassa C, Peña Mora F, Pearson N (2009) An option pricing model to evaluate ADR investments in AEC projects. J Constr Eng Manage 135(3):156–168

Menassa C, Peña Mora F, Pearson N (2010) A study of real options with exogenous competitive entry to analyze ADR investments in AEC projects. J Constr Eng Manage 136(3):377–390

Milner M (2008) Q and A: emissions trading. Available at: http://www.guardian.co.uk/environment/2008/jan/04/emissionstrading.carbonemissions. Accessed 2 July 2012

Mossin J (1966) Equilibrium in a capital market. Econometrica 34(4):768–783

Musall E et al (2010) Net zero energy solar buildings: an overview and analysis on worldwide building projects. In: EuroSun Conference, Graz, Austria. Available at: http://w5.uni-wuppertal.de/Aktuell/Veroeffentlichungen/p_pics/EuroSunConferenceGraz2010WorldWideOverview_paper_100722.pdf. Accessed 8 Aug 2012

Myers SC (1976) Modern developments in Financial Management, Praeger Publishers, New York

National Institute of Standards and Technology (NIST) (2011) Net-zero energy, high-performance buildings program. Available at: http://www.nist.gov/el/building_environment/heattrans/netzero.cfm. Accessed 22 Aug 2012

Parker DS (2009) Very low energy homes in the United States: Perspectives on performance from measured data. Energ Build 41(5):512–520. Available at: http://dx.doi.org/10.1016/j.enbuild.2008.11.017. Accessed 17 April 2012

Peschiera G, Taylor JE, Siegel JA (2010) Response–relapse patterns of building occupant electricity consumption following exposure to personal, contextualized and occupant peer network utilization data. Energ Build 42(8):1329–1336. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810000691. Accessed 6 Aug 2012

Pless S, Torcellini P, Crawley D (2009) Getting to net zero. ASHRAE J 51(9):18–25

Poel B, Van Cruchten G, Balaras CA (2007) Energy performance assessment of existing dwellings. Energ Build 39(4):393–403. Available at: http://dx.doi.org/10.1016/j.enbuild.2006.08.008. Accessed 10 Mar 2012

Robert A, Kummert M (2012) Designing net-zero energy buildings for the future climate, not for the past. Build Environ 55:150–158. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132311004306. Accessed 17 April 2012

Rushing A, Lippiatt B (2009) Energy Price indices and discount factors for life-cycle cost analysis, NIST Interagency/Internal Report (NISTIR)-85-3273-24

Sanchez M et al (2007) Space heaters, computers, cell phone chargers: how plugged in are commercial buildings?". In; Proceedings of ACEEE Summer study on energy efficiency in buildings, less is more, en route to zero energy buildings

Schwartz ES et al (2000) Evaluating research and development investments, project flexibility, agency, and competition—new development in the theory and application of real options. Oxford University Press, New York

Sharpe WF (1964) Capital asset prices: a theory of market equilibrium under conditions of risk. J Financ 19(3):425–442

Sisson W et al (2007) Energy efficiency in buildings. World Business Council for Sustainable Development, Conches-Geneva

Soebarto VI, Williamson TJ (2001) Multi-criteria assessment of building performance: theory and implementation. Build Environ 36(6):681–690. Available at: http://dx.doi.org/10.1016/S0360-1323(00)00068-8. Accessed 20 Nov 2012

Stadler M et al (2009) Optimal technology investment and operation in zero-net-energy buildings with demand response. Available at: http://escholarship.org/uc/item/9334229b.pdf. Accessed 28 Jan 2013

Trigeorgis L (1993) Real options and interactions with financial flexibility. Financ Manage 22(3):202–224

Trigeorgis L (1996) Real Options: managerial flexibility and strategy in resource allocation. MIT Press, Cambridge

Turner Construction (2010) Green building market barometer. Available at:http://www.turnerconstruction.com/content/files/Green%20Market%20Barometer%202010.pdf .Accessed 29 July 2012

U.S. Energy Information Administration (EIA) (2011) International Energy Outlook 2011

U.S. Department of Energy (DOE) (2012) High performance buildings database. Available at: http://eere.buildinggreen.com. Accessed 30 July 2012

U.S. Energy Information Administration (EIA) (2012) Annual Energy Outlook 2012

United Nations Environment Program (2007) Buildings can play a key role in combating climate change. SBCI-Sustainable Construction and Building Initiative. Available at: http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=502&ArticleID=5545&l=en. Accessed 20 Aug 2012

Verbruggen A, Marchohi MA, Janssens B (2011) The anatomy of investing in energy efficient buildings. Energ Build 43(4):905–914. Available at: http://dx.doi.org/10.1016/j.enbuild.2010.12.011. Accessed 15 June 2012

Villani G (2007) A Monte Carlo approach to value exchange options using a single stochastic factor. Department of Mathematics and Statistics, University of Foggia, Italy

Wang L, Gwilliam J, Jones P (2009) Case study of zero energy house design in UK. Energ Build 41(11):1215–1222. Available at: http://dx.doi.org/10.1016/j.enbuild.2009.07.001. Accessed 17 Mar 2012

Wang L, Mathew P, Pang X (2012) Uncertainties in energy consumption introduced by building operations and weather for a medium-size office building. Energ Build 53:152–158. Available at: http://dx.doi.org/10.1016/j.enbuild.2012.06.017. Accessed 26 Nov 2012

Webb T (2010) Copenhagen dampens banks' green commitment. Available at: http://www.guardian.co.uk/environment/2010/jan/24/carbon-emissions-green-copenhagen-banks. Accessed 10 July 2012

Webber CA et al (2007) After-hours power status of office equipment in the USA. J Energ 31(14):2823–2838

Wilmott P, Howison S, Dewynne J (2005) The mathematics of financial derivatives. Cambridge University Press, USA

Ye S, Tiong RLK (2000) NPV at risk method in infrastructure project investment evaluation. J Constr Eng Manage, ASCE 126(3):227–233

Yudelson J (2010) Greening existing buildings, McGraw-Hill, New York. Available at: http://www.worldcat.org/title/greening-existing-buildings/oclc/616863128. Accessed 23 July 2012

# Energy Performance of Buildings: A Comparison of Standard Assessment Methods

**R. Pernetti, L. Magnani and A. Magrini**

**Abstract** Regarding energy performance assessment of existing building, the European Standards EN ISO 13790 and EN 15316, adopted at national level in Italy by Technical Standards UNI/TS 11300 (part 1 and 2), allow different approaches and simplification levels for defining some representative input parameters determining uncertainties in the results. Therefore, the reliability of calculated energy performance could be affected. The analysis has been supported applying a set of refurbishment actions on some representative cases of common national residential building stock, comparing the energy performance obtained with different calculation methods allowed by National Technical Standards and laws. The results show how these differences can lead to uncertainties about the class definition.

## Nomenclature

| | |
|---|---|
| $A_f$ | Internal floor area of the conditioned space [m$^2$] |
| $b_{tr,x}$ | Temperature correction factor [−] |
| $EP_{\mathrm{gl}}$ | Global energy performance index ($EP_H + EP_w$) [kWh/(m$^2$ year)] |
| $EP_H$ | Energy performance index in the heating season [kWh/(m$^2$ year)] |
| $EP_{H,\ \mathrm{env}}$ | Energy performance index in the heating season for building envelope [kWh/(m$^2$ year)] |
| $EP_{H,\ L(2010)}$ | Energy performance index target for the new construction from 2010 |
| $EP_w$ | Energy performance index for domestic hot water production [kWh/(m$^2$ year)] |
| $Q_{l,e}$ | Emission subsystem thermal losses [MJ] |
| $\mathrm{Q}_{H,\ \mathrm{gn}}$ | Total heat gains for the heating mode [MJ] |
| $Q_{H,\ \mathrm{ht}}$ | Total heat transfer for the heating mode [MJ] |
| $Q_{H,\ \mathrm{nd}}$ | Building energy need for continuous heating [MJ] |

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| | |
|---|---|
| $Q_{\mathrm{int}}$ | Sum of internal heat gains [MJ] |
| $Q_{\mathrm{sol}}$ | Sum of solar heat gains over the given period [MJ] |
| $Q_{\mathrm{tr}}$ | Total heat transfer by transmission [MJ] |
| $Q_{\mathrm{ve}}$ | Total heat transfer by ventilation [MJ] |
| $U$ | Thermal transmittance [W/(m$^2$ K)] |
| $U_{\mathrm{g\_floor}}$ | Thermal transmittance of the ground floor [W/(m$^2$ K)] |
| $U_{\mathrm{u\_floor}}$ | Thermal transmittance of the upper floor [W/(m$^2$ K)] |
| $U_{\mathrm{wall}}$ | Thermal transmittance of wall [W/(m$^2$ K)] |
| $U_{\mathrm{window}}$ | Thermal transmittance of window [W/(m$^2$ K)] |
| $\phi_{\mathrm{int}}$ | Heat gains from internal heat sources [W] |
| $\eta_{\mathrm{e}}$ | Emission subsystem efficiency [−] |
| $\eta_{H,\mathrm{gn}}$ | Gain utilization factor [-] |
| $\eta_{\gamma\lambda}$ | Heating system global efficiency [−]. |

## 1 Introduction: EPBD in Europe—State of the Art and National Implementation (The Case of Italy)

Despite the prompt implementation commitment, the member states adopted the Directive 2002/91/EC at various times; therefore, even if there was a common frame, the development at national level is quite fragmented. In fact, the member states decided their own strategy since a series of details, such as minimum requirements for the energy regulation and schemes for calculation methods, were not completely expounded in EPBD (Garcia Casals, 2006). For example, the French transposition of EPBD provides for compulsory requirements for new buildings which are the overall energy demand and, in case of renovation, minimum performance for construction elements, according to the surface, while Germany established some mandatory energetic upgrades for existing buildings to reduce the energy demand. Furthermore, strict minimum requirements were established in case of refurbishment, both on the building components and on the energy class: the target is usually class C, the minimum requirement for major renovation is class B in Austria and Greece, which in case of new buildings defined a detailed series of design requirements (Featuring Country Reports 2010). The common aim for the member states is to estimate the potential energy saving and to find out suitable strategies for the refurbishment of national residential building stock according to the construction typology (Balaras et al. 2007; Poel et al. 2007).

In Italy, European Directive EPBD 2002/91/EC has been implemented with delay, because Decree n. 192/2005 and n. 311/2006 did not indicate an assessment procedure to evaluate the energy performance. Only on 2009, the Decree n. 59 indicated Technical Specification UNI/TS 11300 Part 1 and 2 as the reference for building energy labelling, in acknowledgement of the European Standard EN ISO 13790 for the envelope and EN 15316 for the heating system.

Furthermore, the Decree of the Economical Development Ministry 29th June 2009 “National Guidelines for buildings energy certification” reports the commitments for energy labelling. National guidelines establish the energy label to be determined according to the global performance index (EPgl) which, for the time, takes into account the energy needs for heating and domestic hot water production.

In order to draw up an energy performance certificate, the asset rating provided by UNI/TS 11300 has to be applied; therefore, actual data for the building and standard-use data set have to be collected. In case of existing buildings, finding out all the requested data could be complicated; therefore, Italian procedures allow simplified kind of calculation based on parameters from tables or standard data sets.

Some examples of asset rating application were reported in Ballarini and Corrado 2009, which analysed the differences between calculated and measured energy rating, to underline the effect of user behaviour and weather conditions; furthermore, correlations among input and output data were found out to characterize the energy behaviour of some typical construction of Italian residential building stock.

Some other comparison among different methodologies for asset rating applying Italian procedures were presented in Magrini et al. 2010: the results are expounded in terms of global performance index of the analysed building.

Furthermore, different values of energy performance could be obtained applying various simulation tools (Tronchin and Fabbri 2010) and according to the accuracy of the data input: some parameters are more significant than others, and they influence the results of the simulations.

## 2 Aim of the Work

In the past recent years, an extensive literature has been devoted to the subject of energy performance of buildings with reference to energy labelling (Wang et al. 2012). Some papers investigated differences between standard and measured energy rating calculation methods, to underline the effect of user behaviour and weather conditions (Corrado and Mechri 2009) or problems related to the calculation of the utilization factor in national application of EN ISO 13790 (Fokaides et al. 2011). Some approaches dealt with energy optimization in buildings, by the application of multi-objective optimization techniques, or by incorporating financial aspects (Jokisalo and Kurnitski 2007; Diakaki et al. 2008).

The European Standard EN ISO 13790 proposes calculation methods for the design and the evaluation of thermal and energy performances of buildings, with the possibility to apply detailed or simple dynamic hourly methods, but also quasi-steady-state methods, on monthly or seasonal base. In particular, it also provides procedures for the application at national or regional level for the energy performance certificate issue. In this case, dynamic or detailed calculation methodologies would be too labour-intensive for the purpose of the energy certificate.

In fact, especially in case of old existing buildings, the accurate collection of required input data could be difficult. To this aim, in order to simplify the evaluation, the International Standard offers the possibility to decide at national or regional level which kind of calculation methodology to adopt, including some simplifications and the use of some reference catalogues with input values, suitable for local applications and depending on the type of building and on the purpose of the assessment.

This possibility has been implemented in Italy in national guidelines which in article 4 establish, according to some building features such as dimensions, use, existing or new construction, the possibility of applying different methodologies to determine the energy performance indices. For new buildings and for completely refurbished ones, it is always required to apply assessment methods reported in UNI/TS 11300 (part 1 and part 2), which are the most detailed ones established by Italian laws, but also in this case, the technical standard allows us to use different ways of calculation, such as analytical or simplified ones, and to derive parameters respectively from tables or on the basis of more accurate evaluations.

As the new directive prescribes the development of guidelines for optimizing the relation between cost and energy performances, the choice of the calculation method assumes a particular importance: a kind of intervention could be wrongly considered more efficient than another one, if the parameters or the calculation are not univocal.

Since the existing buildings refurbishment represents a real potential of energy saving, the influence of the method on the energy performance evaluation of a renovated building has been analysed by means of the calculations of a refurbishment action for two typical constructions which characterize the Italian residential building stock of the 60’–80’.

Then a series of interventions have been simulated and compared in order to find, starting from a low-performance construction, how it is possible to approach the definition target of nearly zero-energy building. The analyses represent an example of an operating procedure for the evaluation of building energy performance in case of renewal. Moreover, for the case studies, the effectiveness of a set of energy conservation measurements has been evaluated; in order to obtain general reference strategies for refurbishment, further investigation have to be developed with different construction typologies and building features. At European level, for evaluating the cost optimal level of refurbishment actions, member states have to define some reference buildings according to their use, typology and construction feature (Corgnati et al. 2013).

On the other hand, by testing the refurbishment actions using different assessment methods, it is possible to highlight some uncertainties in the definition of the energy performance of the constructions and in the determination of the energy class, which is the indicator chosen by the European Directive in order to provide an objective parameter to evaluate the energy efficiency.

In particular, the aim of 2002/91/EC Directive, confirmed by the 2010/31/EU, was to introduce energy certification to guarantee a future uniformity in the

European building stock: the uniformity of results seems to be affected by uncertainties since the standards (such as EN ISO 13790 and UNI/TS 11300) leave many possibilities for the definition of input data and assessment methodologies. This is a critical aspect if an asset calculation method is expected to give a general indicator, useful to compare energy performance of different buildings.

## 3 Calculation Method (EN ISO 13790 and UNI/TS 11300)

The UNI EN ISO 13790 standard (Energy performance of buildings—Calculation of energy use for spaces—heating and cooling) provides a series of calculation methods for the design and evaluation of thermal and energy performances of buildings and can be used for the following purposes:

1. evaluating compliance with regulations and laws;
2. comparing the energy performance of various design alternatives for a building;
3. energy certification of buildings and
4. assessing the effect of possible refurbishment measures on existing buildings.

There are two basic types of methods:

- quasi-steady-state methods, calculating the heat balance over one month or the whole season, taking into account dynamic effects by the simplified determination of a gain utilization factor;
- dynamic methods, calculating the heat balance over 1 h and taking into account the heat stored and released from the mass of the building in a detailed way.

The mandatory method has to be defined at national level.

In Italy, the assessment method adopted by UNI/TS 11300 is a quasi-steady-state balance on a monthly basis, and the length of the heating season is provided by the Italian law according to the climatic zone. As prescribed by the European standard, for each calculation step, the building energy need for space heating, $Q_{H,\text{nd}}$, in conditions of continuous heating, is calculated by

$$Q_{H,\text{nd}} = Q_{H,\text{ht}} - h_{H,\text{gn}} Q_{H,\text{gn}} \tag{1}$$

where

- $Q_{H,\text{nd}}$ is the building energy need for continuous heating, assumed to be greater than or equal to 0 [MJ];
- $Q_{H,\text{ht}}$ is the total heat transfer for the heating mode [MJ];
- $Q_{H,\text{gn}}$ gives the total heat gains for the heating mode [MJ];
- $\eta_{H,\text{gn}}$ is the dimensionless gain utilization factor

and the total heat transfer, $Q_{H,\text{ht}}$, is given by:

$$Q_{\text{ht}} = Q_{\text{tr}} + Q_{\text{ve}} \tag{2}$$

where $Q_{\mathrm{tr}}$ is the total heat transfer by transmission and $Q_{\mathrm{ve}}$ is the total heat transfer by ventilation.

As established by the UNI EN ISO 13790, for the monthly and seasonal methods, the total heat transfer by transmission, $Q_{\mathrm{tr}}$, is calculated for each month or season and for each zone and it depends on the overall heat transfer coefficient by transmission and on the monthly mean external and internal temperatures, defined at national level.

Moreover, for natural ventilation in residential buildings, $Q_{\mathrm{ve}}$ is defined at national level by UNI/TS 11300 part 1 and calculated using the ventilation rate default value of 0.3 vol/h.

The total heat gain, $Q_{H,\ \mathrm{gn}}$, of the building zone for a given calculation step are calculated using

$$Q_{\mathrm{gn}} = Q_{\mathrm{int}} + Q_{\mathrm{sol}} \tag{3}$$

where $Q_{\mathrm{int}}$ is the sum of internal heat gains and $Q_{\mathrm{sol}}$ is the sum of solar heat gains over the given period.

The heat gains from internal heat sources are determined for residential buildings (national indications) as

$$\phi_{\mathrm{int}} = 5.294 A_f - 0.01557 A_f^2 \cdots [\mathrm{W}] \tag{4}$$

where $A_f$ [m$^2$] is the internal floor area of the conditioned space.

The energy performance calculation presented in the chapter is carried out by a simulation tool which implements the UNI/TS 11300.

Once determined the building energy need for space heating, $Q_{H,\ \mathrm{nd}}$, it is necessary to calculate thermal losses and electrical consumption of each heating subsystem:

- Emission subsystem;
- Control subsystem;
- Distribution subsystem;
- Storage subsystem and
- Generation subsystem.

It is possible to determine thermal losses for each subsystem by virtue of simplified or detailed procedures. Simplified methods provide for obtaining efficiencies from conventional values depending on subsystem typology, while detailed procedures allow us to calculate distribution losses through the length and the thermal transmittance of each pipe and also generation losses using values declared by the manufacturer or measured.

For example, emission subsystem thermal losses $Q_{l,e}$ is

$$Q_{l,e} = Q_{H,nd} \cdot \frac{1 - \eta_{\mathrm{e}}}{\eta_{\mathrm{e}}} \tag{5}$$

where $\eta_{\mathrm{e}}$ is the corresponding efficiency.

In a similar way, it is possible to calculate also the thermal losses for each other subsystem; by adding thermal losses and electrical energy demand of the heating system to the building energy need, the primary energy need of the building is founded.

# 4 Case Studies

Two examples of typical low-performance constructions widely spread in Italian cities were analysed.

Nevertheless, the case studies are not exhaustive of the overall national building stock; in fact, as it has been highlighted by TABULA Project,(Corrado et al. 2010) which gave an overview of existing typology in 24 European countries, the differences among the climatic zone in Italy caused the diffusion of various building typologies both for the features of the envelope and for shape. Furthermore, even the U-values spread in the territory, without an exact correlation between building age and insulation level. The main features that characterize the national building stock are the large percentage of historical buildings, (61 % of construction built before 1970), and the low renovation rate, so that the potential energy savings achieved by efficient refurbishment measures could be very high.

## *4.1 Case Study A*

Case study A represents an existing single house, located in a suburban area of the city. The building has a regular rectangular plan (Fig. 1), and it has a single inhabited floor, characterized by a non-heated underroof above it. The load bearing structure is made of brick masonry, 35 cm thick, and the envelope is built with bricks without insulation.

The windows have a double glazing with air ($U_{\text{window}} = 2.947$ W/(m$^2$ K)), while the ground and the superior floor, characterized by a 30 cm thickness, are not insulated ($U_{\text{floor}} = 1.500$ W/(m$^2$ K)); hence, the energy demand is very high: the building is characterized by the energy class G.

The heating plant is composed of an old traditional boiler with radiators and low-insulation distribution pipes, while the control of water temperature depends on the external climatic conditions; the consequence is that the global efficiency of the heating system is very low.

## *4.2 Case Study B*

Case study B is a dwelling located on the third floor of a block, border on a stair case with an external wall (Fig. 2) and with heated apartments on the other walls

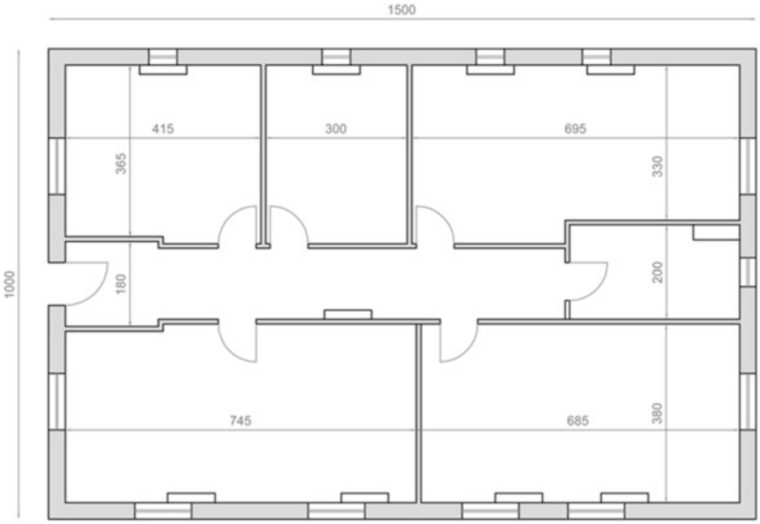


**Fig. 1** Case study A—plan

and floors. The structure is made of concrete, and the envelope is built with hollow brick walls, 36 cm thick. The wall border on the staircase is made of concrete with plaster on the external sides. Even in this case, there is no attention on the energy performance of the building: the windows have single glass with wood frame, and the envelope is not insulated ($U_{\text{window}} = 5.750$ W/(m$^2$ K)).

The main features of the buildings are reported in Table 1.

## 5 Boundary Condition: Climate and Heating Season

Considering the different climate conditions and basing on the degree days, Italy has been divided into six climatic zones; the most significant one for heat consumption, both because of the number of constructions in the territory and because of the severity of climate, is zone E. Therefore, the main part of the work is focused on the analysis of the results related to these climatic conditions.

In fact, the buildings are located in Milan, characterized by a heating season lasting from October 15 to April 15 and 2,404 degree days.

Furthermore, in order to evaluate the influence of the climate on the percentage gap in the results, other locations representative of the overall climatic zone in Italy were chosen (Table 2); in particular, some calculations related to the combination of the intervention are expounded.

**Fig. 2** Case study B—plan

**Table 1** Geometrical features of the dwellings

| Envelope | Case study A | Case study B |
|---|---|---|
| Internal floor area [$m^2$] | 134.22 | 53.39 |
| Overall conditioned volume [$m^3$] | 540.00 | 242.61 |
| External wall surface [$m^2$] | 160.47 | 89.22 |
| Windows total surface [$m^2$] | 17.64 | 13.56 |
| Overall surface of the envelope [$m^2$] | 480.00 | 102.78 |
| Envelope surface/conditioned volume ratio [$m^{-1}$] | 0.890 | 0.424 |
| *Heating system* | | |
| Thermal power [kW] | 26 | 150 (40 dwellings) |
| Global efficiency [%] | 80 | 81 |

**Table 2** Selected location

| Locality | Climatic zone | Degree days [°C day] | Design temperature [°C] |
|---|---|---|---|
| Lampedusa | A | 568 | 4 |
| Palermo | B | 751 | 5 |
| Napoli | C | 1,034 | 2 |
| Roma | D | 1,415 | 0 |
| Milan | E | 2,404 | −5 |

## 6 Possible Intervention Analysis

A set of refurbishment actions has been evaluated on each case study, as shown in Fig. 3 for case A and Fig. 4 for case B, which report the flow chart of the intervention. Each intervention has been labelled by a code so that A0 and B0 indicate, respectively, the energy performance models of the existing buildings, while A1, B1, A2, B2, etc. represent the series of subsequent interventions. Moreover, the different calculation methods adopted are marked with small letter: for example, B1.a represents the first calculation test "a" for case study B (apartment) after the action "1".

## 7 Main Result and Discussion

### *7.1 Determination of the Thermal Transmittance*

The thermal transmittance, which characterizes the building envelope, represents a significant parameter in the calculation of the building energy performance, mostly during the heating season. Defining thermal transmittance can be more or less accurate depending on the knowledge of wall's composition and on the reliability of material thermal properties.

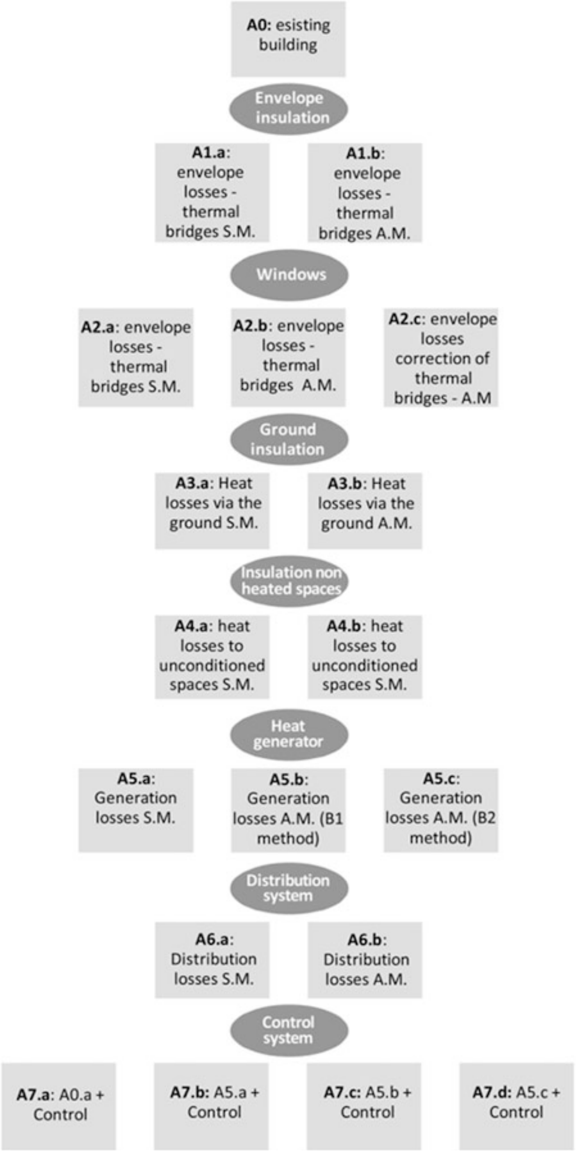
EN ISO 13790 establishes the thermal transmittance of each envelope element to be determined in accordance with EN ISO 6946, but, in case of existing buildings, a simplified method or default values, depending on the characteristics of the considered structures, may be defined at national level.

In fact, UNI/TS 11300 Part 1 assumes that the evaluation of the thermal transmittance can be performed in three different ways:

- by deriving thermo-physical properties of materials from product certificates, if available, or
- assuming thermo-physical properties of materials from UNI 10351, UNI 10355 and EN ISO 6946 or from Appendix B of UNI/TS 11300 Part 1,
- by determining the thermal transmittance according to the building typology and to the year of construction from Appendix A of UNI/TS 11300 Part 1, in default of trustworthy design information about material and wall compositions.

This last method is the most approximate one for the thermal transmittance estimation, because it does not take into account thickness and thermal conductivity of each layer which composes the wall, but rather it provides a thermal transmittance value depending only on the kind of the wall and on its total thickness.

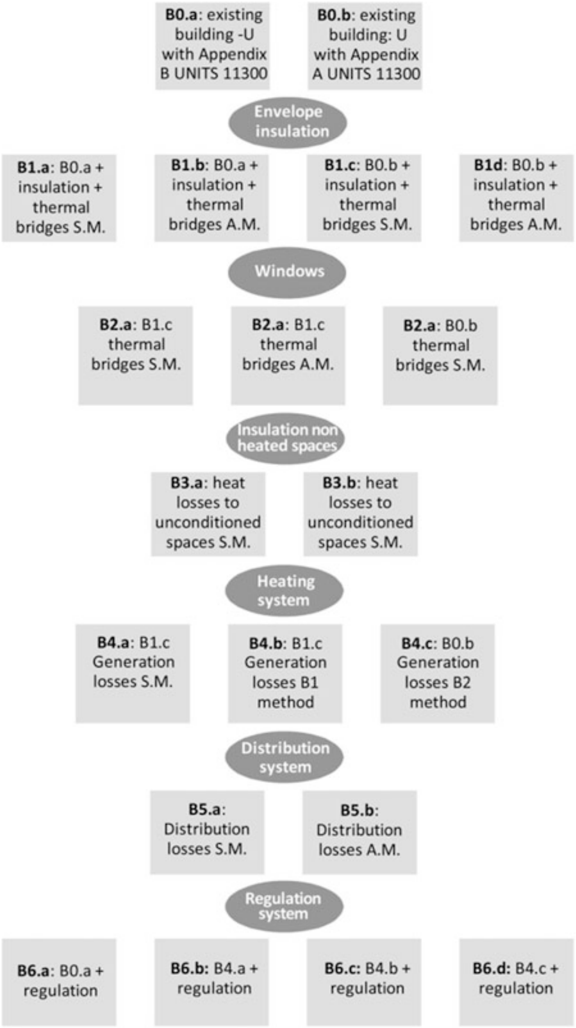
**Fig. 3** Case study A: refurbishment actions and assessment methodologies



It is clear that depending on the calculation method adopted, the technician can obtain different thermal transmittance values and consequently different values of the energy performance of the building.

For example, in the application of UNI/TS 11300 Part 1 to the apartment (case study B), it is possible to obtain two different values for the thermal transmittance *U* of the external wall:

**Fig. 4** Case study B: refurbishment actions and assessment methodologies



- $U = 0.90$ W/(m$^2$ K) knowing or estimating the thickness of each layer and deriving the corresponding thermal conductivities from Appendix B (case B0.a);
- $U = 1.1$ W/(m$^2$ K) by Appendix A by choosing 35-cm hollow brick wall (case B0.b).

For case A, the values of the wall thermal transmittance are similar for each calculation method:

- $U = 1.53$ W/(m$^2$ K) applying Appendix B, (case A0.a);
- $U = 1.56$ W/(m$^2$ K) by Appendix A by choosing 35-cm brick wall, (case A0.b).

Therefore, the gap between the energy need for the base case A related to the method applied for thermal transmittance is negligible. In the following analyses, case A0.a is used as a reference for intervention simulations, while case A0.b is omitted.

The performance indicators for case A.0a are as follows:

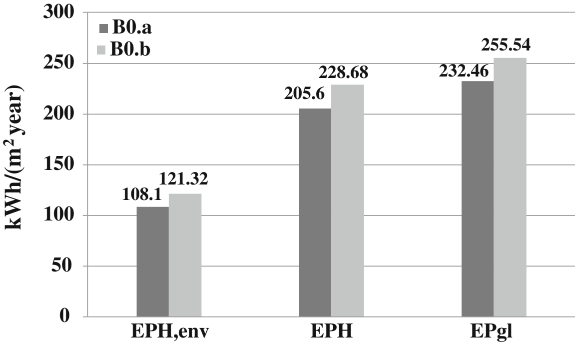
- $EP_{H,\ \mathrm{env}} = 282.08$ kWh/(m$^2$ year);
- $EP_H = 474.40$ kWh/(m$^2$ year);
- $EP_{\mathrm{gl}} = 498.40$ kWh/(m$^2$ year).

In case B0.a, which represents the existing building, keeping constant all the calculation parameters, with a thermal transmittance value $U = 0.90$ W/(m$^2$ K), the corresponding value of the energy performance indicator in the heating season of the envelope, $EP_{H,\ \mathrm{env}}$, is 108.10 kWh/(m$^2$ year), instead of 121.32 kWh/(m$^2$ year), for case B0.b with $U = 1.1$ W/(m$^2$ K)), with a gap of 10.9 % as shown in Fig. 5. In particular, the same trend can be noted in the energy performance indicator for the heating season $EP_H$ and for the global performance index (which is the sum of $EP_H$ and the performance indicator $EP_w$ for domestic hot water production). In fact, the simplified calculation of the thermal transmittance generally introduces an overestimation of the heat transmission through the opaque element. Finally, it should be noted that, for the hollow bricks, it is possible to use the thermal conductivity value of 0.3 W/(m K) derived from Appendix B or from UNI 10351 (corresponding to a thermal resistance of 0.4 (m$^2$ K)/W) or, alternatively, the thermal resistance value of 0.31 (m$^2$ K)/W drawn directly from UNI 10355. Therefore, choosing one value or another one can bring further differences in thermal transmittance and energy performance values.

## 7.2 Thermal Bridges: Simplified and Analytical Calculation

The first kind of refurbishment action is the thermal insulation of external envelope: in this section, the energy performance for both case studies is investigated. For the detached house, the effects of external thermal insulation have been

**Fig. 5** Energy performance indicators



evaluated, while for the apartment, the performance was tested both with external insulation and filling the air gap with loose thermal insulating material.

EN ISO 13790 establishes that the evaluation of thermal bridges should be performed by virtue of EN ISO 14683 and EN 10211. However, in case of old existing buildings, if detailed information about thermal bridges is not available, EN ISO 13790 allows us to evaluate their influence in a simplified way, as a percentage increase in the wall thermal transmittance.

In case of opaque envelope renovation, the Italian laws and UNI/TS 11300 allow the determination of thermal bridge influence with both analytical and simplified methods. In the first case, the analytical calculation of thermal bridges requires the determination of the length and the linear thermal transmittance for each two-dimensional joint, derived, for example, applying ISO 14683 (analytical method). In the second case, the incidence of thermal bridges is evaluated in a simplified way, by increasing the thermal transmittance of the wall by a percentage adjustment coefficient, which depends on wall typology, according to a catalogue which is enclosed in UNI/TS 11300 Part 1 (simplified method).

The first-tested intervention is the thermal insulation with 10-cm EPS of the opaque elements in case A, which allowed to obtain a thermal transmittance value $U_{\text{wall}} = 0.308$ W/(m$^2$ K) for the walls, $U_{\text{u\_floor}} = 0.310$ W/(m$^2$ K) for the upper floor and $U_{\text{g\_floor}} = 0.293$ W/(m$^2$ K) for the ground floor. Considering constant all the other parameters, including the values of thermal transmittance, two cases were simulated using both the simplified (case A1.a) and analytical (case A1.b) methods for taking into account the thermal bridge influence.

Case A1.a is characterized by the use of the simplified calculation method for thermal bridges, by choosing the adjustment coefficient corresponding to *external insulation with overhangs and balconies or not reducing thermal bridges* which accounts for +15 %.

On the contrary, in case A1.b, characterized by the same insulation level, the analytical method was used, applying EN ISO 14683 and considering three structural linkages located between walls and floors and on wall corners, as shown in Fig. 6a, b, c.

The significant differences between the results obtained using the two different procedures are shown in Table 3: the energy performance gap in the heating season accounts for even 18.9 %.

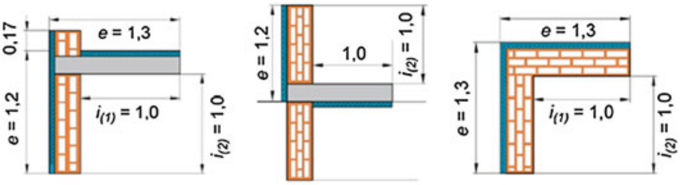


**Fig. 6** Structural linkages—A1.b

**Table 3** Opaque element insulation for case A—thermal bridge influence calculation

| Case Study | Refurbishment action | Calculation method | $EP_{H,\text{ env}}$ | $EP_H$ | $EP_{\text{gl}}$ | Energy class |
|---|---|---|---|---|---|---|
| A1.a | External insulation of the walls and the floors above the heated zone | Simplified | 74.83 | 139.76 | 163.83 | E |
| A1.b | | Analytical | 95.33 | 172.40 | 196.44 | E |
| *Percentage gap* (%) | | | 21.5 | 18.9 | 16.6 | |
| B1. a | B0.b + air-gap insulation | Simplified | 75.61 | 147.04 | 173.91 | G |
| B1.b | | Analytical | 97.29 | 185.62 | 212.48 | G |
| *Percentage gap* (%) | | | 22.2 | 20.8 | 18.1 | |
| B1.c | B0.b + external insulation | Simplified | 70.18 | 137.59 | 164.46 | F |
| B1.d | | Analytical | 79.70 | 153.81 | 180.67 | G |
| *Percentage gap* (%) | | | 11.9 | 10.5 | 8.9 | |

In this example, the use of one method or the other does not bring to different energy classes, but the percentage difference is so wide that in some other cases could imply different energy label, depending on the considered procedure.

In conclusion, using the simplified method for accounting thermal bridges, it is possible to obtain an underestimation of their influence, which can be more significant as much as the building is insulated, and it could bring to obtain a more efficient energy class than the real one. Moreover, the analytical calculations allow both for the design and the realization process, to verify all the possible solutions for structural linkages and to provide a more accurate energy model of buildings.

Regarding case study B, two different kinds of insulation were tested:

- Gap insulation, filling the cavity wall (8 cm thick) to obtain a thermal transmittance $U_{\text{wall}} = 0.356$ W/(m$^2$ K), whose analyses are case B1.a and B1.b,
- External insulation with 10 cm of EPS ($U_{\text{wall}} = 0.279$ W/(m$^2$ K)), whose analyses are case B1.c and B1.d.

Energy performance for cases B1.a and B1.c have been assessed using simplified method for thermal bridges, choosing the correction coefficient, corresponding, respectively, to *hollow brick wall with gap insulation without reduction of thermal bridges* ($b_{\text{tr},x} = 10$ %) and to *external insulation with overhangs and balconies or not reduced thermal bridges* ($b_{\text{tr},x} = 20$ %). In case B1.b and B1.d, the analytical method has been used in determining the linear thermal transmittance from ISO 14683 and considering the structural linkages shown in Fig. 7a–f.

Table 3 shows the influence of thermal bridges, calculated with simplified and analytical methods in both cases: it is apparent that the external insulation guarantees a higher energy saving, because the air gap is only 8 cm thick and does not allow to reach the thermal transmittance $U_{\text{wall}} = 0.279$ W/(m$^2$ K), which is only possible by applying a 10-cm EPS external layer. In fact, considering performance indices for B1.a and B1.b, the air-gap insulation does not allow to improve the energy class of the existing building, even if the value of $EP_{H,\text{ env}}$ is reduced, respectively, to 19.8 and 34.31 % in comparison with case B0.a. Moreover, the

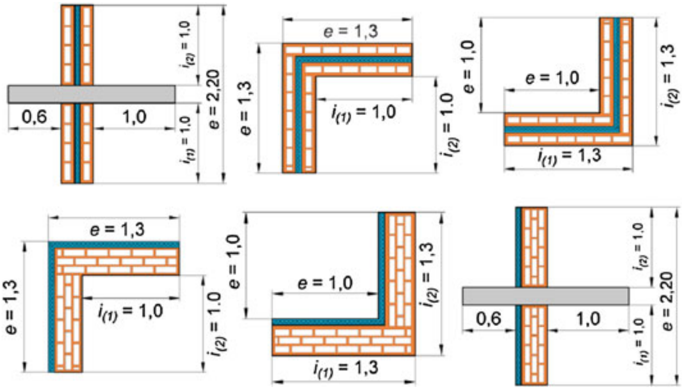


**Fig. 7** Structural linkages—B1.b and B1.d

influence of the methodology is rather significant: in case B1.a, the simplified procedure brought to a value of $EP_{H,\,\mathrm{env}}$ which accounts for 22.2 % of the value obtained for B1.b.

The evaluation of the energy needs for B1.c and B1.d highlights a higher dependence of the results on the assessment method for thermal bridge than in the previous analysis: in fact, different energy classes were obtained. This gap is determined by the influence of thermal bridges which increases according to the reduction in opaque elements' thermal transmittance. This is the reason which entails a worse class using the analytical method, even if the simplified calculation was performed by choosing the most increasing percentage of thermal transmittance provided by the standards.

These analyses highlight not only the variation of the results, depending on the calculation method using same parameters, but also show that, for existing buildings with initial high energy needs, the insulation of the opaque elements assures a remarkable improvement in the performances, but the energy class reached is still far from the A class.

Consequently, it is necessary to design other kinds of intervention for the building envelope, such as the substitution of the windows, with $U_{\mathrm{window}} = 1.5$ W/(m$^2$ K).

Cases A2.a and A2.b are based, respectively, on case A1.a and A1.b with the addition of new windows, while case A2.c simulates only window substitution, without opaque element insulation. As it is expected, the best class is reached with a combination of external insulation and high-performance windows, which brings to E class, while the mere substitution of transparent elements allows an energy saving of just 3 % and does not improve the energy class.

Table 4 highlights how the differences among calculation methods of thermal bridges can bring to different energy performance classes (case B2.a and B2.b), anyway far from A class. On the other hand, for case B, it is possible to derive some other considerations: in fact, in this case, the transparent surfaces represent 13 % of

**Table 4** Influence of opaque and transparent elements insulation

| Case study | Type of intervention | Calculation method | $EP_{H,\ \text{env}}$ | $EP_H$ | $EP_{\text{gl}}$ | Energy class |
|---|---|---|---|---|---|---|
| A2.a | Case A1.a + high-performance windows | Simplified | 66.74 | 123.46 | 147.53 | E |
| A2.b | Case A1.b + high-performance windows | Analytical | 87.52 | 157.63 | 181.68 | E |
| A2.c | A0.a + high-performance windows | Simplified | 274.66 | 459.26 | 483.26 | G |
| B2.a | Case B1.c + high-performance windows | Simplified | 66.74 | 123.46 | 147.53 | D |
| B2.b | | Analytical | 87.52 | 157.63 | 181.68 | E |
| *Percentage gap* (%) | | | 22.9 | 20.3 | 15.3 | |
| B2.c | B0.b + high-performance windows | Simplified | 67.18 | 132.37 | 159.24 | F |

the envelope and just the insulation of the windows, without any intervention on opaque elements, allowing the improvement of energy class from G to F.

Once again, analyzing integrated refurbishment action on opaque and transparent element insulation, the choice of the calculation procedure for thermal bridges brings significant differences in terms of energy performance: in Table 4, the percentage gap accounts for 15.3 % and also the energy class changes from E to D, using the analytical and the simplified method, respectively.

## 7.3 Heat Transfer Via the Ground: Simplified and Analytical Calculations

According to EN ISO 13790 and Italian National Standards, an accurate calculation of the temperature difference between the heated zone and the external environment, accounting for the large inertia of the ground as indicated by EN ISO 13370, is required (analytical method).

Moreover, in order to account the ground effect, it is also possible to consider the temperature difference between the building and the external air and applying an adjustment factor $b_{\text{tr,g}}$ to the heat transfer coefficient (simplified method).

Table 5 shows the results obtained by applying these two different assessment methods for case A: the underfloor has been insulated (10-cm EPS), and it reaches a thermal transmittance of 0.293 W/(m$^2$ K). Case A3.a is characterized by a simplified calculation of the thermal transmission via the ground using the correction factor $b_{\text{tr,g}} = 0.45$ as established for floor close to the ground, while for case A3.b, EN ISO 13370 has been applied. It should be noted that, keeping constant all other conditions, the difference among the three significant performance indicators ($EP_{H,\ \text{env}}$, $EP_H$ and $EP_{\text{gl}}$) in each case is negligible.

Case B was not considered since it is a dwelling positioned in an intermediate floor, and it does not adjoin the ground.

**Table 5** Energy performance depending on heat transfer via the ground for case A

| Case study | Calculation method | $EP_{H,\ \mathrm{env}}$ | $EP_H$ | $EP_{\mathrm{gl}}$ | Energy class |
|---|---|---|---|---|---|
| A3.a | Simplified ($b_{\mathrm{tr,g}} = 0.45$) | 220.57 | 378.46 | 402.50 | G |
| A3.b | Analytical | 222.47 | 381.43 | 405.43 | G |
| *Percentage gap* (%) | | 0.85 | 0.78 | 0.72 | |

## *7.4 Heat Transmission to Adjacent Unconditioned Spaces*

The temperature of unconditioned spaces, adjacent to the heated volume, influences heat transmission; therefore, its correct calculation is very important in the determination of building performance indicators. UNI/TS 11300-1, according to EN ISO 13790, provides two possibilities for the evaluation of the temperature difference between the heated zone and the adjacent unconditioned spaces. The first one is the analytical calculation of the temperature for the unconditioned space by virtue of EN ISO 13789, while the second one is a simplified assessment using an adjustment factor $b_{\mathrm{tr},x}$ for the temperature difference which can be derived from UNI/TS 11300-1.

The comparison between these two possibilities has been tested for both cases A and B using, respectively, the temperature of the unheated space determined by EN ISO 13789 and the adjustment factor $b_{\mathrm{tr},x}$: in case A, the unheated space is the attic and in case B the stair case.

Table 6 shows the results in terms of performance indicators for both cases, and it is apparent that the application of the two methods can significantly influence the heat transfer calculation. By using the adjustment factor (case A4.a), the value of $EP_{H,\mathrm{env}}$ is 13.6 % higher than by applying the calculated and accurate temperatures of the unconditioned space (case A4.b).

Moreover, in case B3.a, the temperature of the staircase is determined by using the adjustment factor, while in case B3.b, the analytical method is adopted, and in this case, the gap between the two procedures in terms of performance indicators accounts for 11 %.

## *7.5 Heat Generator Subsystem Losses*

A typical action which increases the efficiency of the heating system is the substitution of the traditional old generator with a condensation one and, if possible, with the association to radiant panels and an efficient control subsystem, such as

**Table 6** Energy performance depending on the temperature of the non-heated space

| Case study | Calculation method | $EP_{H,\ \mathrm{env}}$ | $EP_H$ | $EP_{\mathrm{gl}}$ | Energy class |
|---|---|---|---|---|---|
| A4.a | Simplified | 207.07 | 357.39 | 381.40 | G |
| A4.b | Analytical | 193.00 | 335.29 | 359.30 | G |
| *Percentage gap* (%) | | 6.79 | 6.18 | 5.79 | |
| B3.a | Simplified | 70.18 | 137.59 | 164.46 | F |
| B3.b | Analytical | 62.00 | 122.73 | 149.60 | F |
| *Percentage gap* (%) | | 11.7 | 10.8 | 9.0 | |

climatic and local controllers. Therefore, in order to evaluate the improvement in the energy performance and the energy class which can be reached, some simulations have been arranged for case A and B. In particular, UNI/TS 11300 Part 2 defines two kinds of assessment method for the generation subsystem efficiency:

- a simplified procedure, by using pre-calculated values for the generator efficiency for the most common type of generators (Table 23—UNI/TS 11300 Part 2);
- two analytical procedures (B1 and B2 method) as reported in the Appendix B of the Standard.

In particular, if the generator typology and the operational conditions correspond to the standard ones reported in Table 23—UNI/TS 11300 Part 2, the first possibility (use of listed values) is allowed. On the contrary, B2 method (analytical) and B1 method (based on efficiencies determined by virtue of 92/42/CEE Directive) describe actual operational conditions.

It should be noted that choosing among different methods for generator efficiency calculation can involve significant gaps in energy performance indicators for the heating season; in particular, the listed values of the simplified method generally overestimate generation losses.

Table 7 shows the results for case A, by using these three different assessment methods: Table 23, B1 method and B2 method. Applying B2 method of UNI/TS 11300 Part 2 brings to the worst energy performance for heating with a gap of 32.6 % in comparison to B1 method.

Considering all the simulations, the boiler substitution does not improve the energy label of the house, even if it brings to a reduction in $EP_{\mathrm{gl}}$ that accounts for 32.5 % in comparison with the performance of the existing building.

In Table 7, the corresponding results for case B are reported, showing that the application of B2 method of UNI/TS 11300 Part 2 brings to the worst energy performance in the heating season with a gap of 9 % with respect to simplified and B1 methods which bring to approximately the same result.

As in case A, the energy label does not change, but the energy saving obtained with the substitution of the generator accounts for 12.3 %.

## 7.6 Distribution Losses

UNI/TS 11300 Part 2 provides that the distribution losses can be evaluated by doing the following:

- using pre-calculated efficiencies as reported in a table of the Technical Specification, distinguishing among the distribution typologies;
- applying the analytical method described in Appendix A of the National Standard.

**Table 7** Influence of heat generator subsystem losses

| Case study | Calculation method | $EP_H$ | $EP_{\mathrm{gl}}$ | Energy class |
|---|---|---|---|---|
| A5.a | Table 23 | 397.54 | 419.81 | G |
| A5.b | B1 | 316.87 | 336.06 | G |
| A5.c | B2 | 420.49 | 437.00 | G |
| B4.a | Table 23 | 177.89 | 205.83 | G |
| B4.b | B1 | 177.76 | 206.46 | G |
| B4.c | B2 | 195.5 | 223.93 | G |

Table 8 shows the results applying the two different methodologies to case A: the gap in terms of performance indicator for heating among the results applying the two procedures is about 3 %.

Table 8 shows also the results obtained by the application of the two different methodologies to case B, and it is apparent that, in this case, the gap in terms of performance indicator is negligible.

## 7.7 *The Influence of Emission and Control Subsystem Losses*

Another possibility of intervention is the improvement of the control subsystem, as an alternative or in addition to heat generator substitution. For case A, the installation of a thermostat with 99 % efficiency is provided, instead of case B, which is characterized by the use of thermostatic radiator valves with 98 % efficiency.

Table 9 highlights how an efficient control system can influence building performances. Moreover, it is apparent that also in this case the methodology adopted for the generation losses calculation significantly affects the global efficiency of the building $\eta_{\mathrm{gl}}$ with a gap of about 23 % between case A7.d and A7.c, even if the class is always G.

Comparing the results for case A7.a with the base case performances (A0.a), it should be noted that the intervention in the control system can lead to a reduction in the $EP_{\mathrm{gl}}$ index which accounts for about 10 %. Regardless of the adopted assessment procedure for the generation losses, considering cases A5 (a, b, c) and A7 (a, b, c), the boiler substitution associated with the improvement in system control reduces the energy needs about 10 %. It is so significant to notice that comparing cases A7.d and A7.c (or A5.b and A5.c), which are characterized by the same level of intervention, but with two different calculation methods for generation losses, the percentage gap in terms of global energy performance accounts for 22 %. Consequently, choosing accurately the calculation method of generation losses, the building could reach a more efficient energy class than the reachable one with the substitution of the control system. Analogue considerations could be done for case B.

**Table 8** Influence of distribution losses

| Case study | Calculation method | $EP_H$ | $EP_{\text{gl}}$ | Energy class |
|---|---|---|---|---|
| A6.a | Simplified | 464.47 | 488.43 | G |
| A6.b | Analytical | 481.38 | 505.37 | G |
| *Percentage gap (%)* | | 3.5 | 3 | |
| B5.a | Simplified | 178.60 | 205.46 | G |
| B5.b | Analytical | 177.04 | 203.91 | G |
| *Percentage gap (%)* | | 0.8 | 0.7 | |

**Table 9** The influence of the control system improvement

| Case study | Intervention | Calculation method | $EP_H$ | $EP_{\text{gl}}$ | $\eta_{\text{gl}}$ | Energy class |
|---|---|---|---|---|---|---|
| A7. a | A0.a + control | Standard | 420.23 | 444.23 | 0.671 | G |
| A7. b | A5.a + control | Table 23 | 352.2 | 374.48 | 0.801 | G |
| A7. c | A5.b + control | B1 | 282.76 | 302.06 | 0.998 | G |
| A7. d | A5.c + control | B2 | 372.24 | 388.97 | 0.758 | G |
| B6. a | B0.a + control | Standard | 179.17 | 206.03 | 0.603 | G |
| B6. b | B4.a + control | Table 23 | 155.19 | 183.19 | 0.700 | G |
| B6. c | B4.b + control | B1 method | 155.46 | 184.26 | 0.695 | G |
| B6. d | B4.c + control | B2 method | 171.6 | 200.22 | 0.630 | G |

## *7.8 Single Refurbishment Action: Final Considerations*

Taking into account the results of previous sections, it is apparent that, according to the kind of method for the energy performance assessment, the global indices could be affected by significant uncertainties.

Therefore, for the refurbishment actions reported in Table 10, uncertainty ranges were defined.

In particular, for each case study and for each action, the following indices were evaluated (Tables 11, 12):

- $EP_{H,\ \text{min}}$: minimum heating performance index, obtained by applying the less-conservative calculation method;
- $EP_{H,\ \text{max}}$: maximum heating performance index, obtained by applying the most conservative calculation method;
- $EP_{H,av}$: medium value of heating performance index.

$$\frac{EP_{H,\text{max}}+EP_{H,\text{min}}}{2} \tag{6}$$

Figures 8 and 9 report the percentages which represent performance indices after the intervention in comparison with the base energy needs; they show a 20 % related to the applied energy calculation method (simplified or analytical) for some

**Table 10** Refurbishment actions

| Refurbishment action | Case study A | Case study B |
|---|---|---|
| Action 1 | Wall—external insulation | Wall—gap insulation |
| Action 2 | Ground floor—insulation | Wall—external insulation |
| Action 3 | Wall adjacent to non-heated zone—insulation | |
| Action 4 | Heating system: boiler substitution | |
| Action 5 | Heating system: distribution system renewal | |
| Action 6 | Heating system: control system renewal | |

particular refurbishment actions; hence, these uncertainties affect the evaluation of the intervention effectiveness.

For example, regarding case A (Fig. 8), action 4 reduces the energy needs to 88 % with respect to the base case, considering $EP_{H,\ \max}$, and to 68 % in terms of $EP_{H,\ \min}$; for action 3, $EP_{H,\ \max}$ and $EP_{H,\ \min}$ account, respectively, for 75 and 70 % of the base case.

Comparing $EP_{H,\ \min(\text{action 3})}$ and $EP_{H,\ \max(\text{action 4})}$, the insulation of the envelope adjacent to a non-heated zone is more effective than the boiler substitution; on the contrary, taking into account $EP_{H,\ \max(\text{action 3})}$ and $EP_{H,\ \min(\text{action 4})}$, the most significant reduction in terms of energy need is associated with the boiler substitution.

Moreover, in Fig. 9, the results for case B are shown: the uncertainty ranges for actions related to the heating system are negligible, while the method of energy performance assessment causes a percentage gap between $EP_{H,\ \max}$ and $EP_{H,\ \min}$ which varies from 7.09 to 16.87 %.

Finally, the uncertainty related to the calculation method could affect the correct evaluation of the energy performance assessment associated with the single refurbishment action.

Therefore, in order to define a reliable index to compare interventions, the average values of EPH have to be considered.

## *7.9 Effects of Parameters Combination*

Basing on the previous analyses, significant differences in energy performance indicators for heating just have been observed related to the uncertainties of a single parameter, caused by the application of different calculation methodologies allowed by UNI/TS 11300.

Consequently, the combination of different assessment method of input parameters can lead to remarkable differences in the results. In particular, it is possible to evaluate which assessment method can be adopted in order to minimize or maximize the energy needs of the building approaching the A.

**Table 11** Case study A—$EP_H$ (minimum, maximum and average values for different refurbishment action)—whole results

| $EP_H$ base case | Action | $EP_{H,\text{min}}$[a] | Comparison with base case [%][b] | $EP_{H,\text{max}}$[a] | Comparison with base case [%][b] | $EP_{H,\text{av}}$[a] | Comparison with base case [%][b] |
|---|---|---|---|---|---|---|---|
| 474.40 | 1 | 139.76 | 29.46 | 172.4 | 36.34 | 156.08 | 32.90 |
| | 2 | 378.46 | 79.78 | 381.43 | 80.40 | 379.945 | 80.09 |
| | 3 | 335.29 | 70.68 | 357.39 | 75.34 | 346.34 | 73.01 |
| | 4 | 316.87 | 66.79 | 420.49 | 88.64 | 368.68 | 77.72 |
| | 5 | 464.47 | 97.91 | 471.38 | 99.36 | 467.925 | 98.64 |
| | 6 | 282.76 | 59.60 | 372.24 | 78.47 | 327.5 | 69.03 |

[a] Energy performance index for heating season—kWh/(m$^2$ year)

[b] Percentage of EPH after the intervention with respect to the base case

**Table 12** Case study B—$EP_H$ (minimum, maximum and average values for different refurbishment action)—whole results

| $EP_H$ base case | Action | $EP_{H,\text{min}}$[a] | Comparison with base case [%][b] | $EP_{H,\text{max}}$[a] | Comparison with base case [%][b] | $EP_{H,\text{av}}$[a] | Comparison with base case [%][b] |
|---|---|---|---|---|---|---|---|
| 228.68 | 1 | 147.04 | 64.30 | 185.62 | 81.17 | 166.33 | 72.73 |
| | 2 | 137.59 | 60.17 | 153.81 | 67.26 | 145.7 | 63.71 |
| | 3 | 122.73 | 53.67 | 137.59 | 60.17 | 130.16 | 56.92 |
| | 4 | 177.89 | 77.79 | 195.5 | 85.49 | 186.695 | 81.64 |
| | 5 | 177.04 | 77.42 | 178.6 | 78.10 | 177.82 | 77.76 |
| | 6 | 155.19 | 67.86 | 171.6 | 75.04 | 163.395 | 71.45 |

[a] Energy performance index for heating season—kWh/(m$^2$ year)

[b] Percentage of EPH after the intervention with respect to the base case

In order to evaluate the energy performances gaps associated with global uncertainties, two different combinations of methods have been tested for both cases A and B; the combination have been defined in order to maximize the gap within the results. In the first case, the input parameters and calculation methodologies have been chosen in order to minimize the energy needs, while in the second case to maximize the energy performance indicator for heating.

Moreover, three different sets of simulations have been performed: the first one is the combination of all the possible intervention in opaque and transparent elements, the second one is the whole heating system improvement and the last one is the combination of refurbishment action both on the envelope and on the heating plant.

Table 13 reports all the calculation methodologies used in each case in order to maximize or minimize performance indicators.

Table 14 shows the energy performance indicators for both cases. The gaps in the results are very high: a suitable combination of methods allows us to obtain a more efficient energy indicator and a different class. In case A, the energy class difference is between D and C, and in case B, the gap is from E to C.

**Fig. 8** Case study A—$EP_H$ (minimum, maximum and average values for different refurbishment action)

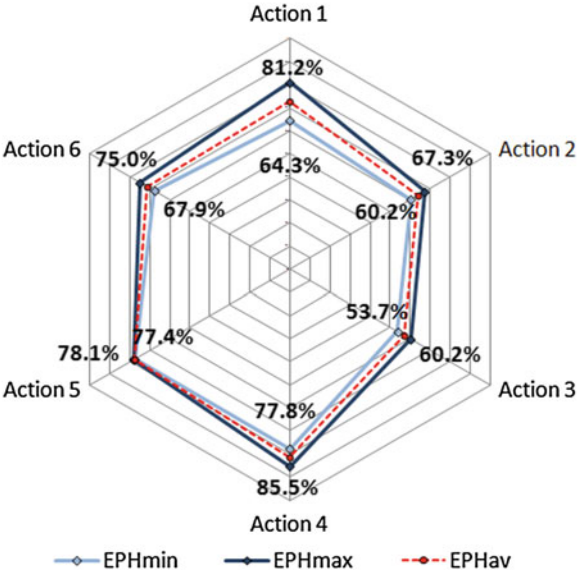
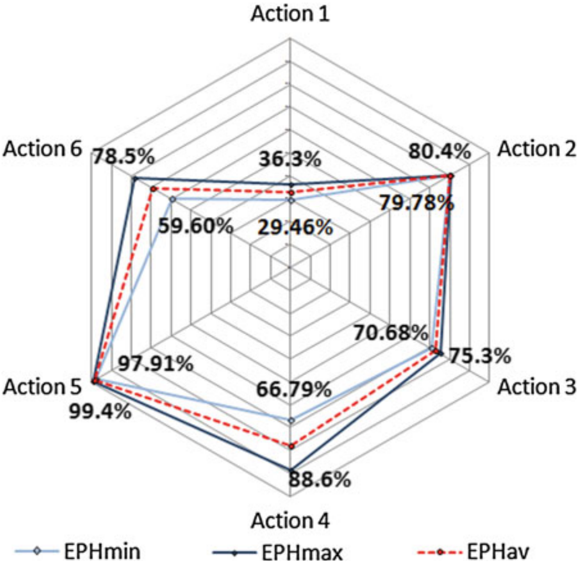


**Fig. 9** Case study B—$EP_H$ (minimum, maximum and average values for different refurbishment action)



The difference in the results due to global uncertainties depending on the combination of input data (taken from tables or calculated) and calculation methodologies is very significant, as highlighted in Fig. 10.

**Table 13** Calculation method combinations—case study A-B

| Type of intervention | Calculation method | Case study A0.a | | Case study B0.b | |
|---|---|---|---|---|---|
| | | BEST | WORST | BEST | WORST |
| *Combination 1—Envelope refurbishment* | | | | | |
| Wall and floors external insulation + high-performance windows | Thermal bridges | S[a] | A[b] | S[a] | A[b] |
| | Heat transmission to the ground | S[a] | A[b] | – | – |
| | Temperature of the unheated space | A[b] | S[a] | A[b] | S[a] |
| *Combination 2—Heating system refurbishment* | | | | | |
| Condensing boiler | Generation losses | B1[c] | B2[c] | T 23[c] | B2[c] |
| Insulation of the distribution system + control improvement | Distribution losses | S[a] | A[b] | A[b] | S[a] |
| | Control efficiency | St[d] | St[d] | St[d] | S[a] |
| *Combination 3 = Combination 1 + Combination 2—Global refurbishment* | | | | | |

[a] Simplified method
[b] Analytical method
[c] B1, B2, Table 23 method from UNI TS 11300-2
[d] Standard method

**Table 14** Results for the combinations

| | Case A | | | Case B | | |
|---|---|---|---|---|---|---|
| | BEST | WORST | Gap (%) | BEST | WORST | Gap (%) |
| *Combination 1* | | | | | | |
| $EP_{H,\,\mathrm{env}}$ | 53.02 | 90.24 | 41.25 | 23.22 | 39.12 | 40.64 |
| $EP_H$ | 101.35 | 161.87 | 37.39 | 50.72 | 81.58 | 37.83 |
| $EP_{\mathrm{gl}}$ | 125.46 | 185.92 | 32.52 | 77.59 | 108.45 | 28.46 |
| Class | D | D | | D | E | |
| *Combination 2* | | | | | | |
| $\eta_{\mathrm{gl}}$ | 1.023 | 0.93 | 8.80 | 0.803 | 0.630 | 21.54 |
| $EP_H$ | 275.74 | 302.44 | 8.83 | 134.63 | 171.60 | 21.54 |
| $EP_{\mathrm{gl}}$ | 295.73 | 324.36 | 8.83 | 163.51 | 220.22 | 18.33 |
| Class | G | G | | F | G | |
| *Combination 3* | | | | | | |
| $EP_{H,\,\mathrm{env}}$ | 90.24 | 53.02 | 41.25 | 23.22 | 39.12 | 40.64 |
| $\eta_{\mathrm{gl}}$ | 0.89 | 0.887 | 0.34 | 0.777 | 0.614 | −26.55 |
| $EP_H$ | 100.29 | 59.8 | 40.37 | 29.88 | 63.67 | 53.07 |
| $EP_{\mathrm{gl}}$ | 122.28 | 80.93 | 33.82 | 59.42 | 92.27 | 35.60 |
| Class | D | C | | C | E | |

## *7.10 Effects of Parameters Combination According to Climatic Zone*

The previous analyses have been developed considering the external condition of Milan, which belongs to climate zone E. Considering some reference locations shown in Table 2, further simulations have been developed in order to understand the incidence of climatic conditions in energy performance global uncertainties caused by different calculation methodology.

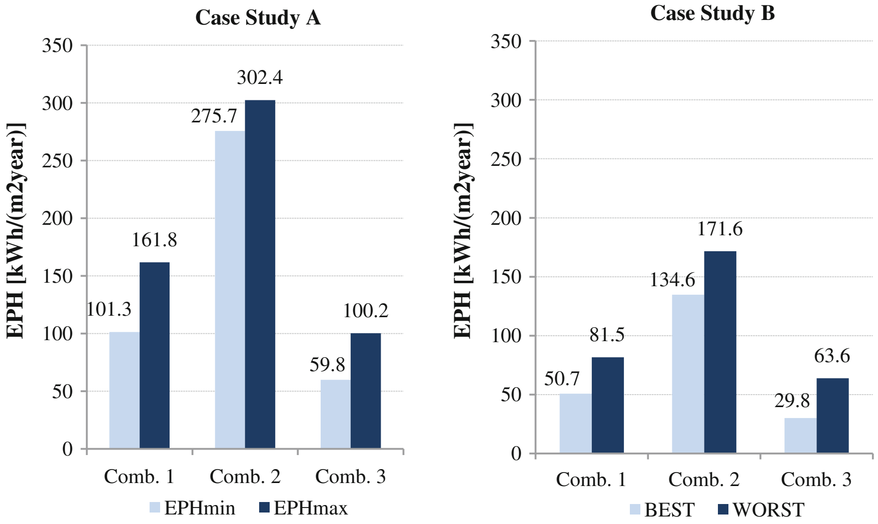


**Fig. 10** Comparison between method combination: refurbishment action on the envelope (comb. 1), on the heating plant (comb. 2) and global action (comb 3)

In particular, the energy performance indices for the combination of interventions shown in Table 10 were calculated in case of the following:

- interventions only on the envelope;
- interventions only on the heating system and
- combined interventions,

which represent the most significant gap obtained in the previous results.

Table 15 highlights that the milder is the climate, the more significant is the uncertainty among the performance indices.

In particular, it could be noted that the actions on the envelope decrease heat transmission losses, and in cold climate, this is the main contribution of energy need for winter, in comparison with solar and internal gains, which are less affected by different kind of assessments; hence, the application of different methodologies has higher incidence compared to warm climate (Fig. 8).

Furthermore, in combination 2, the gap in heating boiler, distribution and control system losses are less significant than combination 1; nevertheless, they are different for the climatic zones, because they depend both on some features of the envelope and on the climatic conditions which differently account for simplified and detailed calculation methodologies.

In Fig. 11, the incidence of the calculation procedure shows the dependence on the climatic zone, since the energy balance is determined according to the external temperature, the length of heating season and other parameters affected by the location.

**Table 15** Main results for various climatic zones—case A

| Location | $EP_{H.\ env}$ | $EP_H$ [kWh/ (m$^2$year)] | $EP_{gl}$ | Class | $EP_{H.\ env}$ | $EP_H$ [kWh/ (m$^2$year)] | $EP_{gl}$ | Class |
|---|---|---|---|---|---|---|---|---|
| *Combination 1—Envelope refurbishment* | | | | | | | | |
| | | BEST | | | | WORST | | |
| Lampedusa | 11.29 | 28.47 | 53.22 | D | 17.13 | 39.66 | 64.37 | E |
| Palermo | 13.89 | 34.06 | 58.69 | D | 22.08 | 49.38 | 73.97 | E |
| Napoli | 16.72 | 39.81 | 64.33 | C | 26.98 | 58.44 | 82.91 | D |
| Roma | 25.76 | 57.52 | 81.83 | C | 44.44 | 89.95 | 114.17 | E |
| Milano | 53.02 | 101.35 | 125.46 | D | 90.24 | 161.87 | 185.92 | D |
| Bressanone | 55.51 | 109.22 | 133.21 | C | 98.95 | 180.74 | 204.66 | E |
| *Combination 2—Heating system refurbishment* | | | | | | | | |
| | | BEST | | | | WORST | | |
| Lampedusa | 67.97 | 72.2 | 93.97 | F | 67.97 | 74.59 | 98.16 | F |
| Palermo | 84.86 | 89.42 | 110.91 | F | 84.86 | 92.81 | 116.04 | F |
| Napoli | 100.91 | 105.55 | 126.76 | F | 100.91 | 110.17 | 133.07 | F |
| Roma | 155.98 | 157.91 | 178.42 | F | 155.98 | 168.71 | 191 | F |
| Milano | 280.41 | 275.74 | 295.73 | G | 280.41 | 302.44 | 324.36 | G |
| Bressanone | 314.53 | 308.98 | 328.66 | F | 314.53 | 338.99 | 360.55 | G |
| *Combination 3—Global refurbishment* | | | | | | | | |
| | | BEST | | | | WORST | | |
| Lampedusa | 11.29 | 14.25 | 36.47 | B | 17.13 | 21.36 | 45.03 | C |
| Palermo | 13.89 | 17.33 | 39.38 | B | 22.08 | 27.03 | 50.37 | C |
| Napoli | 16.72 | 20.66 | 42.53 | B | 26.98 | 32.64 | 55.65 | C |
| Roma | 25.76 | 30.8 | 52.33 | B | 44.44 | 51.64 | 74.04 | C |
| Milano | 53.02 | 59.8 | 80.93 | C | 90.24 | 100.29 | 122.28 | D |
| Bressanone | 55.51 | 62.8 | 83.75 | B | 98.95 | 109.96 | 131.6 | C |

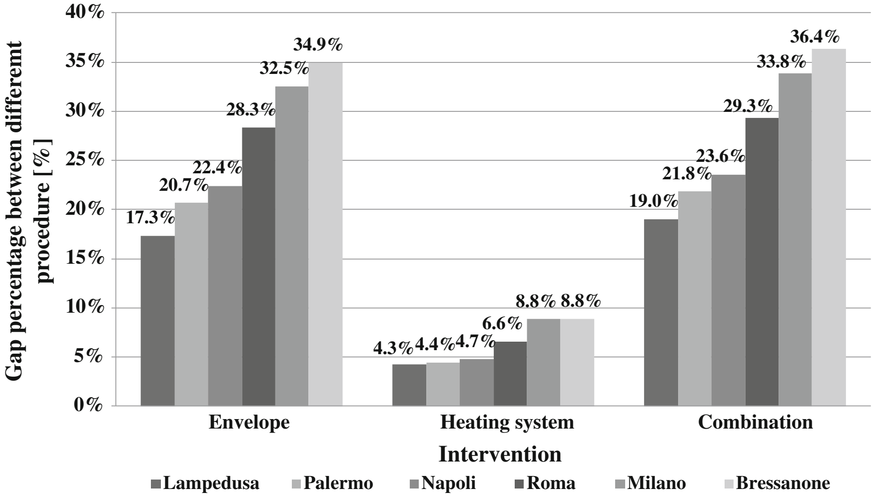


**Fig. 11** Global energy performance gap

## 8 Conclusions

The assessment methodologies to evaluate the energy performance of a building are associated with very detailed and complex procedures and require a large number of input data. The possibility of choosing among different calculation methodologies which can be defined at national or regional level is provided by EN ISO 13790 and EN 15316.

The aim of the analysis is to point out the complexity of the application of the different methodologies provided by Italian Standards in correlation with particular aspects that can be significant in the performance indicators definition.

Lots of typical refurbishment actions on building envelope and heating system have been simulated in order to evaluate the energy performance improvement.

The results highlight that the assessment methods and the parameters evaluation significantly affect global energy performance. Therefore, in order to evaluate the effectiveness of refurbishment actions, the uncertainties related to calculation procedures have to be considered, since in some cases, they determine a different energy class.

Finally, the analyses are related to specific case studies, and further investigations have to be developed considering different building typologies and construction features. Nevertheless, the approach represents a methodological base for energy performance assessment and energy conservation measures evaluation.

## References

Balaras C, Gaglia A, Georgopoulou E, Mirasgedis S, Sarafidis Y, Lalas D (2007) European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. Build Environ 42:1298–1314

Ballarini I, Corrado V (2009) Application of energy rating methods to the existing building stock: analysis of some residential buildings in Turin. Energy Buildings 41:790–800

Corgnati S, Fabrizio E, Filippi M, Monetti V (2013) Reference buildings for cost optimal analysis: method of definition and application. Appl Energy 102:983–993

Corrado V, Ballarini I, Corgnati S, Talà N (2010) Use of building typologies for energy performance assessment of national building stocks, existent experiences in European countries and common approach. First TABULA synthesis report, Available from: http://www.building-typology.eu/existent-concepts.html

Corrado V, Mechri HE (2009) Uncertainty and sensitivity analysis for building energy rating. J Build Phys 33:125–154

Diakaki C, Grigoroudis E, Kolokotsa D (2008) Towards a multiobjective optimization approach for improving energy efficiency in buildings. Energy Buildings 40:1747–1754

Fokaides P, Maxoulis C, Panayiotou G, Neophytou M, Kalogirou S (2011) Comparison between measured and calculated energy performance for dwellings in a summer dominant environment. Energy Buildings 43:3099–3105

Garcıa Casals X (2006) Analysis of building energy regulation and certification in Europe: their role, limitations and differences. Energy Buildings 38:381–392

Implementing the Energy Performance of Buildings Directive (EPBD)—Featuring Country Reports (2010) www.epbd-ca.eu

Jokisalo J, Kurnitski J (2007) Performance of EN ISO 13790 utilisation factor heat demand calculation method in a cold climate. Energy Build 39:236–247

Magrini A, d'Ambrosio FR, Magnani L, Pernetti L (2010) Various approaches to the evaluation of the energy performance of buildings in Italy—some results of calculation procedures application on residential buildings. CESB Central Europe toward Sustainable Building, Prague

Poel B, van Cruchten G, Balaras C (2007) Energy performance assessment of existing dwellings. Energy Build 39:393–403

Tronchin L, Fabbri K (2010) A round robin test for building energy performance in Italy. Energy Build 42:1862–1877

Wang S, Yan C, Xiao F (2012) Quantitative energy performance assessment methods for existing buildings. Energy Build 55:873–888

## Reference Standards

CEN Heating systems in buildings—method of calculation of system energy requirements and system efficiencies, EN 15316:2008, European Committee for Standardization

CEN (2007) Energy performance of buildings—methods for expressing energy performance and for the energy certification of buildings, EN 15217, European Committee for Standardization

CEN, Energy performance of buildings—calculation of energy use for space heating and cooling, EN ISO 13790:2008, European Committee for Standardization

CEN: Building components and building elements—thermal resistance and thermal transmittance, EN ISO 6946: 2008, European Committee for Standardization

CEN: Thermal bridges in building construction—heat flows and surface temperatures—detailed calculations. EN ISO 10211: 2008, European Committee for Standardization

CEN: Thermal performance of buildings—heat transfer via the ground, EN ISO 13370:2001, European Committee for Standardization

CEN: Thermal performance of buildings—transmission heat loss coefficient, EN ISO 13789:2001, European Committee for Standardization

European Union, Directive 2002/91/EC of the European Parliament and of the Council of December 16th, 2002 on the energy performance of buildings. Official Journal of the European Communities, 4th Jan 2003

European Union, Directive 2010/31/EU of the European Parliament and of the Council of May 19th, 2010 on the energy performance of buildings (recast). Official Journal of the European Union, 18 June 2010

Istat, Italian Population Census (2001) http://www.istat.it

Italian government, Decree of the Economical Development Ministry June 29th, 2009 "National Guidelines for buildings energy certification"

Italian government, Legislative Decree August 19th, 2005, no. 192 (D. Lgs. 192/2005), complying the European Directive 2002/91/EC on the energy performance of buildings

Italian government, Legislative Decree December 29th, 2006, n. 311 (D. Lgs. 311/2006), modifying and integrating the Legislative Decree August 19th, 2005, n. 192 (D. Lgs. 192/2005), complying the European Directive 2002/91/EC on the energy performance of buildings

Italian government, Legislative Decree n. 59/2009, 2nd April 2009

National technical standard: building materials- thermal conductivies and vapour permeabilities, UNI 10351:2008

National technical standard: thermal bridges in building construction—linear thermal transmittance, UNI 14683:2008

National Technical Standard: walls and floors—thermal resistance, UNI 10355:2008

UNI (2008) Technical specification, energy performance of buildings. Part 1. Evaluation of energy need for space heating and cooling, UNI/TS 11300-1

UNI (2008) Technical specification, energy performance of buildings. Part 2. Evaluation of primary energy need and of system efficiencies for space heating and domestic hot water production, UNI/TS 11300-2

# Life Cycle Energy Performance Evaluation

**Patxi Hernandez**

The majority of energy used in buildings has been traditionally linked to their operation (heating, cooling, lighting, etc.). Much attention has been directed to assess and reduce this energy use, and future refurbishment projects might aim for 'zero-energy' buildings. As this goal is progressively approached, buildings generally often employ an increasing amount of materials and systems, to the point that the energy associated with these, the so-called embodied energy, can constitute an important part of the building's life cycle energy use. For buildings achieving 'zero-energy' use in operation, the embodied energy is indeed the only life cycle energy use. Despite this, current building energy assessment methods, and strategies from approaching 'zero-energy buildings' or 'nearly-zero-energy buildings', frequently ignore the embodied energy component of building life cycle energy use. This chapter presents the concepts and methodology to evaluate life cycle energy performance of buildings, including embodied energy of the different components, systems and processes. It also introduces the concept of 'net energy ratio' (NER) to the built environment, presenting it as an indicator to support optimization of building refurbishment strategies from a life cycle energy perspective. A practical application is shown for the refurbishment of an Irish typical house.

## 1 Introduction and Context

With buildings accounting for 40 % of the world's energy use, there is now a need to aggressively limit their energy use in order to reduce the planet's energy-related carbon footprint at the level called for by the Intergovernmental Panel on Climate Change (IPCC) (World Business Council for Sustainable Development 2012).

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Understanding and properly evaluating energy performance of buildings is a key preliminary step to define an approach towards reducing building energy use. Energy performance evaluation methods have already been the focus of much research since the 1970s, when efforts to reduced energy use were sparked by the oil crisis. Through the building process, project teams nowadays employ a variety of assessment methods and indicators, which provide information about building energy performance as a project advances. This information, depending on building size and complexity, ranges from building energy benchmarks, guided by regulation and standards, to hourly or subhourly dynamic analysis of building performance. Hundreds of sophisticated methodologies and tools have been developed over the last decades which have been shown to provide accurate and detailed data to evaluate energy performance of buildings and their components and systems.

However, one aspect that is frequently not considered in the building energy evaluation process is that energy used does not correspond solely to the operational phase. Buildings are complex systems comprising of a multitude of materials and components, each of which goes through a different life cycle phase, from material extraction, transport, production, etc., until disposal. The term 'embodied energy' is used by different authors to describe the sum of the energy use through all or some of those phases (Dixit et al. 2010) and can be calculated through different methods as process-based analysis, input–output analysis or a mixture of the two (hybrid analysis).

In some research studies performed since the late 1970s, the embodied energy of building products and the construction process has been analysed. As one of the first examples, Hannon et al. (1978) calculated the embodied energy of building construction, based on an input–output model for energy flows through the US economy in 1967 and concluded that embodied energy was already a very significant factor that needs to be considered in detail for the construction sector. Many other relevant studies have been carried out in the last decades (Cole and Kernan 1996; Adalberth 1997a, b; Treloar et al. 2001) describing embodied energy calculations for buildings and comparing the results with energy use in operation, providing a life cycle energy evaluation of buildings. Some reviews have been compiled with studies (Sartori and Hestnes 2007) and tools (Haapio and Viitaniemi 2008) for building life cycle energy and environmental assessment. Although all these previous studies acknowledge the potential for reducing energy use of buildings by considering a life cycle perspective, the majority still indicate that the operational phase of the buildings is the main factor of the life cycle energy use. For example, in a review of life cycle assessments (LCA) for buildings by Sharma et al. (2010), it is concluded:

> *all the life cycle phases were found to have significant environmental aspects but operational phase has the highest percentage* (80–85 %) *of energy consumption in the life cycle of a building*

This type of statements, together with the difficulty in agreeing boundaries for the analysis and for gathering life cycle information of building components and systems, has resulted in life cycle energy evaluation not being widely applied in practice and generally not being integrated into building energy assessment, or in building regulations and standards.

On the other hand, in recent years, there has been an international effort to move towards buildings approaching zero-energy use in operation, supported by building regulations, policies and standards. It is of particular relevance to note that in this context, while a life cycle energy perspective is still not addressed, it could be an increasingly important factor. If in a refurbishment project we intend to diminish the building energy use in operation, the 'embodied energy' (energy used during other phases of the building life cycle) frequently increases as we add more and more complex materials and systems and can represent a larger part of the life cycle energy use. If the goal is to refurbish a building to 'zero-energy' use in operation, the embodied energy of added products and processes is indeed the only life cycle energy use.

This chapter introduces the concept of LCA in construction and presents a building life cycle energy performance evaluation methodology which can be integrated within the already established building energy assessment methods, facilitating the consideration of a life cycle perspective in building refurbishment as we move towards zero-energy buildings.

The concept of 'NER' is also introduced here as an indicator to support practitioners in building life cycle energy optimization, particularly useful for building refurbishment projects. The methodology is applied in a typical house in Ireland, as a practical case study.

## 2 Life Cycle Assessment in the Construction Sector

Life cycle analysis or LCA originated in the late 1960s and early 1970s, firstly as simple studies focusing on energy use and production of waste (Udo de Haes and Heijungs 2007). LCA progressively evolved to include a detailed analysis of a wide range of environmental impacts, with a set of ISO standards detailing a framework for LCA since 1990s. In ISO 14040 (ISO 2006a), LCA is defined as a 'compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle'. The life cycle inventory (LCI) phase on an LCA quantifies inputs and outputs of the product life cycle, and energy use continues to be a key aspect of the LCI.

There is an active process at international and European level to develop standards for sustainability assessment of buildings, which follows an LCA approach. Within the CEN Technical Committee 350—Sustainability of Construction works, the standard EN 15978 *'Sustainability of construction works—*

*Assessment of environmental performance of buildings—Calculation method'* (CEN 2011) has been developed for the assessment of the environmental performance of buildings, based on LCA and other quantified environmental information.

The standard is applicable to new and existing buildings and refurbishment projects and provides

- the description of the object of assessment;
- the system boundary that applies at the building level;
- the procedure to be used for the inventory analysis;
- the list of indicators and procedures for the calculations of these indicators;
- the requirements for presentation of the results in reporting and communication;
- the requirements for the data necessary for the calculation.

The approach to the assessment covers all stages, which have been structured in four main different life cycle stages: product stage, construction stage, use stage and end of life stage. Inside each building stage, various substages are included, for example, product stage considers raw material supply, transport to product manufacturing and manufacturing process. In the construction stage, transport of the product to the building site and construction or installations of the product are included. The use stage considers issues such as operational energy and water usage, plus activities related to the actual use, repair and maintenance. The end of life stage includes deconstruction or demolition processes, transport and waste processing until final disposal. There is an option for considering the potential benefits of recycling, reusing or recovering products after their end of life within the framework structure. Figure 1 describes the building stages in a simplified diagram.

Not directly related to LCA but frequently used for environmental assessment of buildings, there are a number of voluntary certification methods such as LEED (US Green Building Council 2013) or BREEAM (Building Research Establishment 2013) that consider different environmental aspects of buildings, through a number of criteria that are weighted to obtain a final building environmental performance classification. These systems offer a wide perspective of potential environmental implications of buildings, including besides the evaluation of energy and products, issues such as water or indoor environmental quality. In relation to the assessment of building products, it is not directly linked to the quantified environmental impact or embodied energy, but limited to the consideration of some criteria related to reuse, recyclability, transport used through the supply chain, or to the fact that materials are renewable or not. Therefore, these methods do not fully implement an LCA methodology and their validity to assess the life cycle performance of a building is limited.

There are also detailed LCA tools such as SIMAPRO (PRé Consultants 2013) or GABI (PE International 2013), which offer the possibility of analysing in detail the range of environmental aspects of materials and buildings, including embodied energy. Despite the potential and capabilities of such tools to aid in the design of

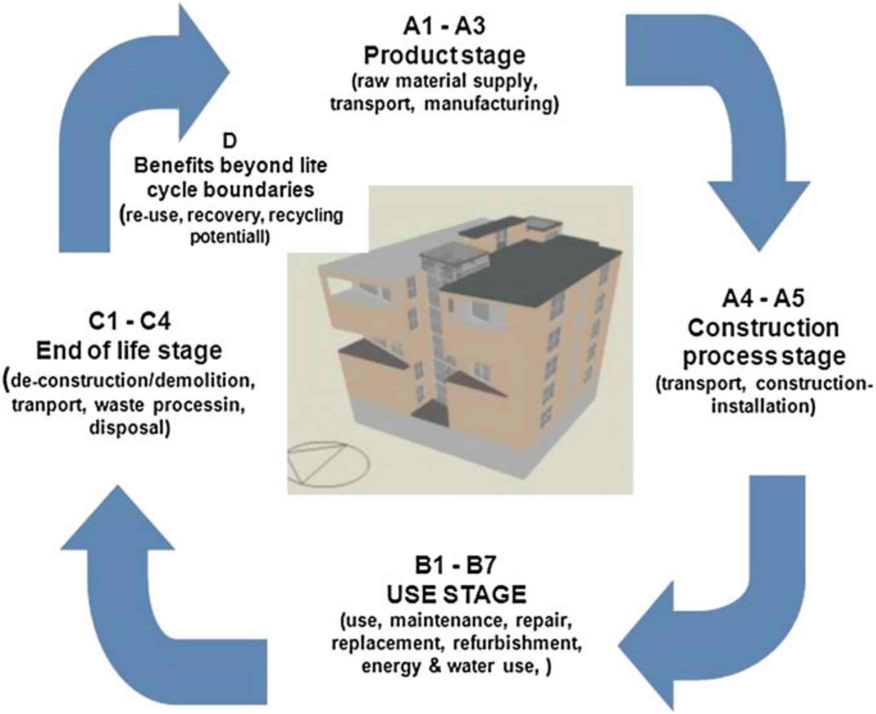

**Fig. 1** Description of building life cycle phases with EN 15978 nomenclature

buildings to minimize the environmental impact, they are still rarely used for building assessment and in particular for refurbishment projects, perhaps because of their relative complexity which makes them impractical for use by a design team.

Finally, there are other recent tools such as ELODIE (CSTB 2012) that provide simplified interfaces that allow building environmental performance assessment following a life cycle structure, or tools such as ENERBUILCA (2012), focusing on life cycle energy performance, which can allow for a calculation following the CEN TC 350 structure and life cycle perspective.

This chapter deals with the concepts of LCA in the context of refurbishing buildings towards ‘zero energy’ and presents a simplified method for evaluation of the life cycle energy performance, which consists of integrating results from the energy performance evaluation at the use stage and the embodied energy of the products added in a refurbishment project.

## 3 Simplified Methodology for Life Cycle Energy Performance Evaluation in Building Refurbishment Projects

The advantage of the proposed simplified methodology is that it can facilitate life cycle energy performance evaluation, through the combination of embodied energy data for products with energy assessment tools already applied for the use stage of the buildings, such as national tools for building regulation compliance and building energy ratings. The embodied energy of the products is in this chapter considered from ‘cradle to gate’, which means including all energy inputs to a product, expressed in primary energy, from extraction to manufacturing, until the product leaves the factory gate. This approach is proposed as the basis for this methodology as it is the most commonly used value referenced in embodied energy studies (Hammond and Jones 2008). It has to be noted, however, that a full life cycle energy performance evaluation would also include transport to the building site, construction processes and the ‘end of life’ part of the life cycle, considering demolition and recycling potential or landfill. These additional life cycle stages have not been considered in this chapter, partly because of lack of relevant data and partly because the energy use on those stages have been reported in various studies as being below 1 % of the total life cycle energy (Sartori and Hestnes 2007). However, it is acknowledged that these aspects could have a potentially high impact in some situations, as discussed by various authors (Itard and Klunder 2007; Thormark 2006; McCall and McNeil 2007), and it is suggested that an extended life cycle should be used if reliable embodied energy data are available. More research is needed in a detailed quantification for these life cycle phases for future inclusion in the analysis, particularly as they gain increasing relative importance as the building use stage decreases towards zero-energy use.

For the life cycle energy performance evaluation method presented here, the embodied energy of construction products and systems used in the refurbishment project, calculated up to the product factory gate, is added to the annual operational energy use, so the influence of the different building options can be compared. The embodied energy values presented in this chapter can therefore be considered slightly underestimated as transport to site, construction and end of life stage have not been considered.

The representation of embodied energy in an annualized form (divided by the expected lifetime of the product) will allow representation of life cycle energy performance in a common indicator, for example, kWh/m$^2$*year, which is an indicator already used for regulations and building energy rating in some EU countries. This is a way of simplifying the understanding and application of life cycle energy performance evaluation by architects and other design team members on a refurbishment project.

The following sections will deal with the different steps included in the life cycle energy performance evaluation and will introduce the concept of ‘NER’, as an indicator to define optimal refurbishment strategies from a life cycle energy perspective.

## 3.1 Calculating Annual Energy Savings (AES)

Methodologies for energy performance assessment of buildings at use stage are well developed and used throughout the world. Energy use calculations have evolved from steady-state heat loss and semi-static monthly energy demand calculations to complex dynamic energy performance simulation tools which can model annual energy use over very short intervals (hours, minutes, even to a fraction of a second). Simulation programs have been compared in various papers (Crawley et al. 2008; van der Veken et al. 2004), and detailed building energy simulation practice is extensive not only within the research community but also in the building industry. International standards such as EN ISO 13790 *'Energy performance of buildings—Calculation of energy use for space heating and cooling'* (CEN 2008a), which include monthly calculation methodologies, are considered of sufficient accuracy for application in energy certification. Although ideally every energy use should be considered in a building energy calculation method, factors such as plug-in loads and equipment are generally excluded in some calculation methods, particularly in energy rating and certification methods. In refurbishment projects, and particularly if the typology and pattern of use of the building are not expected to change after refurbishment, it is generally good practice to analyse historical energy use in the building to more accurately estimate potential energy savings.

In the context of the present methodology for life cycle energy performance evaluation, it is suggested that any validated building energy calculation method could be upgraded to include a 'life cycle' perspective as proposed. The only prerequisite for the application of the proposed methodology is the conversion of the energy use results into 'primary energy' values. Some of the available methodologies' software already provides results directly in the form of primary energy, by using national average factors for the different fuels used. Where the calculation tool does not directly offer this possibility, conversion factors for the different fuels used need to be applied and implemented in accordance with national guidelines. For countries that have no defined national primary energy factors, definitions can be found, for example, in EN 15603 *'Energy performance of buildings—Overall energy use and definition of energy ratings'* (CEN 2008b). However, it must be noted that there are multiple issues related to calculating 'primary energy', in particular when renewable energies are considered, which are the subject of debate, as discussed by Segers (2008).

Once the assessment methodology for energy performance calculation during use stage is selected, the expected annual energy use and corresponding energy savings can be expressed, for example, in kilowatt-hour of primary energy, per square metre and year ($\text{kWh/m}^2\text{*year}$).

## *3.2 Sources for Embodied Energy and Calculating Annualized Embodied Energy (AEE)*

Obtaining embodied energy data for a refurbishment project which can include multiple products and processes is still a challenging task, as reliable data are not easily available for a wide range of products, or existing data for one region are not generally applicable to another region.

Environmental product declarations (EPD) or Type III Ecolabels, according to ISO 14025 *'Environmental labels and declarations—Type III environmental declarations—Principles and procedures'* (ISO 2006b), are one of the most reliable sources of data, as they include third-party verification. The standard EN 15804 *'Sustainability of construction works—EPD—Core rules for the product category of construction products'* (CEN 2012) establishes main rules and information necessary and relevant for carrying out an EPD. The EPDs according to EN 15804 present the results in a set of environmental indicators, which include primary energy use, which is the indicator used in this chapter in the context of life cycle energy performance evaluation for buildings and is what we referred to as 'embodied energy'. EPDs are published by different programme operators in Europe, some of which are listed in Table 1. The European Eco-Platform aims to act as an umbrella body for all national EPD programmes, ensuring the published EPDs follow methodology and rules and aiming for European wide recognition between programmes.

When product-specific EPDs cannot be sourced, generic values for the products need to be used instead. There are countries which already have national databases for environmental data of construction products, such as Germany (www.okobau.dat) or the Netherlands (www.milieudatabase.nl). These databases present default environmental data from which embodied energy values can be gathered in case a product-specific EPD is not available.

There are also some efforts to compile data from different literature sources, specifically for embodied energy and embodied carbon of building products, such as the inventory compiled by Hammond and Jones (2008).

As a final alternative source for information on embodied energy, there are commercial databases like ECOINVENT (Swiss Centre for Life Cycle Inventories 2010), or GABI (PE International 2013), which contain thousands of datasets with a wide range of environmental impacts, from which embodied energy can also be extracted.

Even with the mentioned sources, it can be noted that there is still a low availability of environmental and embodied energy for specific construction products that might be used in a real refurbishment project and particularly for innovative products. However, the situation is likely to improve throughout Europe in the short term, as increasing regulations aim for reducing environmental impacts and for disclosure of environmental information. A key regulation in this aspect is the Construction Product Regulation (EU Parliament and Council 2011),

**Table 1** Some of the main EPD programme operators in Europe

| EPD system | Operator | Web page and EPD publication |
|---|---|---|
| Environmental profiles | BRE (building research establishment) | www.bre.co.uk |
| Umwelt-Deklarationen | IBU (Institut Bauen und Umwelt e.V.) | http://bau-umwelt.de |
| Déclaration Environnementale et Sanitaire pour les produïts de construction (FDE&S) | AFNOR | http://www.inies.fr |
| EPD® system | International EPD consortium | www.environdec.com |

already mentioned in the introductory chapter of this book, which includes a new basic work requirement (BWR 7) stating the following:

*The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:*

1. reuse or recyclability of the construction works, their materials and parts after demolition;
2. durability of the construction works;
3. use of environmentally compatible raw and secondary materials in the construction works.

This BWR 7 is therefore an important step to incorporate sustainability into building products and quantify environmental information, including embodied energy. There is obviously a need for standardization to assess this BWR, and newly developed standards, such as the commented EN 15804:2012, are a good step in this direction and have now to be adapted and applied to the different construction sectors and products. In practice, the BWR 7 became mandatory on July 2013, and since, construction products have to assess the environmental impact and sustainable use of resources, and therefore, availability of indicators such as embodied energy of products should become much more widespread.

Once the embodied energy of a product is sourced, the following task is to estimate their service life, to be able to 'annualize' the embodied energy data, with the aim of integrating with the energy performance in use stage, generally given in annual values. For HVAC or renewable energy systems that might be used in a project, it may be as straightforward as estimating a service life based, for example, on manufacturer's guarantees, although it is preferable to use real-life expectancy if national or regional data are available. For other components of a building or a refurbishment project such as envelope and structure, life expectancy could be much more difficult to establish, as some components might last for hundreds of years with little refurbishment, while others might experience various major refurbishments or even be demolished within 50 years or less. Certain types of buildings, such as speculative office developments, can often be refitted within much shorter periods. ISO 15686 ‘Buildings and constructed assets—Service life planning’ (ISO 2008) provides some guidance on how to predict the service life of buildings and products. 50 years is frequently used as a typical value for the service life of buildings before they undertake major renovations in many studies, (Malmquist et al. 2010) so this value is suggested here where no other data are available.

The embodied energy data for each material, system or product, divided by the expected service life, will be finally presented in kWh of primary energy per year of service life. In this chapter, we will denominate this as AEE.

### *3.3 Calculating Life Cycle Energy Performance*

From a life cycle energy perspective, the annual energy savings of a building refurbishment project must only be taken into account after the embodied energy of added building components and systems is subtracted. In the previous sections, we have explained how the annual energy savings and embodied energy values can be calculated and expressed in primary energy units per year. This now serves to allow direct comparison of the results, so the impact of the building materials can be discounted to the expected energy savings from the refurbishment project. The life cycle energy performance of the refurbishment project will therefore consider both the energy savings and the embodied energy of the products, as shown in Fig. 2.

An optimal refurbishment strategy would be one that would have the best life cycle energy performance, that is, that would achieve high energy savings without a high increase in the embodied energy of the products added to the building.

The life cycle energy performance can be also represented in an XY graph, where the horizontal axis is the AEE and the vertical axis the annual energy use (AEU) of the different refurbishment options.

The life cycle energy saving of a refurbishment strategy would be measured as the distance to a 45° line, which would represent actuations that would have as much embodied energy as the expected energy savings in the use phase, and therefore would not represent any life cycle energy savings. Plotting different refurbishment strategies in this graph, we can observe potential life cycle energy savings for a particular refurbishment project, as it is described in Fig. 3.

A refurbishment project that would be improved to a ‘zero-energy’ building would always have an increase in embodied energy. If the building would produce (export) enough energy to compensate the embodied energy increase, then only in this case the refurbished building could be defined as a life cycle zero-energy

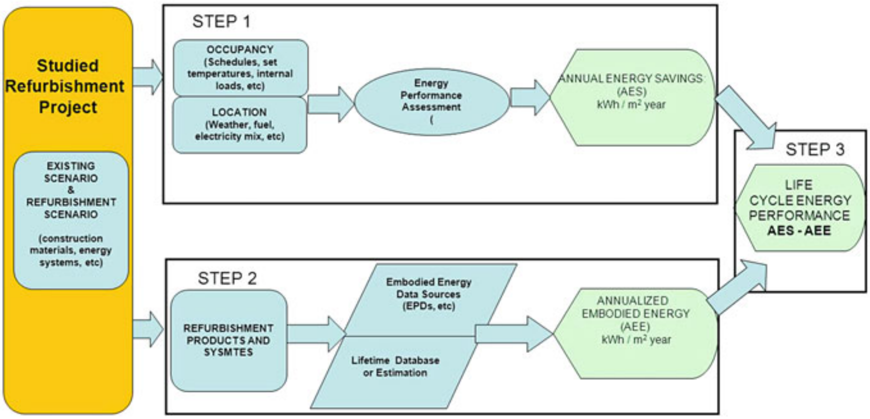

**Fig. 2** Flow diagram of proposed methodology for life cycle energy performance evaluation of refurbishment projects

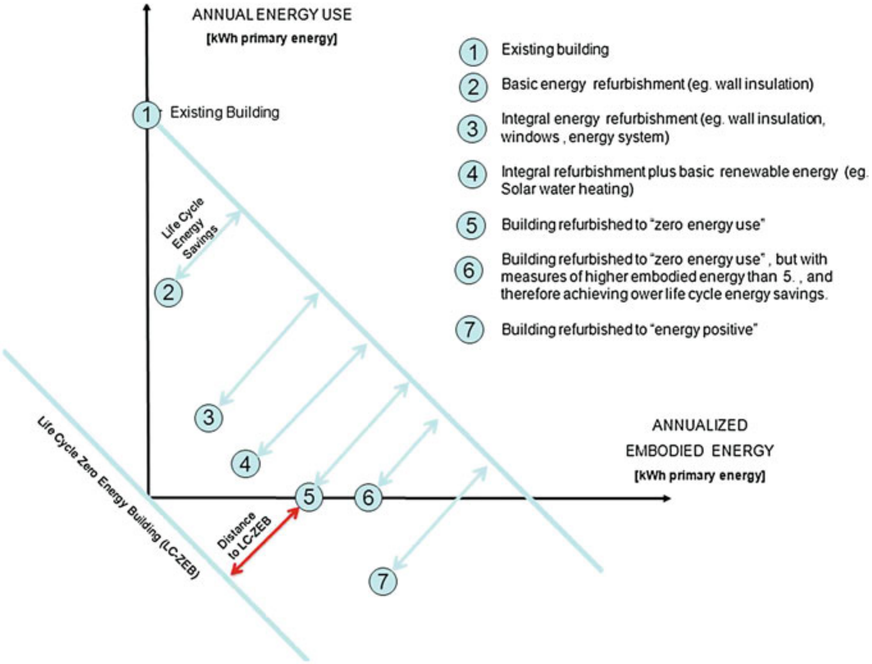

**Fig. 3** XY graph showing life cycle energy savings for some generic refurbishment options. It also shows distance to a life cycle zero-energy building for Option 5, which is a refurbishment of a building to 'zero-energy' use status

building (LC-ZEB). The refurbishment option that will get closer to this LC-ZEB will be those that have the lowest sum of operational and embodied energy and therefore the best life cycle energy performance.

The AEE is always above zero in a refurbishment project when we need to add new products and systems, but ideally the added embodied energy should be as low as possible to ensure that large life cycle energy savings are achieved. When we refurbish a building towards ‘zero-energy’ use in operation, or even to be an ‘energy-positive’ building, this requires the installation of some form of renewable energy systems. However, the renewable energy systems must be considered as any other building component and so their additional embodied energy is also annualized and enters the equation as a part of the AEE. Therefore, when including renewable energy installations in a building refurbishment and trying to optimize life cycle energy performance, installations with a high environmental performance and high ‘net energy’ input, which is a large ratio of energy produced to their embodied energy, would be part of an optimum refurbishment solution. Oversizing of building components or renewable energy systems with the sole intention of bringing the annual energy use to zero could result in a high increase in AEE, meaning that the total life cycle energy savings might not be significantly reduced or could even increase.

The life cycle energy performance calculation presented here can serve as an indicator of the true value of the efforts to minimize energy use in the built environment, taking into account the frequently hidden or indirect energy uses attributed to products and systems. As it will be explained in the next section, this perspective can help to improve life cycle energy performance of a refurbishment project. However, for the life cycle energy optimization presented in the following section, it has to be taken into account that we are in all cases discussing strictly and solely the life cycle energy performance perspective of a refurbishment project, without addressing all other social, economic and environmental issues potentially associated with the project.

## *3.4 Life Cycle Energy Optimization*

The building industry’s advance towards zero energy means a probable increasing integration of additional energy saving and renewable energy products in refurbishment projects. The main advantage of the methodology presented here is that it allows carrying out comparative analysis of the life cycle relevance of design decisions in refurbishment projects, in relation to building envelope design, materials, HVAC and renewable energy systems. All such components can be included in the analysis through the analysis of their impact on annual energy use and AEE. Historically, this approach has not been considered in very low energy building design. There could arise situations where systems or building components are unintentionally overspecified, and it can be argued that some of the first and remarkable examples of ‘zero-energy houses’ in history might have been in this situations. For example, the 1939 MIT Solar House I, which included a large solar thermal collection area and water storage (Butti and Perlin 1980), the 1955 ‘Bliss House’ (Bliss 1955), which used large area of solar air collectors and rock mass storage, or the 1970s Vagn Korsgaard Zero Energy Home in Denmark (Esbensen and Korsgaard 1977), all probably had a very large embodied energy associated with the installed systems. The life cycle performance of those exemplary houses might have been even better with smaller solar collecting surfaces. Hernandez and Kenny (2008a, b) explained how extra care must be taken in current ‘zero-energy’ building design to avoid overspecification of certain components, as the use of large areas of thermal solar collectors for water and space heating together with high levels of insulation, as is often promoted, might not be the most efficient way of reducing the life cycle energy for some building typologies. In the context of refurbishment towards zero-energy buildings, other design strategies might offer more appropriate solutions, particularly in less extreme climates such as in maritime Europe.

To support practitioners willing to consider building energy refurbishment projects from a life cycle perspective and use it as an input for the design, the concept of ‘NER’ can be introduced. This indicator, frequently used in the renewable energy field, sometimes also called Energy Return of Investment, Energy Returned on Energy Invested or Energy Yield Ratio, can be represented for the refurbishment of an existing building through the following formula:

$$\mathrm{NER} = \frac{\mathrm{AEU}_1 - \mathrm{AEU}_2}{\mathrm{AEE}_2 - \mathrm{AEE}_1} \tag{1}$$

The NER can be defined for building refurbishment as the ratio of the decrease in annual energy use (annual energy savings) to the increase in AEE. This ratio can be used to compare refurbishment options for improving energy performance in use: the higher the NER of a particular refurbishment strategy, the more effective it will be in delivering life cycle energy savings.

All options where the NER is greater than one will contribute to an improvement in life cycle energy performance, an energy saved over the life cycle. The higher the NER of a refurbishment strategy, the larger the life cycle energy savings.

This introduction of the NER to the built environment allows different refurbishment strategies, related to building envelope, building control or energy systems, lighting, etc., to be compared with NER values of renewable energy systems, which are extensively published and discussed (Mulder and Hagens 2008). For example, the first layer of insulation in a typical existing house would normally yield very high NER, as would save a large amount of energy with a small amount of material. Subsequent layers of insulation, while adding to the total embodied energy, would not deliver an equivalent energy saving, and so a refurbishment of a building envelope would represent a diminishing NER as we increase the insulation thickness. Technologies such as solar water or space heating systems would also generally represent a diminishing NER with the size of the installation, as the annual solar input rate per square metre of installation decreases at constant heat demand, once we have surpassed the summer base load with the summer solar input. This frequently occurs with large solar installations, which are in practice oversized for the summer, and progressive increases in collector sizes do increase embodied energy but not proportionally increase the solar energy input. Technologies such as PV, however, will have a practically constant NER independent of their size as the production of electricity will be proportional to the quantity of materials used in their production and installation.

In the following section, a life cycle energy performance evaluation will be performed as an example, using a typical house in Ireland as a case study.

## 4 Application of Life Cycle Energy Performance Evaluation to a Case Study Building

To illustrate the method presented, a residential house in Ireland is used as a case study. The house size and type were selected from an example in the Irish Building Regulations Technical Guidance Document L (Minister for the Environment Heritage and Local Government 2007). The details of the case study house correspond to a semi-detached two-storey house, (Fig. 4), with a total floor area of 96 $m^2$, distributed on two floors, and with east–west orientation. A picture of a semi-detached house can be seen in Fig. 4.

Table 2 shows some basic energy performance-related parameters related to the existing house and different options that have been tested to represent refurbishment options. The measures included in the analysis have the refurbishment of the opaque envelope increasing insulation levels, refurbishment of the windows to better efficient ones, installing a mechanical ventilation heat recovery system (MVHR) and installing photovoltaic systems and solar thermal collectors.

The changes in insulation levels can be observed in the provided U-value of the building envelope, reduced from 0.45 W/m2 K in the existing situation, which represents approximately 30 mm of expanded polystyrene insulation in a cavity wall, to values as low as 0.10 W/m2 K for the options with lower energy use, which would represent construction solutions with up to 300 mm of expanded polystyrene insulation. All refurbishment strategies include the substitution of incandescent light energy bulbs for efficient compact fluorescent lamps. They also include changing of the existing boiler of 75 % efficiency for a new one with 90 % seasonal efficiency. Different window specifications can also be observed through the display of U-values and solar transmittance, representing changes to double low-E glazing or to triple glazing.

Solar water heating is included from Option 3 onwards, with 5 $m^2$ of flat-plate collectors initially and doubling the size in options 8 onwards. The introduction of MVHR systems is considered in options 7 onwards, and an efficiency of 85 % and

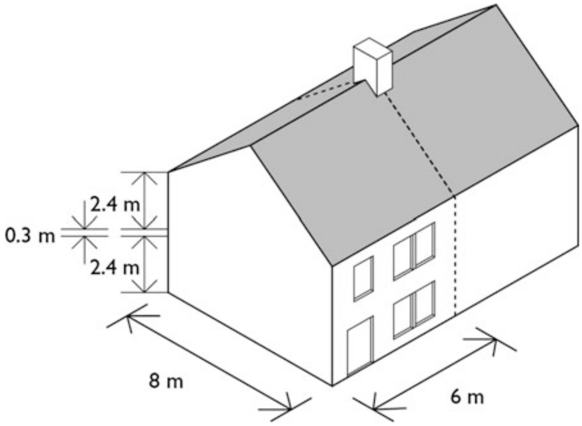

**Fig. 4** Case study semi-detached dwelling characteristics

**Table 2** Main characteristics of existing building and refurbishment options considered in the analysis

| | Opaque envelope $U$-value (W/m$^2$K) | Windows $U$-value (W/m$^2$K) | Solar transmittance | MVHR | Solar thermal (m$^2$) | PV (m$^2$) |
|---|---|---|---|---|---|---|
| 1 (existing) | 0.45 | 3.1 | 0.76 | No | 0 | 0 |
| Option 2 | 0.21 | 2.2 | 0.72 | No | 5 | 0 |
| Option 3 | 0.14 | 1 | 0.6 | No | 5 | 0 |
| Option 4 | 0.12 | 1 | 0.6 | No | 5 | 0 |
| Option 5 | 0.10 | 1 | 0.6 | No | 5 | 0 |
| Option 6 | 0.10 | 1 | 0.6 | Yes | 5 | 0 |
| Option 7 | 0.10 | 1 | 0.6 | Yes | 10 | 0 |
| Option 8 | 0.10 | 1 | 0.6 | Yes | 10 | 6 |
| Option 9 | 0.10 | 1 | 0.6 | Yes | 10 | 12 |
| Option 10 | 0.10 | 1 | 0.6 | Yes | 10 | 18 |

a specific fan power of 1.0 W/l/s have been assumed. The introduction of PV panels is analysed from Option 9, with size increasing for subsequent options.

The solar thermal collectors chosen for this analysis are specified as flat-plate collectors with an efficiency factor of 0.8 and a linear heat loss coefficient factor of 3.5. Solar PV panels are specified as multicrystalline silicon with a peak power coefficient of 0.15 kW/m$^2$, as per standard typical values from EN 15316 (CEN 2007a, b).

Step 1 of methodology described for calculation of life cycle energy performance is to calculate the energy performance in the use phase. The DEAP analysis tool (Sustainable Energy Authority of Ireland 2007) has been used for this purpose, calculating the energy end uses for each of the cases considered. All results, as displayed in Fig. 5, are directly calculated within the DEAP methodology, except

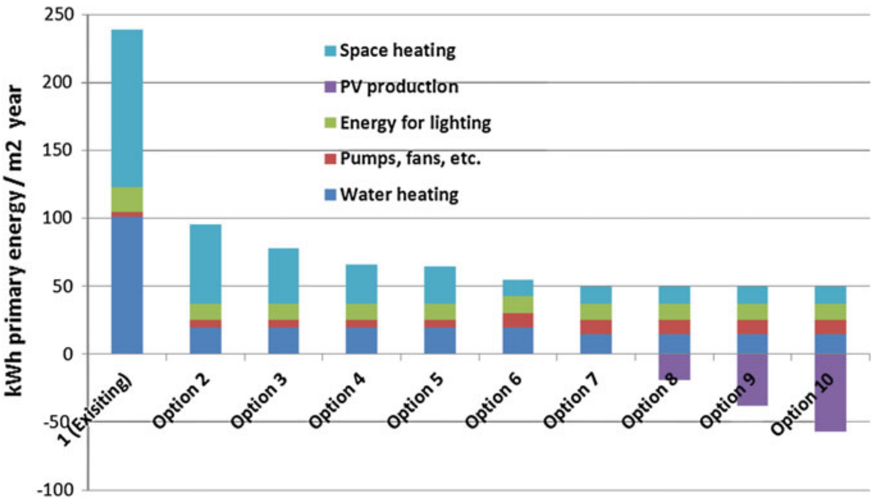

**Fig. 5** Energy performance of the existing building and refurbishment options considered

the production of electricity by PV which has been calculated according to the CEN standard (CEN 2007b). This electricity generation is converted to primary energy using a conversion factor of 2.7, factor used in Ireland within the DEAP methodology. Using this conversion factor, each square metre of installed PV equates to primary energy savings of 304 kWh per year.

It can be observed that space heating is the main energy use for the existing dwelling case study option, accounting for around 50 % of the total energy use. As the different refurbishment strategies are considered, the energy use can be progressively reduced. As it can be observed, energy reduction for heating and hot water can be greatly reduced with the first renovation option, which would include insulation and windows upgrade, efficient lighting and solar thermal collectors. Subsequent options to improve energy performance of the refurbished building do not achieve such large energy savings, and by Options 6 and 7, the savings made with 'passive' building measures are very small. The primary energy use at this stage is, however, quite small, of about 50 kWh/m$^2$ for Option 7. To progress until the zero-energy use objective, which is achieved for Option 10, additional renewable energy has to be added which includes 18 m$^2$ of solar PV and 10 m$^2$ of solar thermal panels.

For the second step of the proposed methodology, which is the quantification of the AEE for the products, the embodied energy has been sourced from some of the sources already commented in previous section such as ECOINVENT database (Swiss Centre for Life Cycle Inventories 2010) and the Inventory of Carbon and Energy by Hammond and Jones (2008). Some additional references were consulted for domestic solar water heating systems with flat-plate collectors (Asif et al. 2007; Ardent et al. 2005a; Kalogirou 2004, 2009; Crawford and Treloar

**Table 3** Estimated embodied energy values for selected materials and components used in the case studies

| Material/system | Embodied energy | Service life (Yrs) |
|---|---|---|
| Polystyrene insulation | 88 MJ/kg (24.4 kWh/kg) | 50 |
| Solar water heating system (5 $m^2$) | 6,000 kWh | 20 |
| Solar water heating system (10 $m^2$) | 10,000 kWh | 20 |
| PV installation, per $m^2$ | 1,700 kWh | 25 |
| Double-glazed windows, per $m^2$ | 300 kWh | 30 |
| Triple-glazed windows, per $m^2$ | 400 kWh | 30 |
| Mechanical ventilation heat recovery system | 9,000 kWh | 50 |

Includes annual replacement of filters and of the ventilation unit every 20 years

**Table 4** AEE for components for each case of building refurbishment options (kWh/year), for the case study house (96 $m^2$)

| | Additional envelope insulation | Triple glazing | Solar water heating | MVHR | PV | Total AEE (kWh/year) |
|---|---|---|---|---|---|---|
| 1 (existing) | 0 | 0.0 | 0 | 0 | 0 | 0 |
| Option 2 | 159 | 0.0 | 300 | 0 | 0 | 459 |
| Option 3 | 284 | 73 | 300 | 0 | 0 | 657 |
| Option 4 | 381 | 73 | 300 | 0 | 0 | 754 |
| Option 5 | 450 | 73 | 300 | 0 | 0 | 824 |
| Option 6 | 450 | 73 | 300 | 180 | 0 | 1,004 |
| Option 7 | 450 | 73 | 500 | 180 | 0 | 1,204 |
| Option 8 | 450 | 73 | 500 | 180 | 408 | 1,612 |
| Option 9 | 450 | 73 | 500 | 180 | 816 | 2,020 |
| Option 10 | 450 | 73 | 500 | 180 | 1,224 | 2,428 |

2004; Hernandez and Kenny 2012) and for PV systems (Pacca et al. 2007; Nawaz and Tiwari 2006; Raugei et al. 2007; Richards and Watt 2007).

Data displayed in Table 3 have been chosen according to those sources by the authors as best estimates for Ireland for some selected building components and also the estimated service life for each of the products. As an Irish database or a consistent methodology for embodied energy calculation does not exist at present, it needs to be emphasized that these estimates are limited exclusively to illustrate the proposed methodology and there is a high degree of uncertainty, particularly regarding the lifetime of the products and embodied energy values for the installations.

Comments on sensitivity of the results are made in a later section (Table 4).

Dividing the total AEE by the building area, the results can be integrated with the annual energy performance calculation, as it is presented in the Fig. 6.

It can be observed that for the first refurbishment Option 2, the AEE represents a very small portion of the total life cycle energy use, so the achieved energy

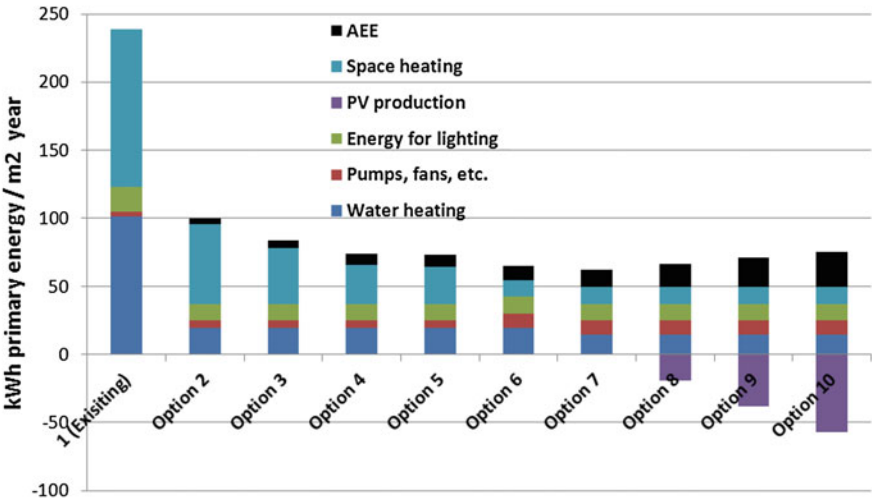

**Fig. 6** Life cycle energy performance of the existing building and refurbishment options considered. *Black* section represents the AEE added in the refurbishment project, per square meter of building area

savings in use phase are very large in comparison with the invested embodied energy.

The importance of AEE progressively increases as the refurbishment keeps improving energy performance, and it can be seen as a relatively important part of the life cycle energy use as we approach the zero energy.

As commented in the previous section, one of the potential uses of this methodology is to provide design advice taking into account the life cycle performance, by using the NER for advising on best energy saving measures. NER can help identifying solutions that would reduce the total energy use over the life cycle of the building. The higher the NER of a refurbishment strategy, the more effective it will be in reducing the life cycle energy use of the building. The NER has been calculated for each progressive improvement between the case study options. The results are shown in Table 5.

It can be observed that initial measure increasing insulation and installing a domestic solar water heating system provides a very high energy ratio of 30 times in energy savings that the energy invested in the products. The following change to Option 3, which includes the installation of further insulation and triple-glazed windows, has a lower ratio below 10, in part due to the relatively lower energy savings that triple-glazing windows achieve in relation to low-E double glazed, in that particular house in the mild Irish climate. It can be observed that improving insulation another step up to Option 4 with $U$-value of 0.12 W/m$^2$ K still gives an NER above 10 and is therefore still a very good option. Another upgrade of insulation levels up to 0.10 W/m$^2$ K does, however, dramatically reduce the NER

**Table 5** NER for successive improvements

| | Annual energy savings ($-\Delta$AEU) (kWh/m2 year) | $\Delta$AEE (kWh/m2 year) | NER ($-\Delta$AEU/$\Delta$AEE) |
|---|---|---|---|
| Existing → Option 2 | 143.9 | 4.8 | 30.1 |
| Option 2 → Option 3 | 17.5 | 2.1 | 8.5 |
| Option 3 → Option 4 | 11.7 | 1.0 | 11.7 |
| Option 4 → Option 5 | 1.5 | 0.7 | 2.1 |
| Option 5 → Option 6 | 9.6 | 1.9 | 5.1 |
| Option 6 → Option 7 | 5.1 | 2.1 | 2.4 |
| Option 7 → Option 8 | 19.0 | 4.3 | 4.5 |
| Option 8 → Option 9 | 19.0 | 4.3 | 4.5 |
| Option 9 → Option 10 | 19.0 | 4.3 | 4.5 |

obtained to just above 2. This result emphasizes the large life cycle energy savings that can be achieved by insulating buildings where there are high transmission losses or by the installation of a small domestic solar hot water system as are the issues considered in Option 2. However, an increase in polystyrene insulation to an already well-insulated building, as described in the proposed improvement between Option 4 and Option 5, only yields an NER of 2.1. In such cases with very high insulation levels, the use of insulation products with lower embodied energy content, such as products based on rapidly renewable materials, which can achieve similar savings compared to conventional materials with little associated embodied energy, could achieve a much higher NER.

Regarding the further options looking for a further decrease in energy use towards zero energy, the measure changing to Option 6 which considers installation of MVHR gives a value above 5, which means that there is a potential, in life cycle energy terms, for the installation of this technology in this case study. Considering a further increase in solar thermal collection area as it is the change to Option 7 shows an NER of 2.4, relatively low which shows that solar heating in this climate with low winter solar access is perhaps not the most adequate measure. For Option 8 onwards, which considers the addition of PV, the calculated NER is 4.5. These values for building integrated renewable energies are relatively small when compared with some off-site renewable energy. For example, off-site renewable energy production from wind energy can have NER values in the range of 10–30 (Kubiszewski et al. 2010; Crawford 2009).

## 5 Uncertainty and Sensitivity Analysis

The presented methodology for life cycle energy performance evaluation is affected by both factors linked to building energy performance in the use phase and factors linked to the assessment of embodied energy of the products.

Regarding energy performance of the building in operation, parameters related to local climate and building design and orientation are mostly fixed in refurbishment projects, and issues such as wind exposure and solar access can be considered in detail before carrying out a refurbishment project. User behaviour and preferences can also be addressed although uncertainty is quite high and they can also largely influence the results. For example, a significant impact on the reduction in household energy use could be achieved without any or little associated embodied energy by assuming more conscious energy behaviour of the occupants. This substantial reduction in energy use, in the case, for example, of appliances and lighting, could also result in diminished internal gains, which would mean that the heating energy demand could increase. On the contrary, careful control of the heating, and flexible approach to thermal comfort by the occupants could mean large savings in HVAC use. Uncertainty and sensitivity analysis on building energy performance calculation methods have already been analysed in detail in various studies (Hopfe 2009), so it will not be discussed in this section.

Regarding calculation of embodied energy for the products, as it has been commented, data on factors such as service life or maintenance required for energy systems of renewable energy present a high degree of uncertainty. While commercial LCA software nowadays contains tools for a detailed sensitivity and uncertainty analysis, including methods such as probabilistic Monte Carlo simulations, many times the data necessary to perform a thorough sensitivity analysis of embodied energy, such as the one performed in this chapter, are lacking. For this reason, the use of a single value has been considered more appropriate in this chapter for clarity and simplicity of the representation of results. However, some comments can be made on the sensitivity of the results:

The choice of insulation material and its assumed lifetime has a large effect on the results. For this study, it has been assumed a combination of an insulation material with large embodied energy (88 MJ/kg), and a relatively long associated service life (50 years). If service life would be diminished, as it could be considered in cases such as external insulation techniques or construction elements in particularly harsh climates, the annualized embodied energy would be proportionally increased, and therefore, life cycle energy savings and NER of the refurbishments would be lower. On the other hand, if equal insulation levels would be achieved with other insulation materials with a lower embodied energy than polystyrene, life cycle energy performance would improve. Options using alternative products might include mineral wools (approximately four times less associated embodied energy than polystyrene) and other natural or rapidly renewable products with practically no associated embodied energy (Hammond and Jones 2008). These observations highlight the influence that the proposed methodology would have on supporting the specification of materials with long associated service life and low embodied energy in refurbishment projects. Ideally in the near future, the application of this method would consider the value of embodied energy given in verified EPD for a component from a specific manufacturer, which will take into account its sourcing and production process, and therefore would promote those products with less associated embodied energy. Some EPDs could even provide information beyond the factory gate, that is, about the construction process or recyclability potential of the product, which could serve for more detailed analysis in an extended methodology, following a methodology such as described in the standard EN 15978:2011 already commented in a previous section.

Taking into account both uncertainty and sensitivity of both issues (energy performance in use and embodied energy) at the same time, it has to be noted that some variables that affect the building use phase, and can be analysed through energy performance evaluation, also have an effect on the other phases of the building and on the embodied energy calculations, adding complexity to a sensitivity analysis. For example, a detailed analysis could show that depending on the user ventilation or temperature preferences, certain building solutions might be possible with less services and systems, therefore having less embodied energy. An analysis of all those questions together and performing a sensitivity analysis of their interaction and implications would require specialized software that at the moment, to the knowledge of the author, is not yet available. In the meantime, the proposed simplified methodology such as the one presented has as the intention is to be understood and preliminary applied taking into account the recognized uncertainty on the sources and sensitivity of the results. As data sources are improved, this method could be applied by relevant stakeholders on building refurbishment, from architects and engineers who could use the methodology for design advice, to policy makers who could use it to improve building energy-related policies, such as the establishment of requisites, goals and funding schemes for building refurbishment projects.

## 6 Discussion and Conclusions

This chapter has presented a methodology to account for life cycle energy performance evaluation in building refurbishment projects, by integrating existing building energy evaluation methods with embodied energy calculations. Using the methodology, the life cycle energy savings of different refurbishment strategies can be compared and analysed, with a wider perspective than looking solely at the energy performance of the building during the use phase. Taking into account this life cycle perspective, there is a recommendation for giving more attention to the types of materials and systems used on refurbishment projects that have the objective of moving towards ‘zero energy’ or ‘net zero energy’. While approaching the zero-energy goal, the life cycle energy savings must be considered and perhaps the objective needs to be redefined as refurbishment for LC-ZEB, where the objective is a building whose primary energy use in operation plus the energy embedded in materials and systems over the life of the building is equal or less than the energy produced by renewable energy systems within the building. The use of this definition could substitute or expand current definitions of 'net zero-energy buildings' or 'near-zero-energy buildings', including a life cycle perspective. The actual lack of data on embodied energy, which makes difficult the immediate application of the presented methodology, has been pointed out. However, as data become increasingly available, for example with the uptake of EPDs, the methodology described could be useful for policy making, including further development of building regulations and schemes as building energy ratings. The concept of 'NER' as a life cycle energy indicator for use within building energy analysis has also been introduced, as an indicator which allows comparing building refurbishment options and specification decisions, in between them and also with other options such as building integration of renewable energies. This indicator has the potential to make clearly visible the true impact of design decisions influencing energy use over the full life cycle of a building.

The adoption of an accepted dataset of embodied energy values and service life of building components and systems is the main difficulty in the application of the proposed methodology for life cycle energy evaluation. Some data sources have been presented, and there is a good development in this area as new regulations such as the Construction Product Regulation requires the declaration on sustainable use of natural resources. The service life of buildings, products and systems is another of the main assumptions that must be applied when using the proposed methodology. A more detailed lifetime prediction for different building types and for different components and products should be used when available. Future improvement in data availability is particularly necessary for HVAC and renewable energy systems, including their maintenance phase, area on which very limited data are available within existing databases.

Further research is also needed to evaluate potential trade-offs between operational and embodied energy efficiency of buildings at local or regional level, considering in detail the issues of climate, energy mix, production processes, transport issues, etc.

## References

Adalberth K (1997a) Energy use during the life cycle of buildings: a method. Build Environ 32:317–320

Adalberth K (1997b) Energy use during the life cycle of single-unit dwellings: examples. Build Environ 32:321–329

Ardent F, Beccali G, Cellura M, Lobrano V (2005) Life cycle assessment of a solar thermal collector. Renew Energy 30:1031–1054

Asif M, Currie J, Muneer T (2007) Comparison of aluminium and stainless steel built-in-storage solar water heater. Build Serv Eng Res Technol 28:337–346

Bliss RW (1955) Design and performance of the nation's only fully solar-heated house. Air Cond Heat Vent 52:92

Building Research Establishment (2013) BRE environmental assessment method, available at www.breeam.org

Butti K, Perlin J (1980) A golden thread, 2,500 years of solar architecture and technology, Van Nostrand Reinhold Company

CEN (2007a) BS EN 15316-4-3:2007, heating systems in buildings—method for calculation of system energy requirements and system efficiencies—part 4-3: heat generation systems, thermal solar systems

CEN (2007b) BS EN 15316-4-6:2007 heating systems in buildings—method for calculation of system energy requirements and system efficiencies—part 4–6: heat generation systems, photovoltaic systems

CEN (2008a) EN ISO 13790:2008 energy performance of buildings—calculation of energy use for space heating and cooling (ISO 13790:2008)

CEN (2008b) EN 15603:2008 energy performance of buildings—overall energy use and definition of energy ratings

CEN (2011) EN 15978:2011, sustainability of construction works—assessment of environmental performance of buildings—calculation method

CEN (2012) EN 15804:2012 'sustainability of construction works—environmental product declarations—core rules for the product category of construction products'

Cole RJ, Kernan PC (1996) Life-cycle energy use in office buildings. Build Environ 31:307–317

Crawford RH (2009) Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. Renew Sustain Energy Rev 13:2653–2660

Crawford RH, Treloar GJ (2004) Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. Sol Energy 76:159–163

Crawley DB, Hand JW, Kummert M, Griffith BT (2008) Contrasting the capabilities of building energy performance simulation programs. Build Environ 43:661–673

CSTB (2012) ELODIE, software for analysis of building life cycle. Available at www.elodie-cstb.fr

Dixit MK, Fernandez-Solís JL, Lavy S, Culp CH (2010) Identification of parameters for embodied energy measurement: a literature review. Energy Build 42:1238–1247

ENERBUILCA (2012) Life cycle assessment for energy efficiency in buildings. www.enerbuilca-sudoe.eu

Esbensen TV, Korsgaard V (1977) Dimensioning of the solar heating system in the zero energy house in Denmark. United States

EU Parliament and Council (2011) Regulation 305/2011 of the European parliament and of the council of 9 March 2011—laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC

Haapio A, Viitaniemi P (2008) A critical review of building environmental assessment tools. Environ Impact Assess Rev 28:469–482

Hammond GP, Jones CI (2008) Embodied energy and carbon in construction materials. In: Proceedings of the institution of civil engineers—energy, vol 161(2), pp 87–98

Hannon B, Stein RG, Segal BZ, Serer D (1978) Energy and Labor in the construction sector. Science 202:837–847

Hernandez P, Kenny P (2008a) Defining zero energy buildings—a life cycle perspective. PLEA 2008—25th conference on passive and low energy architecture. Dublin, Ireland

Hernandez P, Kenny P (2008b) Life cycle energy performance: exploring the limits of passive 'low energy' buildings. World sustainable building conference 2008. Melbourne, Australia

Hernandez P, Kenny P (2012) Net energy analysis of domestic solar water heating installations in operation. Renew Sustain Energy Rev 16(1):170–177

Hopfe CJ (2009) Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization. PhD thesis, University of Eindhoven, Department of Building Engineering

ISO, International Organization for Standardization (2006a) ISO 14040:2006 environmental management—life cycle assessment—principles and framework

ISO, International Organization for Standardization (2006b) ISO 14025 environmental labels and declarations—type III environmental declarations—principles and procedures

ISO, International Organization for Standardization (2008) 15686-8:2008—buildings and constructed assets—service-life planning—part 8: reference service life and service-life estimation

Itard L, Klunder G (2007) Comparing environmental impacts of renovated housing stock with new construction. Build Res Inf 35:252–267

Kalogirou S (2009) Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. Sol Energy 83:39–48

Kalogirou SA (2004) Environmental benefits of domestic solar energy systems. Energy Convers Manage 45:3075–3092

Kubiszewski I, Cleveland CJ, Endres PK (2010) Meta-analysis of net energy return for wind power systems. Renew Energy 35:218–225

Malmqvist T, Glaumann M, Scarpellini S, Zabalza I, Aranda A, Llera E, Díaz S (2010) LCA in buildings: ENSLIC simplified method and guidelines. Energy 36(4):1900–1907

McCall RA, McNeil SJ (2007) Comparison of the energy, time and water usage required for maintaining carpets and hard floors. Indoor Built Environ 16:482–486

Minister for the Environment, Heritage and Local Government (2007) Building regulations 2007 technical guidance document L, conservation of fuel and energy—dwellings. Ireland

Mulder K, Hagens NJ (2008) Energy return on investment: toward a consistent framework. AMBIO: J Hum Environ 37:74–79

Nawaz I, Tiwari GN (2006) Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. Energy Policy 34:3144–3152

Pacca S, Sivaraman D, Keoleian GA (2007) Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 35:3316–3326

PÉ International (2013) Gabi software and database. Available at. www.pe-international.com

PRÉ Consultants (2013) SIMAPRO Software. Available at. www.simapro.com

Raugei M, Bargigli S, Ulgiati S (2007) Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 32:1310–1318

Richards BS, Watt ME (2007) Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. Renew Sustain Energy Rev 11:162–172

Sartori I, Hestnes AG (2007) Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy Build 39:249–257

Segers R (2008) Three options to calculate the percentage renewable energy: an example for a EU policy debate. Energy Policy 36:3243–3248

Sharma A, Saxena A, Sethi M, Shree V, Goel V (2010) Life cycle assessment of buildings: a review. Renewable and sustainable energy reviews. doi:10.1016/j.rser.2010.09.008 (in press)

Sustainable Energy Authority Ireland (2007) Dwelling energy assessment procedure (DEAP)—Irish official method for calculating and rating the energy performance of dwellings

Swiss Centre for Life Cycle Inventories (2010) ECOINVENT, life cycle inventory database. Available at. http://www.ecoinvent.org/

Thormark C (2006) The effect of material choice on the total energy need and recycling potential of a building. Build Environ 41:1019–1026

Treloar GJ, Love PED, Holt GD (2001) Using national input-output data for embodied energy analysis of individual residential buildings. Constr Manage Econ 19:49–61

Udo De Haes HA, Heijungs R (2007) Life-cycle assessment for energy analysis and management. Appl Energy 84:817–827

U.S. Green Building Council (2013), leadership in energy and environmental design (LEED) Green building rating system. Available at. http://www.usgbc.org/LEED van der Veken J, Saelens d, Verbeek G, Hens H (2004) Comparison of steady-state and dynamic building energy simulation programs. The international buildings IX ASHREA conference on the performance of exterior envelopes of whole buildings. Clearwater Beach, Florida, US

World Business Council for Sustainable Development (2012) Energy efficiency in buildings (EEB) 2.0-action on energy in buildings. Available at. www.wbcsd.org

# Refurbishment Scenario to Shift Nearly Net ZEBs Toward Net ZEB Target: An Italian Case Study

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**Abstract** The idea of a Net ZEB arises from the development of design criteria and construction methods, addressed to curb the operating energy, increasing the energy efficiency of building equipment and appliances, and of the thermal insulation of envelope components, and enhancing the on-site energy generation, by means of renewable energy sources, to cover the annual building energy loads. In this chapter, the energy and environmental performances of an Italian nearly Net ZEB following a life cycle approach are carried out. Then, a scenario of refurbishment is foreseen in order to shift the studied building from the nearly Net ZEB condition toward the Net ZEB target, and the arising energy and environmental benefits are assessed. The life cycle approach in the energy and environmental assessment of the foreseen retrofit options is necessary to avoid shifting environmental burdens from one step of the life cycle to another. Further, in order to get a deeper description of the energy performance of the retrofit actions and to compare the different alternatives, the energy payback time (EPT) and the emission payback time (EPT) are assessed for the proposed solutions.

## 1 Introduction

In Europe, many policy tools have been adopted to increase the energy efficiency of the existing building stock, as part of the plan aimed to reach a low-carbon economy. In such a path, the most important legislative tool in the European Union

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(EU) is the Directive 2002/91/EC on the energy performance of buildings (EPBD), which promotes the required measures to increase the energy performance of the buildings for all the EU member states and introduces environmental performances as the most relevant driving force for energy saving in buildings (climate change, resource depletion, toxicity, etc.). Moreover, the EU Directive 2006/32/EC encourages energy efficiency by means of the development of the energy service market and the delivery of energy efficiency strategies and measures addressed to end users.

The Directive 2010/31/EC (known as the EPBD recast) strengthens the energy performance requirements promoted in the Directive 2002/91/EC and clarifies some of its provisions and goals to reduce the large differences among the member states' practices.

According to the EPBD recast, all new buildings should be built as nearly zero energy buildings within 2020. Furthermore, a particular highlight is addressed to the retrofit of existing buildings. In fact, the EPBD recast prescribes that suitable measures should be taken by the EU member states to decrease the energy demand of the existing buildings through retrofit actions addressed toward the target of nearly zero energy buildings. With this regard, the directive defines "nearly net zero energy" a building that has a very high energy performance and whose amount of energy required should be covered to a very significant extent by on-site or nearby renewable sources. Since no minimum or maximum harmonized requirements are given, as well as details of energy performance calculation framework, it will be up to the member states to define what for them exactly constitutes a "very high energy performance." However, until now, the Net ZEB concept has not been implemented yet in national building codes and international standards, owing to the lack of a consistent definition and a commonly agreed energy calculation methodology (Cellura et al. 2011; Salom et al. 2011).

The idea of a Net ZEB arises from the development of design criteria and construction methods, addressed to curb the operating energy, increasing the energy efficiency of building equipment and appliances, and of the thermal insulation of envelope components, and enhancing the on-site energy generation, by means of renewable sources, to cover the annual building energy loads.

Until recently, only operating energy has been considered in many literature studies, owing to its significant share in the total life cycle energy consumption of a standard building (70–90 %) (Napolitano et al. 2012; Chen et al. 2001). Conversely, embodied energy of building materials and components has been traditionally neglected when performing building energy analysis, as in standard buildings, it amounted to a small fraction of the life cycle energy consumption (10–20 %). This made most building regulations and directives overlook this issue (Hernandez and Kenny 2010).

However, from a life cycle perspective, when shifting from standard houses toward low-energy buildings, the relative share of operating energy decreases, while the relative share of embodied energy increases (Dixit et al. 2010; Gustavsson and Joelsson 2010; Ardente et al. 2008, 2011 ). Therefore, the lower the operating energy, the more important it is to adopt a life cycle approach to compare the energy savings achieved in the building operation through the local energy generation with respect to the overall energy consumption (Sartori and Hestnes 2007; Blengini and Di Carlo 2010).

In the following sections, keeping as starting point, the results of the leaf house (LH) designed and built by Loccioni Group in 2008 and chosen as Italian case study of the Sub Task B in the International Energy Agency (IEA) joint solar heating and cooling (SHC) Task 40 and energy conservation in buildings and community systems (ECBCS) Annex 52 titled "Towards Net Zero Energy Solar Buildings" (IEA 2013), the authors carry out the energy and environmental performances of such a case study following a life cycle approach. Then, a set of retrofit options are foreseen in order to shift the studied building from the nearly Net ZEB condition toward the Net ZEB target, and the arising energy and environmental benefits are assessed.

## 2 Description of the Existing Building

The LH, located in Angeli di Rosora, Ancona, Italy, is designed in compliance with innovative sustainable and bioclimatic architecture principles (Fig. 1).

It is built according to the recent requirements of the energy regulations in force and integrating different sources of renewable energy. Table 1 reports the main geographical and climatic data, as well as some building geometric features.

The building is composed by three levels, each one containing a couple of twin flats. The two apartments at the second floor are occasionally occupied, while each of the remaining four flats is occupied by two people.

With regard to the south façade, the ratio of its length to the east one was set to maximize the solar radiation gain. Further, to keep under control overheating, the southern façade presents external fixed overhangs used as shading elements.

**Fig. 1** LH building

**Table 1** Main features and climatic data of the LH

| Climatic data | | Building features | |
|---|---|---|---|
| Minimum and maximum temperature (°C) | −5; 37 | Number of levels | 3 |
| Mean annual humidity (%) | 0.67 | Heated floor area ($m^2$) | 481.76 |
| Mean annual horizontal solar radiation ($W/m^2$) | 302 | Volume ($m^3$) | 1,475.33 |
| Latitude | 43°28' N | Heated floor area to volume | 0.33 |
| Longitude | 13°04' E | S/V ratio | 0.73 |
| Altitude (m) | 130 | | |

**Table 2** *U*-values for the envelope elements

| External structures | *U*-value [$W/(m^2K)$] | Windows | *U*-value [$W/(m^2K)$] |
|---|---|---|---|
| Walls | 0.15 | Global | 1.4 |
| Floor | 0.30 | Glass only | 1.15 |
| Roof | 0.25 | | |

Table 2 presents the thermal properties and the material composition on the building envelope.

The required thermal energy is supplied with an equipment, made of a solar collectors system, three geothermal probes, a heat pump, an air handling unit (AHU), an auxiliary boiler, a photovoltaic system (Fig. 2). The geothermal heat pump exchanges with the ground through vertical probes, the solar thermal collectors and the auxiliary boiler, which operates in case of failure of the other systems.

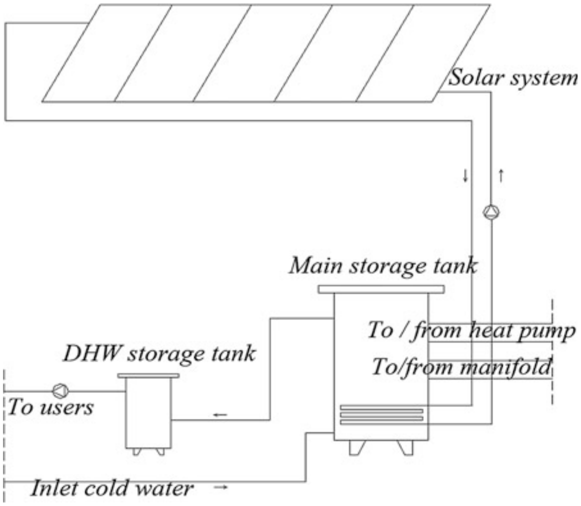
Each flat is heated by means of a radiant floor supplied by the GHP. During the summer season, excluding the hottest days, the cooling system uses the natural cooling provided by a ground-coupled heat exchanger.

In winter, the solar system is integrated by the heat pump in heating mode in order to reach around 40 °C in the upper part of the storage tank, thus allowing the production of domestic hot water (DHW) and of water for feeding the radiant floors from the middle area of the tank. DHW is heated and then collected in a smaller secondary tank, connected to an auxiliary gas burner that is employed when the system needs a thermal integration according to a fixed set point temperature.

During the summer season, the solar system fulfills the DHW requirement and the GHP is used in cooling mode to produce cold water at 15–18 °C through the use of mixing valves, to feed the radiating floors.

A proper mechanical ventilation system is installed with heat recovery and preconditioning in an underground air duct. The AHU supplies neutral air in rooms and there is a heat recovery system before the expulsion of exhausted air. The outer air is naturally preconditioned (heated in winter and cooled in summer) through a 10-m-long underground duct placed before entering the air into the AHU.

**Fig. 2** Sketch of the LH solar thermal system



The thermal solar system, made of seven collectors, is installed to integrate the GHP in the DHW generation. The electricity need of the LH is supplied by a grid-connected PV system, made of 115 panels with 20 kW peak power and 12 % nominal efficiency. Such a system is installed on the south-faced roof, covering a 150-m$^2$ area. To reduce the electricity consumption, there are large windows on the south-oriented façade, while at the rear of the building facing the north, suitable solar tubes convey the sunlight indoor. Furthermore, efficient fluorescent lamps are used and water consumption is reduced by means of rain water collection for sanitary and gardening uses.

LH monitoring is carried out by means of a number of suitable sensors and actuators integrated with drivers which allow communication between devices and systems and distinguished in room sensors and weather station sensors.

## 2.1 Annual Energy Balance of the LH: The Nearly Net ZEB Goal

Energy is required in the LH operation for space heating, cooling, DHW generation, and electricity for ventilation, indoor lighting, and plug loads. Such loads depend on the thermal performances and size of the building shell, on the number of occupants and the activities inside, while the actual energy consumption also depends on the efficiency of energy supply systems.

The annual energy requirement of the assessed building was estimated through a one-year monitoring activity in 2010. With regard to the on-site energy generation, the photovoltaic system produced 24,664 kWh of electricity in 2010. Thermal collectors provided 4,227 kWh, thus supplying the 63 % of the yearly

DHW demand. The consumption of natural gas for the conventional boiler is 2,690 kWh/y.

Starting from the monitored data on electricity generation and loads, the following balance equation is applied to the building case study:

$$E_{\mathrm{net,\,LH}} = |E_{\mathrm{PV}}| - |E_{\mathrm{GRID}}| \tag{1}$$

where

- $E_{\mathrm{PV}}$ is the on-site photovoltaic annual generation of electricity (kWh/y);
- $E_{\mathrm{GRID}}$ is the end use energy for electric needs of the LH (kWh/y).

Based on the monitoring outcomes, the annual balance was calculated according the Eq. (1), as one year is a proper time span to cover all the building operation settings, with respect to the climatic variables and the season succession (Sartori et al. 2012).

Table 3 shows the outcomes of the annual LH balance calculated by means of the Eq. (1), where both generation and load are computed in terms of end-use energy. Energy generation results lower than energy load, with a deficit of 0.9 MWh, that is, 7.7 % of the overall electricity load. This involves that the LH is a nearly Net ZEB, when considering the encountered energy flows at the final use level.

On the basis of the above results for the annual energy balance of the LH, the authors propose a set of retrofit actions for the assessed building, in order to shift the assessed building toward the Net ZEB target. In detail, the following options are undertaken:

- to install more efficient PV panels, with a 19 % efficiency model;
- to install more efficient GHP equipment (nominal COP = 4.6);
- to directly connect the GHP to the storage tank and to the manifold, without the GHP heat exchanger;
- to improve thermal insulation of the roof, by means of proper rock wool boards, 10 cm thickness, taking the *U*-value from 0.25 W/($m^2$ °C) of the existing building to 0.15 W/($m^2$ °C);
- to optimize the volume of the main storage tank in order to reduce the GHP consumption;
- to integrate a night setback on the proportional integrative derivative (PID) temperatures setup;
- to add mobile blinds, on the south-oriented windows, working in the hottest hours during summer season, if occupancy schedules are set to 0.

The reduction in energy load for each end use, due to the above options, is calculated through TRNSYS simulations (TRNSYS 2003). The foreseen PV energy yield (about 38.3 MWh/y) would allow a complete covering of the total building load ($E_{\mathrm{net,\ LH}} = 0$). The other retrofit options would induce an overall electricity saving of 2.8 MWh/y, thus further reducing the electricity consumption to 22.8 MWh/y.

**Table 3** Annual electricity balance of the LH

| Balance | Metric | Nearly net ZEB | Net ZEB (refurbishment) |
|---|---|---|---|
| Energy load | MWh | 25.6 | 22.8 |
| Energy generation | MWh | 24.7 | 38.3 |
| Net energy | MWh | −0.9 | 15.5 |

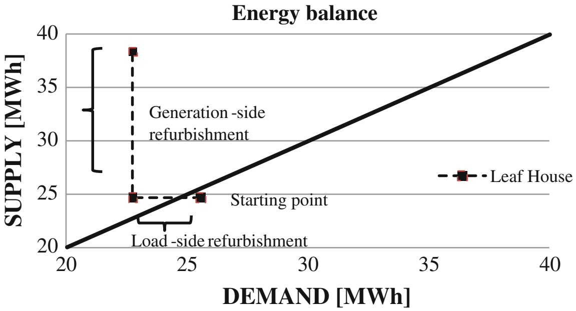


**Fig. 3** Energy balance of the LH and effects of the retrofit

Further, the retrofit scenario would involve a surplus of 15.5 MWh/y, which would be entirely exported to the grid($E_{\text{net, LH}} > 0$), shifting the LH from the nearly Net ZEB condition to the target of Net ZEB, in terms of energy measured at the end-use level. In Fig. 3, such a shift is clearly showed.

The above technical solutions aim at reducing the annual energy loads of the LH and to increase the energy generation. However, they require extra materials and components, thus increasing the embodied energy of the building. Then, the life cycle approach in the energy and environmental assessment of the foreseen retrofit options is necessary to avoid shifting environmental burdens from one step of the life cycle to another. In the following sections, the authors apply the life cycle approach to assess the ecoprofile of the LH, taking into account two different building scenarios:

- Nearly Net ZEB, which represents the building as it was designed and built (Baseline scenario).
- Net ZEB, which represents the refurbished LH according to the above set of energy saving options (Refurbishment scenario).

Further, in order to get a deeper description of the energy performance of the retrofit actions and to compare the different alternatives, the energy payback time (EPT) and the emission payback time (EPT) are calculated (Ardente et al. 2011).

## 3 Life Cycle Assessment of the Leaf House

### 3.1 Goal and Scope Definition

The energy and environmental performances of the LH are assessed applying the life cycle assessment (LCA) (Ardente et al. 2005; Battisti and Corrado 2005; Brown and Aaron 2001), in compliance with the international standards of the ISO 14040 series (UNI EN ISO14040 2006). In particular, the main goals of the study are as follows:

- to assess the energy and environmental impacts owing to all the life cycle phases of the building in both scenarios of analysis;
- to assess the net primary energy saving achievable in Scenario 2;
- to evaluate whether the energy saving involved in Scenario 2, and the consequent avoided environmental impacts would offset the increased embodied energy of the building and the related life cycle environmental impacts.

The life cycle impact assessment (LCIA) is carried out by means of the environmental indicators and characterization factors of the EPD scheme (environmental product declaration—EPD) (The International EPD 2008). Other indicators, on which there is not any scientifically agreed calculation method in the LCA context, such as human toxicity, ecotoxicity, biodiversity, and land use, are not included. Energy consumption in the building life cycle is calculated as primary energy, which represents the most effective indicator to express consumption of energy under different forms. This calculation took into account all the losses related to the processes of extraction of the resources, their transformation and distribution and requires the assessment of electricity and fossil fuel uses, according to different efficiencies in the final uses (heating, DHW, lighting, etc.). Cumulative energy demand method is used to account for the overall primary energy requirement of the assessed actions (PRè-Product Ecology Consultants 2010).

### 3.2 Definition of the Functional Unit and System Boundaries

The selected functional unit for the LCA study is the whole building in both the assessed scenarios are referred. With regard to the system boundary, the assessment of the energy and environmental performance in both scenarios covers upstream and downstream processes needed to establish and maintain the function of the building. The reference study period and the required service life of the building are assumed the same. To this purpose, the energy and environmental impacts arisen from the following stages of the building life cycle are taken into account:

- production of the building, which includes the production processes of all the building-related materials and components, and the construction step of the building, taking into account raw material acquisition and resource supply.

- operation, which covers all the processes occurring during the building service, such as heating, cooling, water supply, electrical appliance usage, and renewable energy generation.
- material and component replacement. A 70-year life service is assumed for the building. Thus, the replacement of those components with shorter life span is considered. In detail, production and installation processes of the replaced components are taken into account. End-of-life of the removed components is assessed within the end-of-life phase of the building.
- end-of-life of the building, which includes all the process from the demolition/dismantling to the disposal/recycling.
- transports, including all the transport steps occurring during the whole life cycle of the building: the transportation of materials and components from the manufacturing gate to the construction site; the transportation of the replaced components from the factory gate to the building site; the transportation of C&D wastes to recycling plants and/or disposal sites, when the end-of-waste state is reached.

The environmental impacts caused by the infrastructures are neglected.

Therefore, the impacts of the construction of roads, trucks used to carry the construction materials are not taken into account.

With regard to the exported energy, in Scenario 1 (nearly Net ZEB), the on-site energy production is delivered to the building to integrate the imported energy from the grid. All the environmental impacts arisen from production, transport, installation, use, maintenance, and end-of-life of the energy production system are fully allocated to the building, as well as the environmental impacts related to the operational energy use (both the on-site produced and the imported).

In the Refurbishment scenario, the surplus of electricity is exported to the grid. No electricity is imported. Only energy for auxiliary thermal needs is imported. All the environmental impacts arisen from production, transport, installation, use, maintenance and end-of-life of the energy production system are fully allocated to the building.

The benefits of the exported electricity, which replaces electricity beyond the building boundary, are assessed in terms of primary energy saving and avoided environmental impacts.

## *3.3 Data Quality and Life Cycle Inventory*

The inventory analysis is carried out in order to quantify the environmentally relevant inputs and outputs of the studied system, by means of a mass and energy balance of the selected functional unit. To this aim, site-specific data are integrated with literature data. In particular, data related to the existing building are derived from Loccioni Group and from some producers of building materials and plant components. Data about the production and installation of the retrofit options are provided by the producer companies in the sector. Inventory datasets on energy supply (electricity and fuels) and transportation are derived from (Frischknecht et al. 2007). LCI model is carried out by using the SimaPro software (PRè-Product Ecology Consultants 2010). Fuel consumption and air emissions from transportation are calculated depending on the transport mode and the distance between sites.

According to the system boundary definition, the authors considered in this phase all the processes which concern the production of materials and plants, and the construction process, including transport to the building site, erection, and installation process.

Figures 4 and 5 show the composition of the materials embedded in the building envelope and in the thermal plant. Moving from the Baseline scenario to the Refurbishment scenario, the mass variation of the embodied materials is assumed negligible.

As highlighted in Fig. 6, the embodied energy for the envelope components and the thermal plant also has negligible variation from the first scenario to the second one.

Energy consumption for space heating and cooling, ventilation, DHW generation, indoor lighting, and electrical appliances is calculated starting from the outcomes of the monitoring activity previously described in Baseline scenario (nearly Net ZEB), while a one-year transient simulation is carried out through TRNSYS software to calculate the energy requirement in Refurbishment scenario (Net ZEB).

With regard to the Refurbishment scenario, the most performing PV system involves higher electricity generation, while the other assumed options contribute to reduce the electricity use.

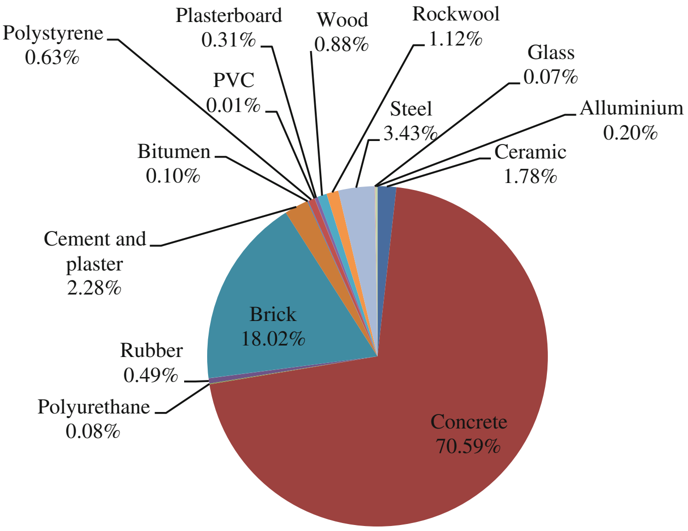


**Fig. 4** Materials embodied in the LH envelope

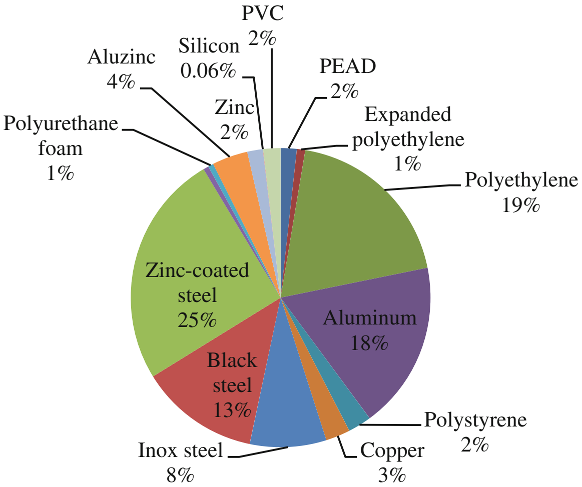


**Fig. 5** Materials embodied in the LH thermal plant

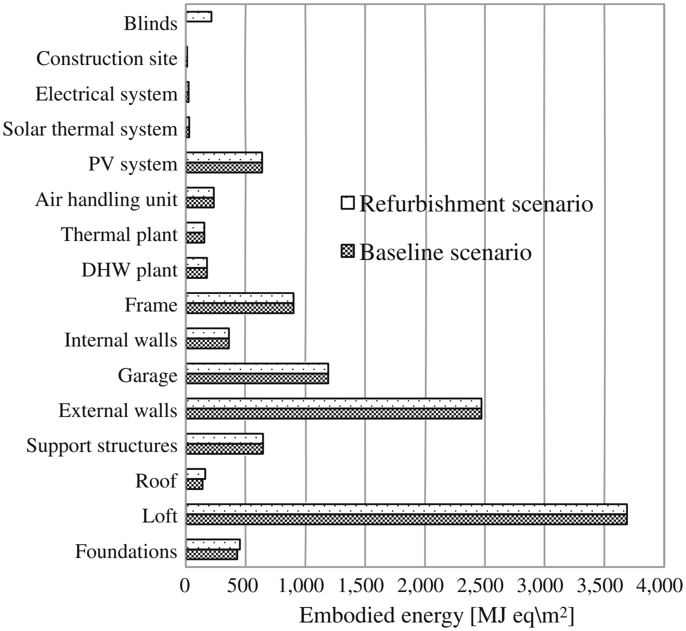


**Fig. 6** Embodied energy of the building

**Table 4** Replaced component and the related life span

| Systems, plant components and envelope elements | Service life (years) |
|---|---|
| Windows and frames | 35 |
| Roof and floors | 35 |
| Walls | 15 |
| Solar systems | 25 |
| DHW system | 50 |
| Thermal plant, radiant floors | 40 |
| Thermal plant, gas distribution system | 35 |
| Thermal plant, heat pump | 25 |
| Thermal plant, boiler | 35 |
| Air handling unit pipes | 50 |
| Air handling unit | 25 |

The replacement of the components with shorter life span than the building service life is considered in the maintenance phase. Table 4 shows the replaced component and the related life span. The same options of maintenance are taken into account in the two assessed scenarios.

With regard to the end-of-life, three distinct steps are included for each building scenario (Beccali et al. 2001; Lo Mastro and Mistretta 2004):

1. selective dismantling of reusable/recyclable materials and structures, such as windows, steel, and aluminum;
2. controlled demolition of the structural system by hammers and shears;
3. operations for C&D waste treatment and recycling, reuse, or landfill.

All the energy consumption and environmental impacts due to transportation, demolition, and recycling operations are calculated. Inventory data relevant to recycling of aluminum, steel, glass, and copper are retrieved from the Ecoinvent database (Frischknecht et al. 2007). Thus, energy and environmental benefits in the building life cycle due to the recycling of secondary raw materials are accounted for.

## *3.4 Life Cycle Impact Assessment*

LCIA was carried out in order to assess the energy and environmental impacts of the building in the two scenarios of analysis by means of suitable and meaningful indicators.

The LCIA results were presented at the level of mid-point indicators. In order to select relevant environmental indicators able to represent in a synthetic and comprehensive way the LCI results about the material and energy resource consumption and the environmental releases, the chosen impacts categories were referred to the main environmental indices and characterization factors included in the "Environmental Product Declaration" scheme. In detail, life cycle primary energy consumption is calculated according to the Cumulative energy demand method. In particular, the following mid-point indicators were selected, since they are widely known and applied by LCA experts:

- Cumulative energy demand (CED), distinguished in:
  - Non-renewable primary energy (including energy resources used as raw material)
  - Renewable primary energy (including energy resources used as raw material)
- Global-warming potential (GWP)
- Depletion potential of the Ozone layer (ODP)
- Acidification potential of land and water (AP)
- Eutrophication potential (EP)
- Photochemical ozone creation potential (POCP).

Table 5 shows the outcomes of the above-described LCIA performed for the existing LH (Scenario 1) and for the refurbished building (Scenario 2), respectively.

Building production represents the most significant step of the building life cycle, as it induces the largest contribution in the energy and environmental impacts. Figure 7 shows the contribution of each life cycle phase to the building CED. Production and maintenance are the most weighing phases on the life cycle primary energy demand in both scenarios. With regard to the Baseline scenario, they accounts for 55 and 45 %, respectively. The production and maintenance shares also prevail over the other phases with respect to the environmental impact indicators. In particular, production contribution varies from 43 % for EP to 64 % for EP. Its contribution on GWP is nearly 63 %. Maintenance contribution varies from 31 % for EP to 57 % for ODP. Its contribution on GWP is around 43 %.

Moving from the Baseline scenario to the Refurbishment scenario, production and maintenance have a slight increase (1 % and about 4 %, respectively), while end-of-life involves a reduction of 15 %, owing to larger rates of recyclable materials in the Refurbishment scenario.

Conversely, the building operation presents the lowest energy and environmental impacts in comparison with the other life cycle phases in both scenarios. In the Scenario 1, it accounts for about 8.5 % on the CED.

With regard to the Refurbishment scenario, owing to the surplus of electricity generated by the PV system, the operation phase involves significant negative

**Table 5** Life cycle impact assessment results in both scenarios

| Indicators | Metric | Baseline scenario | Refurbishment scenario |
|---|---|---|---|
| GWP | kg $CO_2$eq | 925,058 | 194,571 |
| OPD | kg CFC-11 eq | 0.09 | 0.004 |
| POCP | kg $C_2H_4$eq | 864.3 | 487.5 |
| AP | kg $SO_2$eq | 2,841 | −344.2 |
| NP | kg $PO_4^{3-}$eq | 1,751 | 912 |
| CED | MJeq | 18,292,625 | 5,973,867 |

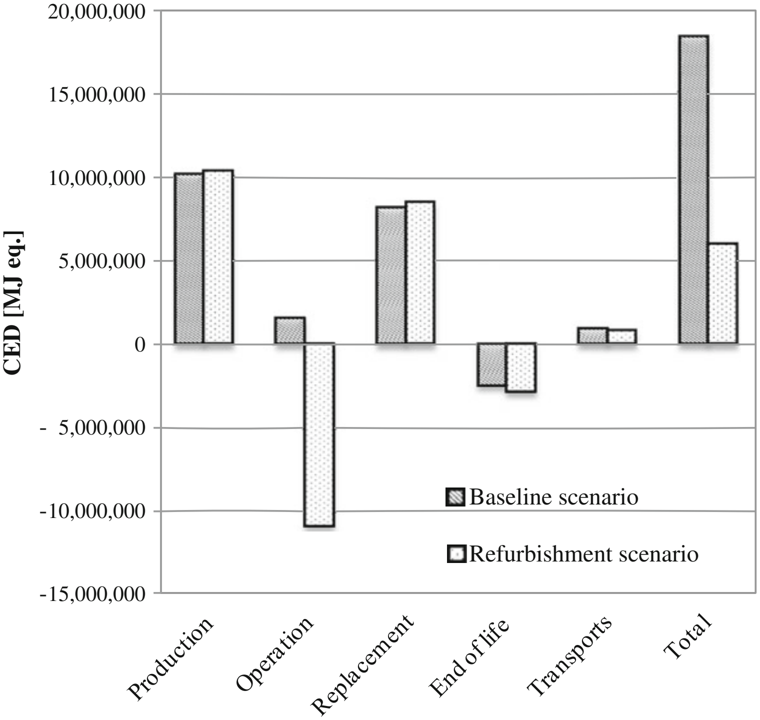


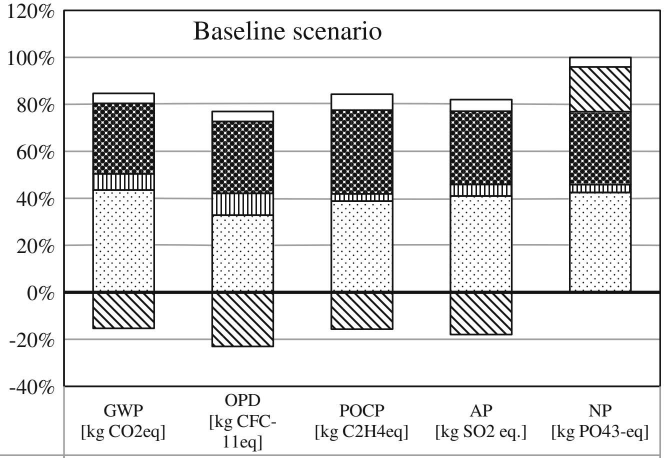
**Fig. 7** Contribution of each life cycle phase to the building CED in both scenarios

contributions in all the energy and environmental indicators. With regard to the CED, it involves primary energy saving of 10,803 GJ, thus reducing the CED of about 60 % with respect to the Baseline scenario. Such a saving was estimated taking into account the efficiency of the Italian electricity mix.

The results of the LCIA put into evidence that for each impact category, the accomplishment of the Refurbishment scenario would involve a significant reduction.

Figures 8 and 9 show the contribution analysis of the different life cycle phases to the environmental impact indicators in the two scenarios of analysis. As it can be easily noted, the operation remains the most affecting phase for all environmental indicators. In particular, a GWP reduction of about 70 % of primary energy consumption is related to the operation phase. ODP goes down to about 28 %, while AP and EP decrease almost by 100 %. POCP decreases nearly of 40 %.

All of the previous indicators have negative value in the Refurbishment scenario, involving related avoided impacts. To not be neglected is the end-of-life phase, which involves a range reduction from 20 % (EP) to 50 % (ODP), when moving from the Baseline to the Refurbishment scenario. It involves a reduction of 25 % in GWP. Worth of note is that in both scenarios, the environmental impacts induced by the end-of-life have negative values, which implies related avoided



| | GWP [kg CO2eq] | OPD [kg CFC-11eq] | POCP [kg C2H4eq] | AP [kg SO2 eq.] | NP [kg PO43-eq] |
|---|---|---|---|---|---|
| □ Transports | 56,106 | 0.01 | 86 | 220 | 71 |
| ▧ End of life | -203,815 | -0.04 | -196 | -795 | 334 |
| ■ Replacement | 400,997 | 0.05 | 447 | 1,381 | 542 |
| ▥ Operation | 91,081 | 0.02 | 40 | 216 | 59 |
| ▫ Production | 580,689 | 0.06 | 488 | 1,819 | 744 |

**Fig. 8** Contribution analysis of the different life cycle phases to the other environmental impact indicators in the baseline scenario

impacts. This fact is essentially due to the assessment of the energy and environmental benefits arisen from the C&D waste recycling.

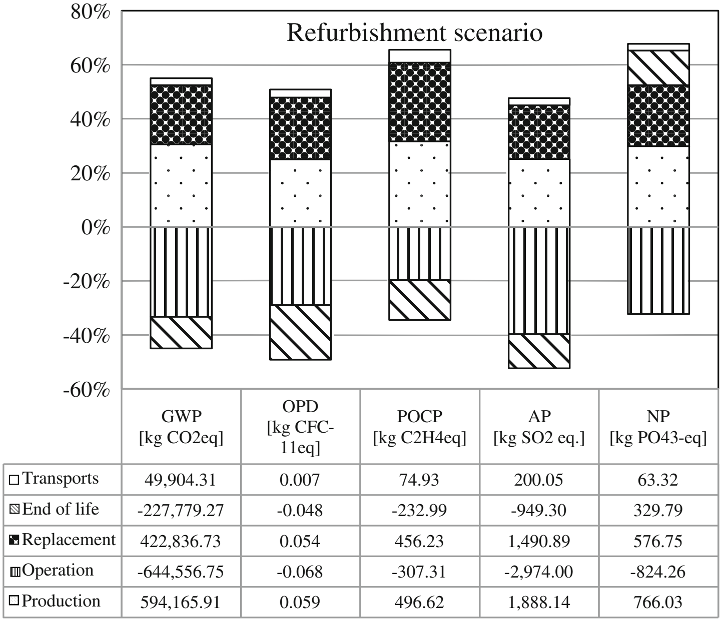
With regard to the transport phase, it involves a slight decrease in all the environmental indicators (not more than 2 %).

### *3.5 Energy and Environmental Benefits Arisen from the Refurbishment Scenario*

The one-year monitoring activity was carried out to quantify the annual energy input and output flows across the existing building. The outcomes allowed to perform the annual net energy balance at final use level (see Sect. 2.1).

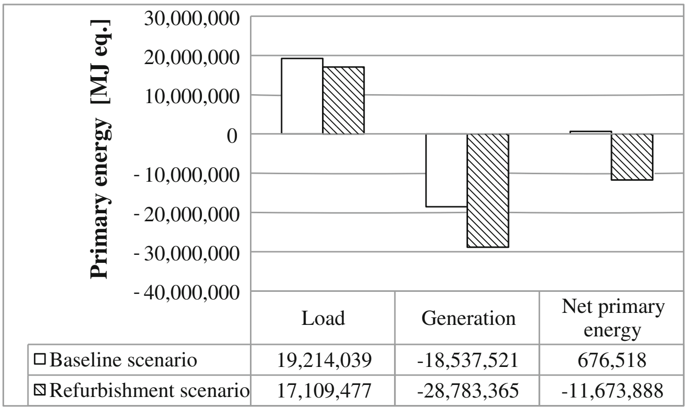
Taking into account a service life of 70 years, the net primary energy consumption for electricity during the building operation is assessed in both scenarios (Fig. 10). No variation is taken into account for the primary energy consumption related to the auxiliary thermal need, as well as that one due to the water use during the building life cycle, when moving from the Baseline scenario to the Refurbishment one.

Figure 11 shows the GWP balance during the operation phase of the building in both scenarios. In detail, the GWP due to the primary energy consumption during



| | GWP [kg CO2eq] | OPD [kg CFC-11eq] | POCP [kg C2H4eq] | AP [kg SO2 eq.] | NP [kg PO43-eq] |
|---|---|---|---|---|---|
| □ Transports | 49,904.31 | 0.007 | 74.93 | 200.05 | 63.32 |
| ▧ End of life | -227,779.27 | -0.048 | -232.99 | -949.30 | 329.79 |
| ▩ Replacement | 422,836.73 | 0.054 | 456.23 | 1,490.89 | 576.75 |
| ▥ Operation | -644,556.75 | -0.068 | -307.31 | -2,974.00 | -824.26 |
| □ Production | 594,165.91 | 0.059 | 496.62 | 1,888.14 | 766.03 |

**Fig. 9** Contribution analysis of the different life cycle phases to the other environmental impact indicators in the refurbishment scenario

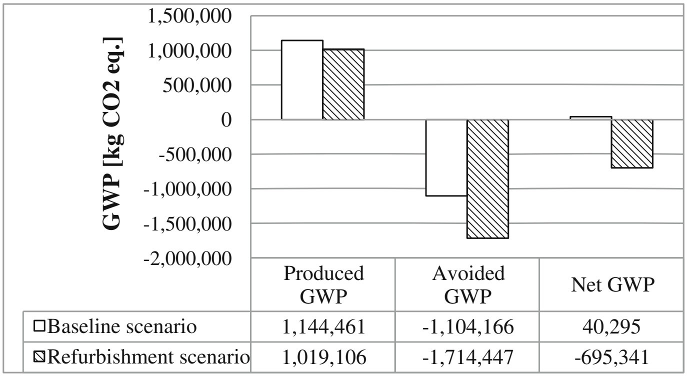


| | Load | Generation | Net primary energy |
|---|---|---|---|
| □ Baseline scenario | 19,214,039 | -18,537,521 | 676,518 |
| ▧ Refurbishment scenario | 17,109,477 | -28,783,365 | -11,673,888 |

**Fig. 10** Net primary energy consumption in the building operation

the building operation, the avoided GWP related to the saving of primary energy arisen from the on-site electricity generation is reported.

In order to assess the environmental effects when shifting the LH from the nearly Net ZEB condition toward the Net ZEB target, the energy and environmental impacts arisen during the building life cycle (see Table 5) are compared to



| | Produced GWP | Avoided GWP | Net GWP |
|---|---|---|---|
| □Baseline scenario | 1,144,461 | -1,104,166 | 40,295 |
| ▨Refurbishment scenario | 1,019,106 | -1,714,447 | -695,341 |

**Fig. 11** GWP balance in the two assessed scenarios

the avoided ones during the operational phase, due to the on-site electricity generation by the PV system (Table 6).

In order to get a deeper description of the energy and environmental performance of the retrofit options in the Refurbishment scenario, the following payback indices were added to the EPD set: the EPT and the EPT.

In detail, the EPT of the building retrofit is defined as the time needed to save as much energy (valued as primary) by means of the retrofit options as that consumed during the whole building life cycle:

$$E_{P,T} = \frac{\mathrm{CED}_{\mathrm{Building}}}{E_{s,y}} \tag{2}$$

where

- $\mathrm{CED}_{\mathrm{Building}}$ is calculated with regard to the life cycle of the building in the Refurbishment scenario (GJ);
- $E_{s,\ y}$ is the yearly saving of primary energy due to the retrofit actions, which results 411 GJ/y.

The yearly saving of electricity was converted into primary energy based on the Italian energy mix for the production of electricity.

The EPT ($\mathrm{Em}_{\mathrm{PT}}$) is the time during which the avoided emissions by the accomplishment of the Refurbishment scenario are equal to those released during the building life cycle. The authors decided to calculate the $\mathrm{Em}_{\mathrm{PT}}$ with regard to the GWP index to express the environmental pollution.

Then, it was defined as

$$\mathrm{Em}_{P,T} = \frac{\mathrm{GWP}_{\mathrm{Building}}}{\mathrm{GWP}_{a,y}} \tag{3}$$

where

- $GWP_{Building}$ is calculated with regard to the building life cycle ($kgCO_{2eq}$);
- $GWP_{a,\ y}$ is the GWP avoided yearly in the Refurbishment scenario, which results 24,492 $kgCO_{2eq}$/y. It depends on the typology and efficiency of the used plants. It is based on the previous $E_{s,\ y}$ and on the reference emission factor of each electricity mix and national gas-fired heating plants.

The two indexes assessed for the case study are 14 and 8 years, respectively.

These outcomes involve that the energy and environmental benefits related to Refurbishment scenario would fully repay the life cycle impacts in a short period in comparison with the expected lifetime of the building itself.

## 4 Discussion and Conclusions

The above life cycle energy and environmental assessment aims to highlight the variation of the ecoprofile of the LH, when it is shifted from nearly Net ZEB toward the Net ZEB target, at final energy level.

Globally, in the Refurbishment scenario, all the life cycle energy and environmental impact indicators present lower values than the Baseline scenario.

As it can be noted from the results, the production and the replacement give the highest contribution on the building life cycle ecoprofile in both assessed scenarios, with regard to CED and the environmental indicators. They slightly increase moving from the existing nearly Net ZEB to the refurbished Net ZEB.

Building operation results the most affected phase. In fact, when moving from the Baseline to the Refurbishment scenario, the building not only reaches the energy balance condition ($E_{\mathrm{net,\ LH}} = 0$), but also generates a surplus as final energy ($E_{\mathrm{net,\ LH}} > 0$). Then, the sum of the covered deficit from the nearly Net ZEB to the Net ZEB condition and the energy surplus, which is assumed to be exported to the grid, involves significant saving of primary energy and avoided environmental impacts, depending on the Italian energy mix for the production of electricity.

Therefore, the main conclusion of the presented study is that taking the step from a nearly Net ZEB to Net ZEB results in a small increase in primary energy consumption and environmental impacts in the production and maintenance steps, while the operating energy demand goes down to zero. However, each energy and environmental indicator results decreased and, consequently, the ecoprofile of the refurbished building is globally improved with respect to the existing building. Further, the surplus generation owing to the PV plant retrofit involves energy and environmental benefits beyond the building boundary, in terms of primary energy saving and avoided environmental impacts.

## References

Ardente F, Beccali G, Cellura M, Lo Brano V (2005) Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances. Renew Energy 30:109–130

Ardente F, Beccali M, Cellura M, Mistretta M (2008) Building energy performance: a LCA case study of kenaf fibres insulation board. Energy Build 40:1–10

Ardente F, Beccali M, Cellura M, Mistretta M (2011) Energy and environmental benefits in public buildings as a result of retrofit actions. Renew Energy Sustain Rev 15:460–470

Battisti R, Corrado (2005) A Environmental assessment of solar thermal collectors with integrated water storage. J Cleaner Prod 13:1295–1300

Beccali G, Cellura M, Mistretta M (2001) Managing municipal solid waste: energetic and environmental comparison among different management options. Int J Life Cycle Assess 6(4):243–249

Blengini GA, Di Carlo T (2010) The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy Build 42:869–880

Brown B, Aaron M (2001) The politics of nature. In: Smith J (ed) The rise of modern genomics, 3rd edn. Wiley, New York

Cellura M, Campanella L, Ciulla G, Guarino F, Nardi Cesarini D, Lo Brano V, Orioli A (2011) A net zero energy building in Italy: design studies to reach the net zero energy target. In: Proceedings of building simulation 2011, an IBPSA—AIRAH conference, Sydney, Australia

Chen TY, Burnett J, Chau CK (2001) Analysis of embodied energy use in the residential building of Hong Kong. Energy 26:323–340

Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings

Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)

Dixit MN, Fernández-Solís JL, Lavy S, Culp CH (2010) Identification of parameters for embodied energy measurement: a literature review. Energy Build 42:1238–1247

Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2007) Overview and methodology. Ecoinvent report no. 1, ver. 2.0, Swiss centre for life cycle inventories. Dübendorf (CH)

Gustavsson L, Joelsson A (2010) Life cycle primary energy analysis of residential buildings. Energy Build 42:210–220

Hernandez P, Kenny P (2010) From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB). Energy Build 42:815–821

IEA (2013) SHCTask40/ECBCS Annex 52, towards net zero energy solar buildings. http://task40,.iea-shc.org/. (Last accessed 08/02/2013)

Lo Mastro F, Mistretta M (2004) Cogeneration from thermal treatment of selected municipal solid wastes. A stoichiometric model building for the case study on Palermo. Waste Manage 24(3):309–317

Napolitano A, Sartori I, Voss K (2012) Net zero energy buildings: a consistent definition framework. Energy Build 48:220–232

PRè-Product Ecology Consultants (2010) SimaPro7.2, environmental database 2010. Amersfoort, The Netherlands

Salom J, Widén J, Candanedo J, Sartori I, Voss K, Marszal A (2011) Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators. In: Proceedings of building simulation 2011: 12th conference of international building performance simulation association, Sydney, 14–16 Nov 2011

Sartori I, Hestnes AG (2007) Energy use in the life cycle of conventional and low energy buildings: a review article. Energy Build 39:249–257

Sartori I, Napolitano A, Voss K (2012) Net zero energy building: a consistent definition framework. Energy Build. doi:10.1016/j.enbuild.2012.01.032

The International EPD Cooperation, General Programme instructions for Environmental product declarations, EPD. Version 1.0, 2008

Torcellini P, Pless S, Deru M (2006) Zero energy buildings: a critical look at the definition. ACEEE Summer Study, Pacific Grove

TRNSYS v. 16.1 (2003) A transient system simulation program. Solar Energy Laboratory, University of Wisconsin

UNI EN ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework, International organisation for standardisation

# A Multiple-Case Study of Passive House Retrofits of School Buildings in Austria

**Xavier Dequaire**

**Abstract** Strong increases in energy efficiency in buildings is central to reducing energy consumption and costs, reducing greenhouse gas emissions, tackling climate change, and at the same time, improving energy security. The concept of "nearly zero energy buildings" gives an indication of what is considered achievable, and this has now been widely demonstrated for new buildings of all kinds. However, the large number of buildings that have already been built emphasises the need to carry out extensive energy efficiency upgrades of the existing building stock in order to the "nearly zero energy" concept to achieve its real societal importance. This article highlights retrofits of large buildings using Austrian schools as examples, which have been chosen to illustrate reductions of more than 80 % in heat demand. Key issues are addressed through a multiple-case study of four school retrofits in Austria. All four buildings demonstrate the achievement of the energy efficiency level of the Passivhaus standard for new buildings. They present a paradigm for this form of upgrades and thus validate the Passivhaus standard.

## 1 Introduction

Recent years have seen the continuous strengthening of different legislations concerning energy use, and in particular energy efficiency in buildings. As a broad trend, particularly occurring across Europe, all new developments will be required to reach the level of nearly zero energy buildings—and even the energy plus level by 2020 (The European Parliament 2010; Heinze and Voss 2009; Marszal et al. 2011; Srinivasan et al. 2012). Heavy refurbishments will also have similar low-energy requirements. New buildings, however, only represent one to two per cent

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of the building mass (Itard et al. 2008, pp. 32–33); therefore, existing buildings provide the main potential for energy savings and require a strong focus.

Any need for retrofit, repair or maintenance to the envelope of a building is a good opportunity to undertake an upgrade in energy efficiency. Several studies (Plöderl et al. 2008; Dokka and Klinski 2010; Bretzke 2009) indicate that a radical energy retrofit can subsequently even pay for itself due to the important energy savings. Several levels of retrofits can be identified. Very limited actions may not interfere with the energy efficiency, but in general, most actions—even minor actions—have an impact on the overall energy efficiency of a building, or may impair the ability to improve this efficiency at a later date (Bodem 2010; Feist et al. 2009). Consequently, a radical approach to energy efficiency improvement is needed to get the best return on investments.

The case of small residential buildings retrofits seems well covered (Feist et al. 2001; Schnieders and Hermelink 2006; Pedersen and Peuhkuri 2009; Herkel and Kagerer 2010; IBGE 2009; Beedel et al. 2007). Larger non-residential buildings are, however, subject to increased interest (Itard et al. 2008; Thomsen and Wittchen 2008; Waide 2006; Herkel and Kagerer 2010). Among these, school buildings are an interesting group (Kluttig et al. 2002; IEA 1991; Butala and Novak 1999). Due to the many challenging conditions during extensive energy upgrade, they deserve special attention. Meeting the requirements in such buildings may provide important knowledge in upgrading towards highly energy-efficient buildings on a broader scale. Austria is a European country providing extensive models and practical examples on how such radical energy retrofits can be attained. Notably, several school buildings have been retrofitted achieving between 80 and 90 % reductions in heat demand. Such reductions actually go far beyond the levels of most of other international references (Kluttig et al. 2002; Butala and Novak 1999), while knowledge about these retrofit projects has had only limited attention in international scientific publications. A systematic, in-depth knowledge is largely lacking. The main aim of our study was to make such knowledge public to an international scientific audience.

Four Austrian school buildings, that could be visited and studied in situ in 2010, were selected for a multiple-case study. They all represent implementations of the Passivhaus standard (Lang 2009); an approach with clear principles, and a validation scheme that allow radical improvements of energy efficiency of buildings at the expected level of nearly zero energy. Such a system also provides a solid foundation for coherent case studies, analyses and comparisons.

First developed in 1994 as a standard for residential buildings by the Passivhaus Institute (PHI http://www.passiv.de), the Passivhaus standard has won wide international recognition and application in a variety of climates. The standard is linked to the “passive house planning package” (PHPP), a tool that allows validation of the design (Feist 2007). This standard is now used for all kinds of building and also as a reference for retrofits.

Retrofits represent larger challenges. The PHI has recently (2010) introduced a set of requirements for the certification of retrofits of existing buildings called EnerPHit. The substantial number of constructions designed or retrofitted according to the Passivhaus standard provided a good set of references for state of the art in nearly zero energy buildings.

Our study explored a larger collection of projects from Austria, all including approaches to retrofit with Passivhaus components. These upgraded buildings generally achieved the energy efficiency level of the Passivhaus standard for new buildings. They showed a reduction in heating demand of more than 80 %. For these reasons, there is a need to understand what can be achieved using the new frame of reference provided by the Passivhaus standard when applied to refurbishing schools from the perspective of very low-energy buildings.

Through a systematic analysis of the available project data for several cases of school upgrades, a picture of the key elements of these achievements is drawn. Schwanenstadt school is described in three reports written in German (interim (Lang et al. 2006), final (Plöderl et al. 2008) and post-occupancy (Wagner et al. 2009)) for the Austrian development project "Haus der Zukunft" [Building of Tomorrow] (http://www.hausderzukunft.at/english.htm). These are the only published documents of this kind we have found that describe a school upgrade attaining such a high level of energy efficiency. Because of the asymmetry of the available data, the Schwanenstadt project—which has been the best documented—is used as a main reference for other projects as considered appropriate. This written documentation is the base of this research. Specific data for the other projects are available in the international multilingual internet database for passive houses: Passivhaus-Datenbank (IG passivhaus Österreich n.d.). Additional information was gathered on a study tour in Austria that visited four schools: Schwanenstadt, Polytechn. u. Hauptschule II in Schwanenstadt; Allgemeine Sonderschule 06 in Linz; Allgemeine Sonderschule 04/Karlhofschule in Linz; and Hauptschule Zams-Schönwies, close to Innsbruck.

## 2 Context

### 2.1 Energy Efficiency in Buildings

Reduction in energy use can be identified as an important field of action justified by the subsequent decrease in running costs of buildings, the limitation of greenhouse gas emissions and energy independence. There has been much discussion and many ideas on energy efficiency in buildings. Consequently, the last decades have seen words, expressions and terminologies identifying numerous concepts, solutions, systems and more precise definitions of energy-efficient buildings (Marszal et al. 2011; Abel 1994; Laustsen 2008; Dequaire 2012; Mlecnik 2011). Sometimes, energy efficiency is included in the broader perspective of environmentally friendly approaches (Ebert et al. 2011), which are themselves associated with different words, definitions and scopes. Sometimes, it is reduced to a question of greenhouse gas emissions. A "nearly zero energy building", as termed in the EU directive (The European Parliament 2010), requires reducing the energy consumption of buildings to the point that renewable energy can meet the remaining loads. Even though the freedom of interpretation and of the means to be used are left to the different member states, a radical improvement in energy efficiency for buildings will be the most appropriate approach in reducing energy consumption.

Two main approaches for the reduction in energy use in buildings can be identified: (1) high thermal performance, expressed by a maximum value for heat demand and (2) limitation of delivered energy, expressed by a maximum value for primary energy (Dequaire 2012). The first usually supports the second, while the opposite is not necessary true. The Passivhaus standard used in the cases presented in this article is of the first type. The EU directive, and therefore several buildings codes in Europe, qualifies for the second type.

## *2.2 Upgrade of Large Buildings*

Different reasons can prompt the retrofit of a building, and, independently of any of these reasons, the opportunity to add other qualities can also be present. For example, different types of concerns, or the necessity to comply with new laws like building codes, fire regulations, universal design or heritage, can generate the different reasons to be taken into account in the retrofitting process. Maintenance and renovation projects extend from façade painting or window replacement to structural repair or upgrades of technical installations. Occasionally, a building can be almost totally rebuilt in cases where, for example, only the concrete structure is kept. In any case, the size of the building and eventually the large number of users involved require a good analysis of the project. An economic evaluation of reconstruction versus demolition and construction of a new building can be realised. For example, in the case of the municipality of Linz, if calculated retrofit costs are higher than 80 % of what a new building would cost, then a new building is constructed (Personal communication, November, 2010).

## *2.3 Passivhaus*

The precise definition is: “A Passive House is a building, for which thermal comfort (*ISO* 7730) can be provided solely by post heating or post cooling of the fresh air flow, which is required for good indoor air quality (IAQ) (DIN 1946) – without using recirculated air in addition”.

This is a purely functional definition, which does not contain any numerical values and is valid for all climates. It clarifies that the Passive House is a fundamental concept and not a randomly set standard.

From this initial definition, it is usually assumed that all thermal corrections, heating or cooling, are provided by the ventilation system, which is necessary to secure fresh air and remove used air and pollution. In association to the Passivhaus standard, this ventilation is most likely provided by a mechanical system with very efficient heat recovery (PHi n.d.).

This definition has been the basis for the development of the Passivhaus standard for residential buildings in central Europe, and the setting values are based on that definition, especially the heat demand to allow heat distribution with the ventilation system. The extension of application of the standard to other types of buildings and other climates has implied that the definition does not fit to the reality of use of the standard, and often the ventilation system is not sufficient to provide heating or cooling and simple heating or cooling sources are installed in the buildings. This is especially true for retrofitted buildings for which a specific standard has been later developed.

The PHI is an independent research institute into the field of highly efficient use of energy in buildings. It was established in 1996 and is headed by Professor Dr. W. Feist. The Passivhaus standard is studied widely through diverse approaches, for example, IEA and EU international projects, and scientific articles and practices in different countries. Historically, the concept was developed in an academic environment (Lund University, Sweden). Later work, if not always within a formal academic world, is not the only output from the PHI; research and development workshops are regularly organised and a large number of dedicated scientific conferences have taken place.

The Passivhaus standard focuses on reducing heat losses, securing air tightness and providing ventilation with an efficient heat recovery. Significant characteristics are good indoor climate and low-energy costs. Meeting the standard means complying with three requirements validated by calculations made using PHPP (in addition, several recommendations are provided to help achieve these requirements):

1. The first requirement is that the yearly heating demand of the treated area is a maximum of 15 kWh/($m^2$.y) or the heating power needed is at a maximum of 10 W/$m^2$. The latter condition exists to ensure that enough heating power is available for the worst weather conditions. Both these values have to be calculated with PHPP for the local climatic conditions.
2. The second requirement is the air tightness of the envelope of the conditioned space, which is required to be measured as less than 0.6 Air Changes by Hour (ACH) at n50 (measured on site for a pressure difference of 50 Pa). PHPP also uses the unit $h^{-1}$ or 1/h.
3. The third requirement limits the total weighted primary energy to be less than 120 kWh/($m^2$.y) when calculated with PHPP.

Reducing heat loss is firstly achieved by improving the thermal envelope with a special thermal bridge-free construction. Secondly, sufficient air tightness limits heat loss from uncontrolled air exchanges between indoors and outdoors. These two aspects need to be solved at the envelope level of the building. Increased insulation of the opaque elements is usually achieved by thicker insulation layers or the use of material with better thermal resistance, and by a thorough treatment of structural features to reduce, or preferably to eliminate, thermal bridges.

Windows have insulated frames and triple glazing. Doors are highly insulated. To sum up, the parts of the envelope are usually identified as walls, roof, ground and windows and doors with a thermal bridge-free design. Triple glazing also provides efficient acoustic insulation—an added value in noisy urban environments.

There also needs to be a continuous airtight layer around the volume of the whole building. A precise design is necessary to support this requirement. One control procedure performed at the design stage is to be able to draw a line with a pen on a building plan, and to follow the air tightness layer and come back to the starting point without leaving the paper. Glazing is a part of this air tightness layer. Special attention is paid to reducing penetration through the air tightness layer. Good sealing materials (membranes and tapes) are used in the connections. Critical connections are where different elements meet—like roof-wall, wall-floor, building boards, penetration of ventilation ducts, electrical cables or plumbing through the envelope, windows and door openings. When the air tightness layer is installed, a pressure test must be executed to check the air tightness value.

When such a high level of air tightness is achieved, ventilation is secured in a controlled manner. Good indoor climate requires a minimum flow of air to remove excess moisture and pollutants and to provide fresh air. Expelled air takes heat with it, creating heat losses. To limit these heat losses through ventilation, a balanced ventilation system with highly efficient heat recovery is usually recommended. The general PHPP recommendation for ventilation is 30 $m^3$/h per person, a level that refers to the requirements of the German standard DIN 1946 part 6 (Feist 2007). Filtration of incoming air removes particles and pollen, offering an added value. It is recommended to use low-emitting materials to limit the need for ventilation. Ventilation is always designed so that there is no noise annoyance from it.

The requirements of the Passivhaus standard apply to any building; however, it has been recognised that upgrading to that level of energy efficiency is not always feasible. Recently, “EnerPHit—Quality-Approved Modernisation with Passive House Components” was introduced by the PHI to allow a certification for the retrofit to the Passivhaus standard where the heat demand has to be lower than 25 kWh/($m^2$.y). Otherwise, according to EnerPHit, the same characteristics have to be addressed, with a focus on the same design principles based on the use of Passivhaus elements. The designer is confronted with particular challenges, including limiting existing thermal bridges, securing air tightness and implementing balanced ventilation. For example, existing buildings usually have large thermal bridges that can be inaccessible (such as the building’s foundations). Ventilation systems may require new space for the ductwork and technical room. In addition, existing structural elements might need to be perforated. Attention is also drawn towards other energy uses in a building, such as domestic hot water (DHW) and electricity for light and amenities. Therefore, daylight use is optimised for both comfort and energy, and presence controls and light controls can be implemented. Heritage buildings, though, present additional constraints.

The Passivhaus Institute offers certification of building elements or components. The process of certification for a building is simplified by the use of certified elements and certified designers (PHi 2011).

### 2.4 School Buildings

Historically school buildings seem to have suffered from deficient maintenance resulting in poor indoor climates (Limb 1997). Restricted budgets and continuous operation of a school argue for limiting the school closing time. Furthermore, high levels of noise and local air pollution during construction can be incompatible with school activities. Schools are buildings with specific requirements and properties for operation; this is especially true for their schedules of use, with varying lengths of time during which they are not occupied inducing fast changing internal loads.

Loads that change quickly require fast responses from a building and its systems in order to respond well in handling air moisture and pollutants, in providing fresh air, and in keeping thermal comfort while energy demand is kept low. Therefore, in Passivhaus design, there is high interest and focus on IAQ and indoor environment quality (IEQ). It is worth noting that, based on experience, the PHPP recommendation for ventilation is to provide 15–20 $m^3$/h of fresh air per school pupil (Feist 2007). These values are adapted to the various room types with their different usages and needs as found in the context of a school building. Lighting is also given special attention: optimised use of daylight and provision for solar protection to avoid blending and overheating are evaluated as an integral part of the Passivhaus concept. For the scope of our research, the focus is on certain important features of the Passivhaus concept: the envelope, air tightness, thermal bridge reduction and ventilation strategies.

A school building is constructed and designed to allow education, where the qualities are defined according to, or derived from, national requirements. A school building usually includes conventional classrooms, special dedicated rooms and workshops, meeting rooms, halls, toilets, and eventually a kitchen and restaurant, offices, sports hall and showers. As for all categories of building, it is assumed that a good indoor climate is a prerequisite, and that good IAQ and thermal comfort are required. For school buildings, clear requirements for daylight and acoustic comfort are given and schedules usually include limited or no activity on evenings, weekends and holidays. The Passivhaus standard has demonstrated its applicability to school buildings (Bretzke 2009; Feist et al. 2006), and is therefore widely used for new school constructions as well as upgrading.

## 3 Methodology

### 3.1 Approach

The methodological approach used for this research can be termed a descriptive multiple-case study as described by Robert K. Yin in his book ≪ Case Study Research ≫ (Yin 2008). The case study provides a means of systematic and in-depth studies on how Passivhaus retrofits of schools in Austria are achieved, identifying the common elements of the cases, and discussing the differences.

### 3.2 Defining a Performance Reference

In the Passivhaus-Datenbank (IG passivhaus Österreich n.d.), retrofit with Passivhaus components is defined as retrofit that results in a building with low-energy demand. The heat demand is then $\leq 35$ kWh/($m^2$.y). The Passivhaus Institute has developed a specific standard for retrofit, EnerPHit (Passivhaus Institut 2010), limited today to residential buildings, in which the certification limit for heat demand is $\leq 25$ kWh/($m^2$.y). Alternatively, if this value is not met, a set of requirements for the building components applies. In this latter case, the certification will describe the building as "EnerPHit—Quality-Approved Modernisation with Passive House Components". For the cases studied here, all the buildings achieved a level of heat demand $\leq 15$ kWh/($m^2$.y), as required for new buildings by the Passivhaus standard according to the PHPP (Feist 2007). In this article, "Passivhaus" refers to the original German standard, while "passive house" refers to the general underlying concepts.

### 3.3 Case Studies

The research focuses on the achievement of four Austrian experiences, which demonstrated the ability of the buildings to meet the criteria of the Passivhaus standard through upgrading. Austria has shown to be in the forefront of Passivhaus development (Lang 2009). The result is a description of a common approach allowing the Passivhaus level of energy efficiency and an analysis to identify similarities and differences. The choice of the schools studied as empirical material was determined and limited by the opportunity to visit those buildings during a single trip and the relationships with relevant people developed during those visits allowing access to key data. The four cases provide the foundation of the multiple-case study. The case study is designed with the help of a protocol used as a guideline for interviews and data collection and guaranteeing the reliability of the research design. Interviews were held with key personal involved in the projects, and these were guided by the protocol presented below. The Passivhaus-Datenbank is a good source of basic information for all four projects. The Schwanenstadt project is further described in several German reports (Lang et al. 2006; Plöderl et al. 2008), which besides factual information about the construction, such as U-values and energy consumption, feature analysis of the development of some critical elements of the retrofit process. Reduction in thermal bridges, façade changes which include glazing as part of the improved thermal envelope, and ventilation strategies are also addressed there in more restricted units of analysis (Yin 2008).

These cases can be qualified as exemplary as the concept is described by Yin (2008). The exemplarity can be expressed at different levels: they are exemplary in the context of building renovations in general, school retrofits in particular, and in the achievement of the level of the Passivhaus standard in renovation. And because the multiple-case study provides multiple source of evidence from key informants, we can confirm according to Yin that his provides construct validity, while internal validity is secured by data coherence. Analytical generalisation is used to draw the key conclusions.

It must be noted that the choice of cases does not exclude the existence of several other buildings and projects, which themselves may have the same relevance to this research.

### *3.4 Data Sources*

In our process, the publicly available material was reviewed first; this included the already available and most comprehensive information about Schwanenstadt and the data published in the Passivhaus-Datenbank for the other schools was taken into account. The data collection protocol was designed on the basis of a general understanding of passive house concepts, of the Passivhaus standard more specifically, and of the challenges of building upgrades towards a high level of energy efficiency (Baker 2009).

This protocol was developed to gather and structure the core information of the research and to provide an effective tool for storing and comparing the data. It was not restrictive, and any suitable information found to be relevant was added as comments. This data is stored in a spreadsheet.

Data collection began with an analysis of the previously published material found in the reports about Schwanenstadt (Lang et al. 2006; Plöderl et al. 2008) and the Passivhaus-Datenbank. A study trip was organised to Austria in the autumn of 2010, including the visits of the four retrofitted schools of this study that allowed outside inspections, indoor exploration and technical room visits. The guides were key personnel involved in the projects as architects and engineers. In addition, some users answered questions during the visits. Subsequently, some additional documentation such as the PHPP spreadsheets was sent in by the key personnel.

### *3.5 Buildings Elements and Features*

An analysis of the renovation requires understanding and organising the knowledge about the buildings and then identifying the relevant items for this study. For a Passivhaus renovation, the following list was compiled (the list is not exhaustive and is meant as a tool for this specific case research) (Fig. 1).

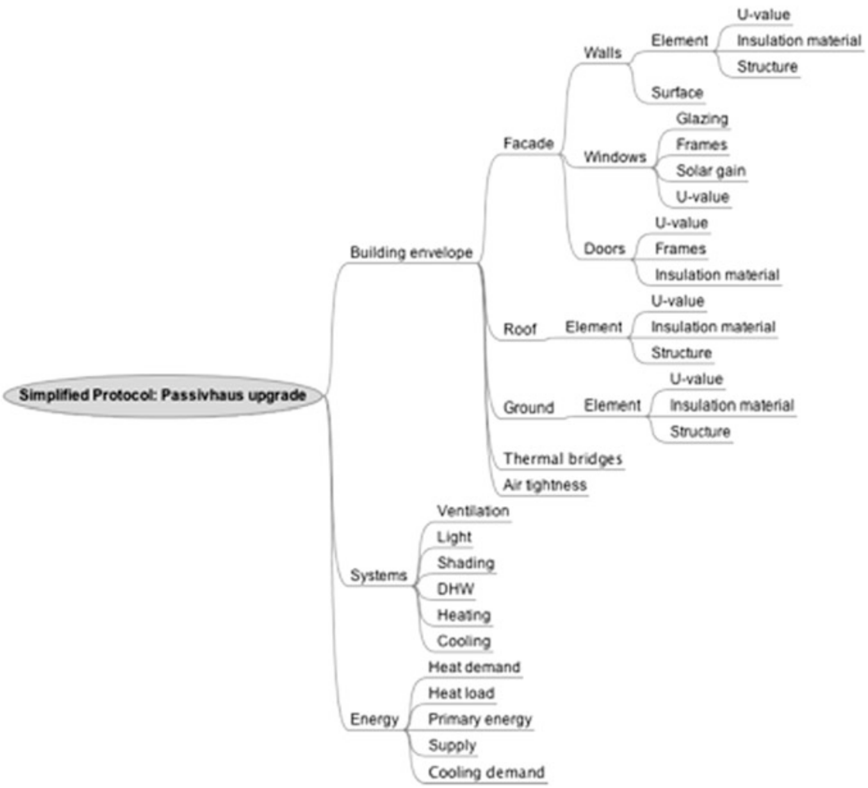

**Fig. 1** Visualisation of the protocol of the case study

## 4 Cases

Austria has a temperate continental climate, meaning cold winters and warm summers with local differentiations due to altitude. The four schools featured in the present study were built between 1961 and 1977, using similar mixed constructions methods and including concrete structures. The bearing columns of the façades were in several cases outside the thermal envelope, creating serious thermal bridges with the concrete slabs of the floors. Leaky doors, poor windows and limited insulation contributed to low thermal performance.

The Austrian Institute for Building Technique [Österreichisches Institut für Bautechnik, OIB (http://www.oib.or.at)] grants an energy certification [Energiausweis] that gives the building a category with reference to its heat demand.

### 4.1 Case 1: Hauptschulen II and Polytechnischen Schule, Schwanenstadt

The building was built in 1972 at an altitude of 270 m. Two schools occupy the building in two different parts—the Polytechnische with two stories and the Hauptschule with three stories. During the retrofit, the Polytechnische is extended partially with a third floor and an extension on three stories while the Hauptschule is also extended at the north end over the three stories with a full revision of the interior design. The whole appears now as two–three-storey blocks linked by a lower two-storey section. A sports hall is included in the thermal envelope. The renovation project, completed in 2007, was a demonstration project which was part of the national Austrian project “Haus der Zukunft”. According to PHPP, the heat demand has been reduced by 88.5 % to 14 kWh/(m$^2$.y) and is 82.4 % lower than that for the originally planned refurbishment. Some part of the water-based heating system is kept to distribute heat in the building (Fig. 2).

The buildings have concrete structures. The columns around the perimeter originally stood outside of the thermal envelope, creating thermal bridges. These exterior concrete constructions are now included in the thermal envelope by covering the façade with large prefabricated elements. Better ground insulation was achieved through the injection of glass foam granulate into the 50–70-cm-high existing space under the floor through openings drilled in the thick concrete slab. The ventilation is provided by decentralised systems for each room, including the classrooms, the dining room and the kitchen. Additional daylight is provided by new roof openings. Prefabrication allowed for a short construction time with low impact on the function of the schools.

Weather proofing of the extension of the Polytechnische is made of orange cladding plates and the rest is untreated wooden siding. Otherwise renewable energy is provided in the form of heat by a pellet boiler, and a 6-kWp photovoltaic plant is integrated on the south façade of the two-storey section (Fig. 3).

The documentation available includes two project reports: Demonstrationsprojekt—Erste Passivhaus-Schulsanierung—Zwischenbericht [Demonstration

**Fig. 2** Schwanenstadt: a compact shape and large windows for increased daylight. Shading is provided by venetian blinds. *Square vents* for the decentralised ventilation units are visible. *Photo* Xavier Dequaire

**Fig. 3** Schwanenstadt: the old concrete structure is visible with the position of the old thermal envelope including windows. Under the ceiling, a ventilation unit with vents is directly connected to the outdoors. *Photo* Xavier Dequaire

Project—First School Renovation as a Passive House—Interim report]; Erste Passivhaus-Schulsanierung [First School Renovation as a Passive House], the entry in the Passivhaus-Datenbank and the PHPP file.

## *4.2 Case 2: Sonderschule 4, Linz*

A "Sonderschule" is a special school for children and teenagers who cannot attend an ordinary school, and these children need special attention and sometimes special equipment (Figs. 4 and 5).

The school was originally built in 1961, at an altitude of 266 m and was in poor condition before the renovation, which was completed in September 2009. The building was expanded with an additional floor, and a connecting corridor to the neighbouring building was replaced by a bridge built with passive house elements. Two outdoor recreational spaces were then united by the freed space under this bridge. Because of a weak existing structure, the additional storey was built with a

**Fig. 4** Sonderschulen 4 in 2009 just before renovation, Credti: Immobilien Linz GmbH & Co KG and archipicture.at

**Fig. 5** Sonderschule 4: a new storey provides additional space preserving a compact shape. Large windows increase daylight. Venetian blinds provide shading. The original columns are included into the thermal envelope. *Photo* Xavier Dequaire

light timber frame construction. The construction work was mostly executed during the summer holidays (Immobilien Linz Gmbh 2009a); the additional storey was constructed in the summer of 2008, and the façade replaced in summer 2009. 30 cm of cellulose was used in the walls and a combination of expanded polystyrene (EPS) and extruded polystyrene (XPS) was used in the roof.

The external venetian blinds have two levels of closure, keeping the upper part more open to let more daylight in. Prefabricated elements were used for the new storey. New furniture was designed and the interior fully renewed. The façade cladding is made of uncoated wood fibre boards. The school building received a special acknowledgement by earning a Holzbaupreis 2009 [prize for wooden construction]. The school reduced its heat demand to 7.2 kWh/($m^2$.y) corrected for altitude. This number is calculated by the official Austrian method, not PHPP, and it can be assumed that the PHPP value would be below 15 kWh/($m^2$.y). (See a comment later).

The documentation available includes the entry in the Passivhaus-Datenbank, a brochure published by the municipality of Linz and a leaflet printed by the architect (Fig. 6).

## *4.3 Case 3: Sonderschule 6, Linz*

The school was built in 1977 and was in a poor condition before the renovation was completed in September 2009. The building was expanded with an additional floor to incorporate new functions; overall, the building includes 12 classrooms, group rooms, kitchens and offices (Immobilien Linz Gmbh 2009b). A large roof opening above the original stairwell was opened to allow deep penetration of daylight. In addition, narrow vertical glazing between the classrooms and the circulation area provides additional daylight. Small separated windows were replaced by large fields, and screens provide solar protection. The entrance was changed completely with a large overhang added and the façade is plastered. The

**Fig. 6** Sonderschule 4: closed shutters show two levels of blending, allowing additional daylight to enter through the upper part of the blinds. In the middle, protective louvers for the window are used for night cooling. *Photo* Xavier Dequaire

school has reduced its heat demand to 12.9 kWh/($m^2$.y) according to PHPP. The building structure was weak, so the additional floor was built up with a light construction of timber frames. The interior was fully renewed with specially designed furniture. The walls were insulated all the way with 30-cm EPS. The ventilation is provided by a centralised system, with the ductwork hidden above hanging ceilings. Solar thermal panels and PV provide some renewable energy.

The documentation available includes the entry in the Passivhaus-Datenbank, an energy certification form and a brochure published by the municipality of Linz (Figs. 7 and 8).

### *4.4 Case 4: Hauptschule Zams-Schönwies*

This school was constructed in 1975, 767 m above sea level. The building is owned by the municipalities of two large villages of Tyrol: Zams and Schönwies. A sports hall is included in the thermal envelope. The renovation work was carried out over three summer holidays in 2007, 2008 and 2009 to limit the impact on the school's activities (Ehrlich 2009). The project achieved a 95 % reduction in heat

**Fig. 7** Sonderschulen 6 in 2009 just before renovation, Credit: Immobilien Linz GmbH & Co KG and Fotostudio Meister Eder

**Fig. 8** Sonderschule 6: a compact shape and large windows for increased daylight. Shading is provided by screens rolled up in slim casings *Photo* Xavier Dequaire

demand down to 14 kWh/($m^2$.y) according to PHPP. Budget constraints limited some actions resulting in, for example, partial replacement of light fixtures and no major change to the interior design, although the gymnasium included in the building had some specific acoustic improvements in addition to the passive house thermal retrofit. The first step was completed during the first summer holidays in 2007. The removal of the asbestos cladding and the aluminium façade was carried out in the second summer, 2008, followed by the installation of a highly efficient new façade on a wooden structure in 2009. The windows are PHI certified. A new central ventilation system was installed, and most of the ducts and installations are kept visible. The fresh air is taken through an underground heat exchanger. Regulation is made for each classroom with a $CO_2$ metre at the exhaust vent. The existing water-based heating system was modified: redundant radiators were removed, and additional heat can be provided in the classrooms by water-based radiators controlled with a thermostat. The fresh air is brought by horizontal ventilation ducts on the floor and delivered on the upper side and through the fined tube radiators. Heat is provided by local district heating (Figs. 9 and 10).

**Fig. 9** Zams-Schönwies the south façade before renovation. *Photo* Robert Ehrlich

**Fig. 10** Zams-Schönwies, south façade after upgrade: columns are inside the new thermal envelope. *Photo* Xavier Dequaire

Daylight in the cellar rooms has been improved by setting larger Passivhaus windows, and by removing the narrow shafts and excavating the ground into a slope, which allows for a sky view and solar access. The recreation areas received improved daylight thanks to a double-storey glazed façade towards the north. Large roof windows allow daylight penetration through the stairwell and can be used for ventilation, especially night cooling.

Solar protection is ensured by exterior venetian blinds that are centrally controlled with provision made for individual adjustment. The façade cladding is made of stone-like rectangular plates. The project received a renovation prize for public buildings: Tiroler Sanierungspreis, 2009.

What the PHPP shows: except for the floor slab and walls of the underground, the thermal envelope elements have U-values expected for Passivhaus.

The documentation available includes the entry in the Passivhaus-Datenbank, a leaflet printed by the architect and a PHPP file (Fig. 11).

**Fig. 11** Hauptschule Zams-Schönwies: exposed vertical ventilation ducts. *Photo* Xavier Dequaire

## 5 Analysis

A building is a very complex object, with many pieces and parts. The analysis here focuses on the functions of larger building elements. The four buildings comprising the case study were originally constructed in the same period (1961–1977) and have a similar construction: a concrete frame and slabs, flat roofs and two or three stories. The renovation projects were conducted in the same period of time between 2007 and 2009. The initial and well-documented Schwanenstadt project, completed in 2007, was inspirational for the other projects, and the solutions proposed were quite similar for the envelopes, though they differ for ventilation. For the architecture, none of the buildings had any heritage requirements and this allowed free redesign and external insulation. The Passivhaus standard leaves extensive freedom for architectural expression as shown by the cases, with among other things, different weather proofing solutions for all four buildings. It is worth noted that the interviewed users of the schools have expressed their high satisfaction on the improvement.

## 5.1 Compactness

The compactness of a building expresses the relationship between the surface of the envelope, through which thermal losses happen, and the volume to be heated. A ratio is then calculated as area/volume, or envelope area/heated area. Energy efficiency depends on reduced heat losses for a given volume to be heated, and as a consequence is helped by a low compactness ratio. The compactness of the building of the schools was retained or increased. Sonderschule 6, as a cube (see Fig. 4), is the most compact building. The other three buildings are elongated and have the common feature of the second floor being extended as an overhang covering the entrance, and are still very compact.

## 5.2 Concrete Structure

Three of the schools were extended; the extensions consisted primarily of the addition of a full storey for both Sonderschule, and an additional storey was also part of the extension for Schwanenstadt. The original buildings and their concrete structures were not designed to accommodate additional stories. To cope with this circumstance at both Sonderschule, light timber frame constructions were used to allow the construction of an additional storey without extensive reconstruction of the weight-bearing structure. Sonderschule 4's additional wooden columns carry the new second floor. They are built on the outside of the old building, but inside the thermal envelope. Further analysis follows the protocol described earlier in Fig. 1.

## 5.3 Building Envelope

### 5.3.1 Façade

Schwanenstadt and Zams-Schönwies originally had external and/or exposed concrete columns on the façades with associated thermal bridges. For Sonderschule 4, the columns were exposed at the window level. In all cases, those columns are now incorporated into the building volume, so new façade elements were placed on the outside of the former columns. The internal volume of the building has increased by the thickness of the original concrete structure (for Schwanenstadt, 50 cm of added space on the perimeter).

Windows are of passive house quality with a mean installed U-value of 0.8 $W/(m^2.K)$.

### 5.3.2 Roofs

Except for Zams-Schönwies and some parts of Schwanensdtadt, most roofs of the cases are new structures and are also now highly insulated. Added external insulated layers provide effective means of eliminating thermal bridges, and for all four schools, the mean U-value of the walls and the roof is = 0.1 W/($m^2$.K); the range for this value was between 0.08 and 0.17 W/($m^2$.K).

### 5.3.3 Ground

Insulation under the ground of existing buildings is a complicated task and a challenge to confront while achieving the passive house standard. Most existing buildings either do not have any insulation under the ground, or have some centimetres of EPS. Walls under the ground can sometimes get accessed from outside, which is especially opportune if drainage work is done, and allows for installation of additional insulation. This was not the case for the schools studied. For Schwanenstadt, a unique solution was provided for the ground slab allowing a mean U-value towards the ground of 0.16 W/($m^2$.K).

### 5.3.4 Thermal Bridges

For Schwanenstadt, an interesting analysis shows the comparison between two thermal bridge mitigation approaches (Lang et al. 2006). An initially proposed approach could have kept the same placement of windows, on the inner side of the columns, and packed the columns with insulation to reduce the thermal bridge. However, such a cumbersome and costly job would not have made achievement of the same thermal resistance possible compared with the prefabricated façade elements designed to be placed on the outside of the columns. The thermal bridge is limited to the outside of the column and insulation is placed in a continuous plan, limiting the angles that imply complicated handwork to avoid thermal bridges. The continuous plan also simplifies the air tightness and cladding work. This improved approach brings the walls' mean U-Value from 0.37 to 0.08 W/($m^2$.K) (Lang et al. 2006). A similar approach was taken with the other schools, with a complete redesign of the façades (Fig. 12).

Shown above is the first proposal for thermal bridge mitigation. Shown below is the final strategy which provides a much better insulation and a straightforward construction. Drawing by Xavier Dequaire from an original by LANG consulting, Vienna.

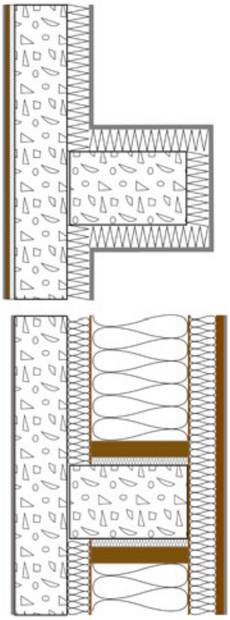

**Fig. 12** Schwanenstadt: cross sections seen from above, inside on the *left*

### 5.3.5 Air Tightness

A good level of air tightness was achieved in the retrofitted buildings, typically around 0.56 1/h. The air tightness is achieved together with the new exterior insulation. For Schwanenstadt, the process was not straightforward as an intervention in the windows was necessary to remove the excessive leakages there (Plöderl et al. 2008), achieving a limit of 0.6 1/h (Wagner et al. 2009). In any cases, the air tightness is measured for validation towards the standard.

## *5.4 Systems*

### 5.4.1 Ventilation

The use of heat recovery from ventilated air requires that both fresh air and used air pass through the same heat exchanger. As a consequence, duct work needs to be designed and installed accordingly. A Passivhaus design principle is to reduce the length of such duct work, which allows fan power to be limited and subsequently reduces electricity consumption. Maintenance is also easier. The installation of new duct work in an existing concrete building, though, is quite challenging, as the structural concrete may need to be perforated in many places to allow both incoming fresh air and extraction. To address these challenges, two main strategies can be chosen: centralised or decentralised. Additionally, there is a possibility to make provision for night cooling. For the cases studied, both kinds of solutions were used.

For Schwanenstadt, a decentralised solution was chosen throughout the whole building, and the same type of heat recovery unit was installed everywhere. This unit is based on a plate heat exchanger with an 85 % nominal rate of heat recovery. The unit hangs under the ceiling and is placed directly towards the exterior wall allowing short ducts. When necessary, two units are placed in the same room. Toilets have their own systems, while the sports hall has openings in relation to the windows. There is provision for night cooling through natural ventilation.

The three other schools use centralised ventilation systems. For Zams-Schönwies, to minimise the concrete perforation, the fresh air is distributed though horizontal ducts in the cellar, and further through vertical ducts up through the floors. Each duct serves two classrooms on two different stories. A water-based fin radiator in front of the vent provides additional heat when needed. To limit costs, the exhaust air is extracted through visible horizontal duct work below the ceiling, collected on each floor and taken down to the cellar in the existing stairwell space.

For Zams-Schönwies and Sonderschule 6, the incoming air is preheated by an underground heat exchanger. For Sonderschule 4, the ventilation system is partially hidden.

### 5.4.2 Light

Lighting is an important source of electricity consumption, and concerns about this consumption are part of the passive house concept. A first step in low-energy design is to improve the use of daylight and then to implement control systems to reduce the time when artificial light is used. The PHPP has an extended style sheet to assess the need for electricity for lighting for different zones of the buildings taking into account the access to day light. In the four schools, different actions have been taken to increase the use of daylight. Skylights have been added in all the buildings, especially above stairwells. In Sonderschule 6, new internal glazing distributes the light deep in the building. Except in Zams-Schönwies where budget limitation limited this option, the schools have new low-energy fixtures and control systems. Lighting is closely related to solar protection, shading and glare.

### 5.4.3 Shading

All the windows exposed to direct sunlight are equipped with external movable shading, screens for Sondeschule 6, and venetian blinds for the others. An interesting solution was chosen for Sonderschule 4 (Fig. 3) and Schwanenstadt; the upper part of the blinds lets more light in when the lower portion of these blinds is fully shaded, allowing more daylight into the room. All systems are automatically driven with possibility for local override.

### 5.4.4 DHW and Heating

Provision is made for renewable energies to meet the requirements for primary energy.

### 5.4.5 Passive Cooling

For Sonderschule 4, the old internal concrete structure was partially kept open on the ground floor under the ceilings to help thermal summer balance and night cooling. For the same reason, the new concrete floor for the second storey was also kept visible as a ceiling for the first floor. Night cooling is further enhanced by specific window openings and specially designed catches to keep classroom doors partially open. The excess warm air is expelled by natural buoyancy through shafts above the stairwell. Schwanenstadt is similarly equipped for night cooling (Fig. 13).

## *5.5 Other Considerations*

In the case of the two schools in Linz, the motivation to move forward with the Passivhaus standard came from the owners (where the municipality seems convinced of the value of the Passivhaus standard for their buildings). In Schwanenstadt and Zams-Schöwies, a long discussion process was required (personal communications, study tour, 2010). For example, in Schwannensadt, the project was initiated by Günter Lang (who was seeking a relevant project for the Haus der Zukunft/EU project) and permitted a redirection of the project towards the Passivhaus standard. In all cases, the people met during the visits expressed their satisfaction with the retrofits of the school building, being teachers with the IAQ, light and comfort, or the municipality with the improved quality of the offer to the children.

**Fig. 13** Sonderschule 4: catches to keep door open allowing night cooling. *Photo* Xavier Dequaire

In addition to the four cases presented here, the Passivhaus-Datenbank shows (as of November 2010) a non-exhaustive list of 8 additional projects for retrofits with PH components: Ainet, Neumarkt, Wolfurt, Velden, Bezau, Alberschwende, Hörbranz and Mäder. Their performances, as calculated with PHPP, show heat demands between 7 and 27 kWh/($m^2$.y), and heat loads between 10 and 27 W/$m^2$. Some projects mention air tightness values between 0.3 and 0.6 1/h. Primary energy was not requested for the first version of the database and the information is missing for most projects. However, considering the spreading of Passivhaus renovation for residential buildings, it is reasonable to suppose a similarity for school buildings and that the results described in this study can be achieved in most school renovations.

Nevertheless, a lack of clarity can arise as to whether the Passivhaus fulfilment is real or approximate, or whether it actually meets the exact requirements of the Passivhaus standard. This is because the studied buildings are not certified to the Passivhaus standard and some alternative methods are used to calculate some values. Methods of energy calculations in buildings are described by standards like ISO, but in our case, the national Austrian norm was used, which delivered a specific energy certification (OIB-Energiausweis). Generally, numbers for heat demand obtained from this official calculation (as with, for example, Sonderschule 4) differ from numbers calculated with PHPP. These differences can be consequential, with the OIB number being 20–50 % lower than the PHPP number—as the examples from the Passivhaus-Datenbank show—and this fact is confirmed by Austrian expertise (personal communication, Günter Lang, November 2010). Nevertheless, Passivhaus concepts were fully applied in the cases presented.

## 6 Conclusion

The four cases of this research, all large buildings from the 1960s and 1970s, show a remarkable exemplarity with reductions in heat demand better than 80 %. In particular, Schwanenstadt shows a striking 82.4 % improvement compared to the original traditionally planned refurbishment. The results of the case study provide a strong paradigm for a radical upgrade of energy efficiency. Within this paradigm, these school retrofits addressed important design issues and provided appropriate solutions for a strong control of thermal performances such as continuous external insulation solving thermal bridges on the façades. Both prefabricated elements and on site construction were used. Both these approaches allowed to also secure air tightness. In addition, mechanical ventilation with highly efficient heat recovery has been installed in all the buildings allowing good IAQ and highly improved comfort. Two approaches are equally valid: central systems or room units. The buildings have not been certified as Passivhaus; therefore, the judgment of the quality of the buildings as Passivhaus is only based on the control of air tightness, the design calculations with PHPP (and the trust that these calculations are true), and that the buildings are built according to the calculated design. Nevertheless, not meeting the air tightness requirement would reveal weak design and faulty implementation.

Considering the complexity of school retrofits, it makes sense that the different types of exemplarity that these cases show can be generalised to other types of large building. In particular, the article documents how a school building can be renovated and upgraded using the approach of the Passivhaus standard. The four retrofits described here show the possibilities for achieving highly comfortable learning arenas with particularly low heat demands below 15 kWh/($m^2$.y) according to the Passivhaus standard for new buildings. This is also remarkable for Passivhaus projects, where the requirement for retrofit is heat demand below 25 kWh/($m^2$.y). Considering that the climate in Austria can be particularly hard, with cold winters and high altitudes, there are good reasons to believe that similar energy efficiency results could be achieved in many similar locations of central and northern Europe as well as in milder climates (Sartori and Wachenfeldt 2008).

These results demonstrate that the Passivhaus approach to the renovation of large buildings—in particular school buildings—is appropriate in meeting the expectations of nearly zero energy buildings and thus presents a reliable approach in achieving radical improvements of energy efficiency for large buildings. This also indicates a possible methodological generalisation of the protocol used and the typology of passive house to nearly zero energy buildings.

Energy efficiency is a concern that has become most evident in today's building management, and also internationally with the ambition of nearly zero energy buildings. In that context, the improvement of the existing building mass is critical for achieving energy efficiency and for reducing the emission of greenhouse gasses at the societal level. As shown here, the retrofit of a building can prompt a radical energy efficiency upgrade when appropriate approaches are chosen. A move forward would be to implement a measure-and-validation programme to reveal the post-occupancy numbers that can validate the design and radical improvement in energy efficiency.

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## References

Abel E (1994) Low-energy buildings. Energy Build 21(3):169–174

Baker NV (2009) The handbook of sustainable refurbishment: non-domestic buildings. Earthscan Ltd

Beedel C, Philips R, Hodgson G (2007) Promotion of European Passive House/Final Report WP 3.4 PassivHaus Certifications

Bodem M (2010) “Reconstruction of the reconstruction”—dealing with the mistakes of the past. In: Conference Proceedings. 14th Internaional Passive House Conference. Passivhaus Institut, Dresden

Bretzke A (2009) Benefits of the passive house standard in schools: cost-effectiveness and user convenience. In: Conference Proceedings. 13th International Passive House Conference. Passivhaus Institut, Frankfurt am Main

Butala V, Novak P (1999) Energy consumption and potential energy savings in old school buildings. Energy Build 29(3):241–246

Dequaire X (2012) Passivhaus as a low-energy building standard: contribution to a typology. Energ Effi 05(01):1–15 XDi

Dokka TH, Klinski M (2010) Myhrerenga borettslag: Ambisiøs rehabilitering av 1960-talls blokker med passivhuskomponenter [Myhrerenga housing cooperative: Ambitious retrofit of a 1960’s apartment block with passive house components]. In PassivhusNorden. PassivhusNorden. Gothenburg, Sweden

Thomsen KE, Wittchen KB (2008) European national strategies to move towards very low energy buildings. 1st edn SBi, Statens Byggeforskningsinstitut

Ebert T, Eßig N, Hauser G (2011) Green building certification systems. 1st edn Institut für internationnale Architektur-Dokumentation

Ehrlich R (2009) Passive House Renovation Hauptschule Zams-Schönwies

Feist W (2007) Passive house planning package 2007—requirements for quality approved passive houses

Feist W et al (2009) Schrittweise Modernisierung mit Passivhaus-Komponenten [Stepwise modernisation with Passivhaus components], Passivhaus Institut

Feist W, Kah O, Vahid S (2006) Passivhaus-Schulen [The Passive House School], Passivhaus Institut

Feist W, Peper S, Görg M (2001) CEPHEUS-Project information No. 36 Final Technical Report

Heinze M, Voss K (2009) Goal: zero energy building exemplary experience based on the solar estate Solarsiedlung Freiburg am Schlierberg. J Green Building 4(4):93–100,Germany

Herkel S, Kagerer F (2010) Advances in housing retrofit—processes, concepts and technologies, IEA/SHC Task 37 advanced housing renovation with solar and conservation

IBGE (2009) Vert Bruxelles! Architectures à Suivre…, Bruxelles Environnement

IEA (1991) IEA ECBCS Annex 15: Energy Efficiency in Schools—Final report, IEA—International Energy Agency

IG passivhaus Österreich Passivhaus-Datenbank, Available at: http://www.passivehousedatabase.eu. Accessed 20 June 2011

Immobilien Linz Gmbh (2009a) AS04 Allgemeine Sonderschule 4 Karlhofschule Schule für Alle [School for All]

Immobilien Linz Gmbh (2009b) Sonderschule 6 Schule für Dich und Mich [School for you and me]

Itard L et al (2008) Building renovation and modernisation in Europe: state of the art review, OTB Research Institute for Housing, Urban and Mobility Studies

Kluttig H, Erhorn H, Mørck O (2002) IEA ECBCS Annex 36: Retrofitting in Educational Buildings—REDUCE 25 Case Study Reports from 10 different Countries, IEA—International Energy Agency

Lang G et al (2006) Demonstrationsprojekt—Erste Passivhaus-Schulsanierung—Zwischenbericht [Demonstration Project—First School Renovation as a Passive House—Interim report]

Lang G (2009) Passive house standard for schools the energy turnaround is possible!

Laustsen J (2008) Energy efficiency requirements in building codes, energy efficiency policies for new buildings, IEA

Limb MJ (1997) Ventilation in schools—an annotated bibliography. IEA Annex 5

Marszal AJ et al (2011) Zero energy building—a review of definitions and calculation methodologies. Energy Build 43(4):971–979

Mlecnik E (2011) Defining nearly zero-energy housing in Belgium and the Netherlands. Energy Efficiency. Available at: http://www.springerlink.com/content/x4066655x3876865/. Accessed 4 Jan 2012

Passivhaus Institut (2010) EnerPHit criteria for residential-use refurbished buildings (preliminary version). Available at: http://passiv.de/07_eng/03_cert/Gebaud/EnerPHit_Criteria_Residential_EN.pdf

Pedersen S, Peuhkuri R (2009) A real passive house in Finland. In: 13th international passive house conference. Passivhaus Institut, Frankfurt am Main

PHi (2011) Certified passive house components. Available at: http://passiv.de/03_zer/Komp/Z_Komp_F.htm

PHi The passive house—historical review. Passipedia. Available at: http://passipedia.passiv.de/passipedia_en/basics/the_passive_house_-_historical_review#literature. Accessed 11 Jan 2011

Plöderl H et al (2008) Erste Passivhaus-Schulsanierung [First School Renovation as a Passive House], Available at: http://www.hausderzukunft.at/hdz_pdf/endbericht_0833_passivhaus_schulsanierung.pdf

Sartori I, Wachenfeldt B (2008) Case study on retrofit of a Norwegian school: possible to achieve the passive house standard? In PassivhusNorden 2008

Schnieders E, Hermelink A (2006) CEPHEUS results: measurements and occupants' satisfaction provide evidence for passive houses being an option for sustainable building. Energy Policy 34(2):151–171

Srinivasan RS et al (2012) Re(De)fining net zero energy: renewable energy balance in environmental building design. Build Environ 47:300–315

The European Parliament (2010) Directive 2010/31/eu of the European parliament and of the council of 19 May 2010 on the energy performance of buildings (recast)

Wagner W et al (2009) Energietechnische und baubiologische Begleituntersuchung Passivhaus-Schulsanierung Schwanenstadt, AEE-Institut für Nachhaltige Technologien [Institute for Sustainable Technologies]

Waide P (2006) High-rise refurbishment: the energy efficiency upgrade of multi-story residences in the European Union. IEA. Available at: http://www.iea.org/papers/2006/pw_highrise.pdf

Yin RK (2008) Case study research: design and methods. 4th Revised edn, SAGE Publications Inc

# State of the Art on Retrofit Strategies Selection Using Multi-objective Optimization and Genetic Algorithms

**Ehsan Asadi, M. Gameiro da Silva, C. Henggeler Antunes and Luís Dias**

**Abstract** The retrofit of a building involves not just the fulfillment of functional requirements, but also considerations such as investment costs, energy consumption, environmental impact, and occupant well-being. Careful long-term decisions in the retrofit and operation of buildings can significantly improve their thermal performance and thus reduce their consumption of energy. Moreover, they can improve indoor environmental quality in buildings. Alternative building energy conservation measures, standards compliance, and economic optimization can be evaluated using available energy analysis and decision-aid techniques. These may range from simplified energy analysis methods for approximate energy use estimates to detailed computerized hourly simulation coupled with decision-aid techniques. This chapter reviews the research and development in the decision support processes in building retrofit. Special attention is devoted to the methodologies using multi-objective optimization and genetic algorithms. Accordingly, the decision methodologies are broadly separated into two main categories: approaches in which alternatives are explicitly known a priori and approaches in which alternatives are implicitly defined by an optimization model. The advantages and drawbacks of the various methods in each category are also discussed.

## 1 Introduction

The building sector is the largest user of energy and $CO_2$ emitter in Europe and the USA. Besides, it is responsible for about 40 % of the EU's and the USA's total final energy consumption. Even if all future buildings were to be built so that their energy demand was very low, this would still only mean that the increase in energy

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demand would be reduced and it would not reduce the present demands (Asadi et al. 2012a). For many years to come, only measures taken in existing buildings will have a significant effect on the total energy demand in the building stock. Therefore, rapid enhancement of energy efficiency in existing buildings is essential for a timely reduction in global energy use and promotion of environmental sustainability.

During the last decade, many governments and international organizations have put significant effort toward energy efficiency improvement in existing buildings, as evidenced by the EU Energy Efficiency Action Plan and President Obama's Better Buildings Initiative, among others (White House 2011). In EU, the cornerstone of the European energy policy has an explicit orientation to the conservation and rational use of energy in buildings as the energy performance of building directive (EPBD) 2002/91/EC and its recast (EPBD) 2010/31/EU indicate (EC 2002, 2010). The EPBD's main objective is to promote the cost-effective improvement of the overall energy performance of buildings. One of the best opportunities to do so would be during building retrofit.

Existing building retrofits offer many challenges and opportunities. The main challenge is that many uncertainties are at stake, such as climate change, services change, human behavior change, government policy change, etc., all of which directly affect the selection of retrofit technologies and hence the success of a retrofit project. The subsystems in buildings are highly interdependent. Different retrofit measures may have different impacts on distinct building subsystems due to these interdependencies, which make the selection of retrofit technologies very complex. Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building retrofit project. Other challenges may include financial limitations and barriers, perceived long payback periods, and interruptions to operations of buildings. The willingness of building owners to pay for retrofits is another challenge if there is no financial support from the government, particularly since the issue of "split incentives" is often a key factor because the retrofit cost generally falls to the building owner, whereas the benefit often flows primarily to the tenants. On the other hand, building retrofit offers great opportunities for improved energy efficiency, increased staff productivity, reduced maintenance costs, and better indoor comfort. It may also help to improve a nation's energy security and corporate social responsibility, reduce exposure to energy price volatility, create job opportunities, and make buildings more livable (Ma et al. 2012).

According to Ma et al. (2012), the overall process of a building retrofit can be divided into five major steps (Fig. 1). The first phase is the project setup and pre-retrofit survey. In this phase, the building owners, or their agents, first need to define the scope of the work and set project targets. The available resources to frame the budget and program of work can then be determined. A pre-retrofit survey may also be required in order to better understand building operational problems and the main concerns of occupants.

The second phase comprises an energy audit and performance assessment (and diagnostics). Energy auditing is used to analyze building energy data, understand building energy use, identify areas with energy waste, and propose no-cost and

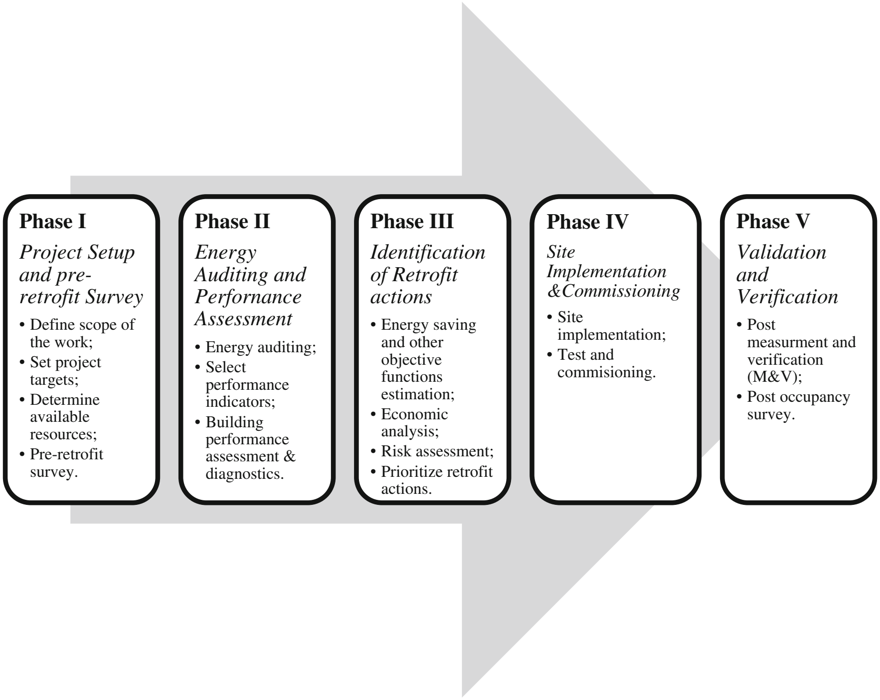

**Fig. 1** Key phases in a sustainable building retrofit program (Ma et al. 2012)

low-cost energy conservation measures (ECMs). Performance assessment is employed to benchmark building energy use by means of selected key performance indicators or green building rating systems. Diagnostics can be used to identify inefficient equipment, improper control schemes, and any malfunctions in the building operation.

The third phase is the identification of retrofit actions. By using appropriate energy models, economic analysis tools, and risk assessment methods, the performance of a range of retrofit alternatives can be assessed quantitatively. The retrofit alternatives can then be prioritized based on the relevant energy-related and non-energy-related objectives such as the increase in retrofitted building market value.

The fourth phase is site implementation and commissioning. The selected retrofit measures will be implemented on-site. Test and commissioning are then employed to tune the retrofit measures to ensure that the building and its services systems operate in an optimal manner. It is worth noting that the implementation of some retrofit measures may necessitate significant interruption to the building and occupants operations.

The final phase is validation and verification of energy savings. Once the retrofit measures are implemented and well tuned, standard measurement and verification methods can be used to verify energy savings. A post-occupancy survey is also needed to understand whether the building occupants and building owners are satisfied with the overall retrofit result.

This chapter aims at providing an overview of recent research and development in the third phase, that is, identification of retrofit actions by paying special attention to the methodologies using multi-objective optimization and genetic algorithms.

## 2 Building Retrofit Methodologies and Strategies

Nowadays, a great number of innovative technologies and energy efficiency measures for building retrofit exist. The main issue is to identify those that will prove to be the more effective and reliable in the long term. When choosing among a variety of proposed measures, the decision maker (DM) has to reconcile environmental, energy-related, financial, legal regulation, and social factors to reach the best possible compromise to satisfy the final occupant needs. In practice, seeking such a solution is mainly attempted via two main approaches (Diakaki et al. 2008).

In the first approach, an energy analysis of the building is carried out and several alternative scenarios predefined by a building expert are developed and evaluated mainly through simulation (Krarti 2000). Although many sophisticated energy simulation programs (e.g., TRNSYS, Energy Plus) are valuable to study the impact of alternative scenarios on building performance, the iterative trial-and-error process of searching for a better retrofit action is time consuming and ineffective due to inherent difficulty in exploring a large decision space.

The second approach, which is the focus of this chapter, includes decision-aid techniques that are usually combined with simulation to assist reaching a final decision among a set of alternative actions. In this chapter, a conceptual distinction is made between multi-criteria and multi-objective models, according to the scientific literature. In a multi-criteria model, the finite set of alternatives (e.g., three different types of windows) is explicitly known a priori, in general predefined by the building expert, to be evaluated according to multiple (quantitative and/or qualitative) criteria that may be expressed in different types of scales. In multi-objective optimization (mathematical programming) models, the set of feasible solutions (e.g., the thickness of the wall) is implicitly defined by the decision variables and the constraints, and the evaluation aspects of the merit of those solutions are operationalized through objective functions to be optimized.

Jaggs and Palmar (2000), Flourentzou and Roulet (2002), and Rey (2004) proposed MC-based approaches for the evaluation of retrofitting scenarios. Kaklauskas et al. (2005) developed a multivariate design method and multi-criteria analysis for building retrofit, determining the significance, priorities, and utility degree of building retrofit alternatives and selecting the most recommended variant. Juan et al. (2009) developed a genetic algorithm-based decision support system for housing condition assessment, which suggests optimal retrofit actions considering the trade-off between cost and quality.

These lines of research have allowed addressing many problems as far as building retrofit is concerned. However, most of them consider that a list of predefined and pre-evaluated alternative variants of the building retrofit options is given. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the opposite, when a large number of solutions are defined, the required evaluation and selection process may become extremely difficult to handle.

The problem faced by the DM may also be framed as a multi-objective optimization model, in which multiple and competing objective functions are formulated to assess feasible alternatives, which are not predefined but are implicitly defined by a set of constraints.

Based on an extensive literature review and Fig. 1, it could be stated that most methodologies for decision support in energy management and sustainability in building sector follow three major steps:

- Definition of main objectives/criteria of the project;
- Definition of alternative retrofit actions, either by stating them explicitly or defining a comprehensive mathematical model; and
- Selection of assessment methodologies adequate to the model.

Accordingly, the remainder of this chapter overviews the main objectives in the course of building retrofit. Different building retrofit technologies are reviewed in Sect. 2.2. Furthermore, retrofit action selection methodologies are discussed in Sect. 2.3. Finally, Sects. 2.4 and 3 in summarize conclusions and discuss issues for future research and development.

## 2.1 Objectives in Building Retrofit

The objectives for building retrofit can be either quantitative or qualitative and can be divided into four main categories depicted in Fig. 2 (Kolokotsa et al. 2009).

More specifically, regarding energy use (primary or final), the following objectives have been utilized (Kolokotsa et al. 2009):

- heating and cooling load for conditioned buildings (D'Cruz and Radford 1987; Bouchlaghem 2000);
- normalized annual energy consumption and energy use for heating in kWh/m$^2$;
- (Rey 2004; Zhu 2006);
- annual electricity use in kWh/m$^2$ (Rey 2004);
- embodied energy (Chen et al. 2006);
- energy and time consumption index (ETI) (Chen et al. 2006); and
- energy savings due to building retrofit in kWh/year (Gholap and Khan 2007; Asadi et al. 2012a).

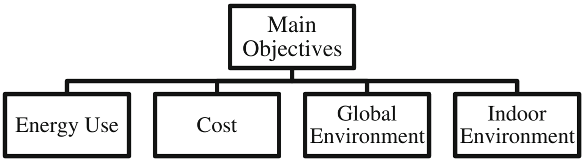

**Fig. 2** The main objectives for building retrofit (Kolokotsa et al. 2009)

Regarding costs, the following objectives have been used:

- direct costs and initial investment costs (Rosenfeld and Shohet 1999);
- cost of retrofit (Asadi et al. 2012a);
- economic life span (Rosenfeld and Shohet 1999);
- annual ongoing maintenance charges (Rosenfeld and Shohet 1999; Rey 2004);
- annual ongoing charges (Rey 2004);
- net present value (NPV) of the energy investment (Martinaitis et al. 2007);
- internal rate of return (IRR) of the energy investment (Martinaitis et al. 2004);
- cost of conserved energy (CCE) (Martinaitis et al. 2004); and
- life cycle cost (LCC) (Wang et al. 2005).

As far as global environment is concerned, the objectives usually set are as follows:

- annual emissions global warming potential (GWP) in kgeq$CO_2/m^2$ (Rey 2004);
- reduction potential of global warming emissions (Alanne 2004);
- life cycle environmental impact (Wang et al. 2005);
- acidification potential in kgeq$SO_2/m^2$ (Rey 2004; Alanne et al. 2007); and
- water use (Alanne et al. 2007).

Indoor environmental quality and comfort have subcategories for the evaluation of thermal sensation, visual comfort, indoor air quality, and acoustic comfort (Kolokotsa et al. 2009). More specifically, regarding thermal comfort, the following objectives and indicators have been used:

- PMV-PPD thermal comfort indices based on ISO-7730 standard (ISO 2005);
- dry resultant temperature for unconditioned buildings (Bouchlaghem 2000);
- indoor temperature and humidity (Jaggs and Palmer 2000);
- discomfort hours during summer or winter (Roulet et al. 2002);
- daily overheating in $K$ (Rey 2004);
- effective draught temperature index (Rutman et al. 2005);
- summer thermal discomfort severity index, which indicates the severity of excessive mean radiant temperature during summer (Becker et al. 2007); and
- total percentage of cumulative time with discomfort (Asadi et al. 2012b).

For visual comfort, the assessment objectives can be as follows:

- daylight availability (Radford and Gero 1980b);
- lighting and visual comfort [e.g., EPIQR method, see (Bluyssen and Cox 2002; Rey 2004)];

- daylight factor (Rey 2004); and
- discomfort glare severity indicator, which indicates the annual severity of excessive discomfort glare (Becker et al. 2007).

Indoor air quality is generally assessed via the following:

- $CO_2$ concentration index (Doukas et al. 2007);
- maximum ratio between the mean concentration of a contaminant over the occupancy period and the contaminant's threshold limit value for short-term or long-term exposure (Blondeau et al. 2002); and
- ventilation rates (Blondeau et al. 2002).

Acoustic comfort objectives include:

- noise level at workplace in dB (Rey 2004) and
- noise rating index (Rutman et al. 2005).

These objectives are, in general, competitive, in the sense that it is impossible to find a global solution to optimize all of them simultaneously. For this reason, several decision-aid approaches have been developed for addressing the mentioned problem, namely based on multi-criteria and multi-objective models. A review of descriptors usually used to assess the indoor environmental quality of confined compartments is presented in Gameiro da Silva 2002. Some other descriptors not included in the previous list, but suitable for the assessment of quality of indoor environment are as follows:

- Operative Temperature ($T_o$) and Equivalent Temperature ($T_{\text{equi}}$), for thermal comfort. The percentage of permanence of indoor thermal conditions inside the comfort band defined in an adaptive comfort chart (ISO 2007), where $T_o$ is depicted versus the outdoor mean running temperature, is a suitable indicator of the performance of buildings without mechanical systems to provide comfortable conditions to occupants.
- Average illuminance level in the working/activity plan (ISO 2002), as regards visual comfort.
- Percentage of dissatisfied with IAQ. It may be calculated from the concentration of $CO_2$ using the expressions presented in CEN 1998.
- Noise equivalent level $L_{\text{Aeq}}$ during the working period, in dB(A).
- Reverberation T of the room along the frequency spectrum of noise.
- Sound transmission index (STI).

## *2.2 Building Retrofit Technologies*

According to Ma et al. (2012), the retrofit technologies can be categorized into three groups: supply-side management, demand-side management, and change of energy consumption patterns, i.e., human factors. Figure 3 illustrates major possible retrofit technology types that can be used in building applications.

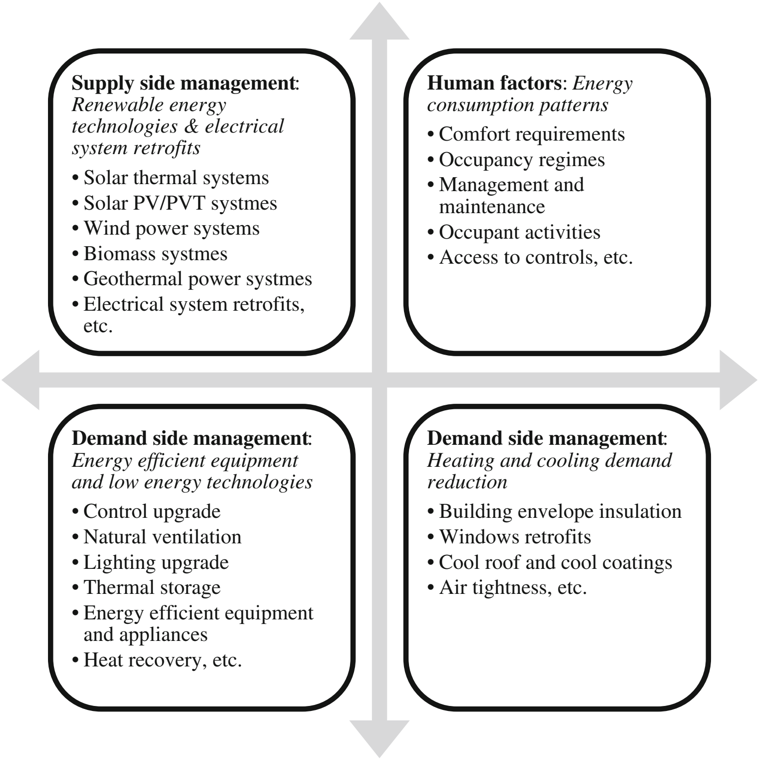

**Fig. 3** Main categories of building retrofit technologies (Ma et al. 2012)

The retrofit technologies for supply-side management include electrical system retrofits and the use of renewable energy, such as solar hot water, solar photovoltaic (PV), wind energy, geothermal energy, etc., as alternative energy supply systems to provide electricity and/or thermal energy for buildings. In the last years, there has been an increasing interest in the use of renewable energy technologies as building retrofit solutions due to the increased awareness of environmental issues.

The retrofit technologies for demand-side management consist of strategies to reduce building heating and cooling demand and the use of energy-efficient equipment and low-energy technologies. The heating and cooling demand of a building can be reduced through retrofitting the building envelope and the use of other advanced technologies such as air tightness, windows shading, etc.

Low-energy technologies may include advanced control schemes, natural ventilation, heat recovery, thermal storage systems, etc. (Ma et al. 2012).

## *2.3 Assessment Methodologies*

In the building retrofit, the assessment phase involves the evaluation of ECM or retrofit actions versus the selected objective functions mentioned in Sect. 2.1 with respect to logical, physical, and technical constraints concerning building retrofit strategies.

Therefore, the assessment procedure is an iterative procedure influenced by the objectives, the alternative actions, and set of constraints. This iterative procedure is illustrated in Fig. 4.

The methodologies for assisting decision making in the appraisal of retrofit actions according to multiple, generally conflicting, and incommensurate evaluation aspects may be distinguished into two main approaches (Fig. 5), according to the distinction made above of models in which alternatives are explicitly known a priori and alternatives are *implicitly* defined in the setting of an optimization model.

These approaches are subcategorized and analyzed in the following sections.

### 2.3.1 MCDA Approaches (Alternatives Explicitly Known a Priori)

In this category, there is a relatively small list of alternatives to choose from. In general, an impact matrix is developed in close cooperation between the problem owners and experts, which expresses in a given scale the performance of each alternative for each evaluation criterion. Several methodological approaches may then be used to combine this information with the DM's preferences in order to reach a final recommendation that establishes a good compromise between the evaluation criteria.

*Multi-criteria Decision Analysis Approaches*

Traditionally, the selection of energy alternatives and retrofit actions was based only on cost optimization. The need to incorporate the environmental and social impacts of different alternatives and viewpoints of different actors in the analysis

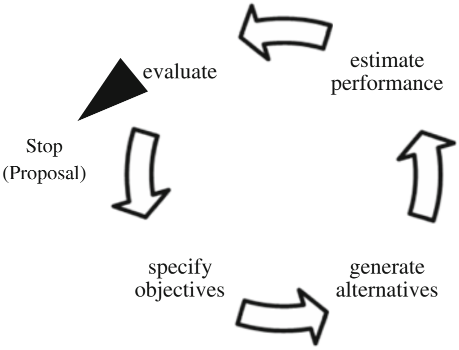

**Fig. 4** The iterative decision support process (Alanne 2004)

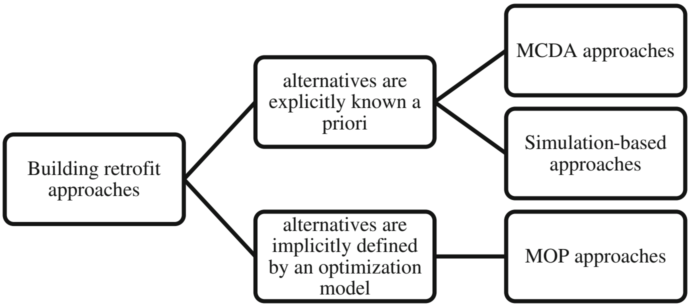

**Fig. 5** Categorization of methodological approaches for building retrofit

promoted the use of multi-criteria decision analysis methods. A wide range of MCDA methods have been applied in the energy-planning area (Diakoulaki et al. 2005). In an MCDA approach, it is necessary to define the problem clearly, identify the actors involved in the decision-making process and their values, develop a coherent set of evaluation criteria, and establish realistic alternatives. An MCDA method is selected to aggregate the performance of each alternative according to the set of criteria using the preferences elicited from the DM through technical parameters. Most MCDA methods require weighting of the criteria, although the meaning of weights may be very different from method to method. The application of MCDA methods may provide a selection of the best alternative, a ranking of the alternatives, or a sorting of the alternatives in predefined ordered categories of merit. Most representative MCDA methods may be included in the broad classifications of methods, developing an overall synthesis value (e.g., multi-attribute value/utility function approaches, AHP) and outranking-based approaches (e.g., ELECTRE, PROMETHEE).

Blondeau et al. (2002) used both combinatorial method based on the multiple attribute utility theory (MAUT) and outranking methods to determine the most suitable ventilation strategy of a university building, that is, to ensure the best possible indoor air quality and thermal comfort of the occupants, and the lower energy consumption in case of accelerated diurnal or nocturnal ventilation and/or air-conditioning. It was shown that the results of the analysis by combinatorial method strongly depend on the definition of the total utility function, and the pernicious effects may affect its validity. On the other hand, outranking method most probably allows to best fit the DM's way of thinking, but their result is not always as clear as the one obtained with combinatorial method.

Roulet et al. (2002) used principal component analysis, as well as multi-criteria ranking method, based on ELECTRE III and VI algorithms to develop a method for ranking office buildings (ORME—office rating methodology) according to an extended list of parameters, including energy use for heating, cooling, and other appliances, impact on external environment, indoor environment quality, and cost.

Outranking methods are also used by Rey. The ELECTRE III method is used to rank office building retrofitting strategies.

Energy Performance Indoor Environmental Quality Retrofit Methods for Apartment Building Refurbishment (EPIQR) (Jaggs and Palmer 2000) and Tool for Selecting Office Building Upgrading Solutions (TOBUS) (Caccavelli and Gugerli 2002) are other tools using MCDA techniques for building retrofit actions selection. The TOBUS method aims at offering a tool for selecting office building's retrofit solutions with respect to multiple criteria. One of the key elements to reach this goal was an assessment of the degree of physical degradation, extent of any degradation, extent of the necessary work to retrofit the building, and the costs.

Kaklauskas et al. (2005) used multivariate design and MCDA to prioritize and rank the alternative solutions for the refurbishment of a building envelope. The alternatives' significance, utility degree, and priority are extracted using this methodology and, as a consequence, the strongest and weakest points of the refurbishment are revealed.

Alanne (2004) combines MCDA and a knapsack (multi-objective) model to support building retrofit. MCDA is used to extract the utilities of the retrofit actions proposed, as well as the total utility versus the selected criteria. The utility scores obtained are then used as weights in a knapsack optimization model to identify the actions that should be undertaken, through the maximization of the objective function (that is, utility score achieved by selecting the retrofit action, specified by environmental value and functionality) subject to budget constraints.

### *Simulation-based Approaches*

Simulation-based approaches are either simplified (analytical methods) or detailed (numerical methods) using powerful simulation programs.

In the simulation-based process, a basic model of the building is developed using simulation tools. Then, through an iterative procedure, a series of recommendations are defined using the best construction practice (Horsley et al. 2003). These recommendations may include increase in insulation, change of glazing, etc.

There are a number of detailed building energy simulation packages, such as EnergyPlus, eQuest, DOE-2, ESP-r, BLAST, HVAC-SIM+, TRNSYS, etc. A detailed comparison of the capabilities of 20 building energy simulation packages can be found in Ref (Crawley et al. 2008).

For example, TRNSYS is used by Santamouris et al. (2007) to investigate the energy-saving potential of green roofs in a nursery school in Greece. EnergyPlus is used by Becker et al. (2007) to assess specific factors of building design elements (window orientation, glazing type, thermal resistance of walls, etc.) and 20 ventilation strategies for schools' energy consumption and efficiency. Zmeureanu et al. (1999) employed DOE-2 to estimate the energy savings due to building retrofits.

Although many sophisticated energy simulation programs are valuable to study the impacts of different ECM on building performance, the iterative trial-and-error process of searching for a better solution is time consuming and ineffective because of the inherent difficulty in exploring a large design space.

The main problem when employing MCDA techniques is that they are applied upon a set of predefined alternative courses of action. In case that a limited number of such alternatives have been defined, there is no guarantee that the solution finally reached is the optimal one. Also, the selection of a representative set of alternatives is usually a difficult problem, while the final solution is heavily affected by these predefined alternatives. On the opposite case, i.e., when numerous alternatives are defined, the required evaluation and selection process may become extremely difficult to handle. In any case, however, the MCDA approach limits the study to a potentially large but certainly finite number of alternatives, when the real opportunities are enormous considering all the available ECM that may be employed (Diakaki et al. 2008).

### 2.3.2 MOP Approaches (Alternatives Implicitly in a Mathematical Model)

Decision support for improving energy efficiency in buildings problems is also tackled using multi-objective optimization models stated as mathematical programming models with multiple competing objective functions to be optimized, being the set of feasible solutions implicitly defined by a set of constraints.

*Multi-objective Programming* (*MOP*) *Approaches*

The modeling of real-world problems generally requires the consideration of distinct axes of evaluation of the merits of potential solutions. In engineering problems, aspects of operational, economical, environmental, and quality of service nature are at stake. Therefore, mathematical models must explicitly address these multiple, incommensurate, and often conflicting aspects of evaluation as objective functions to be optimized. Besides, MOP models enlarge the variety of potential solutions to be considered and enable to grasp the trade-offs between the objective functions helping to reach a satisfactory compromise solution. The essential concept in multi-objective optimization is the one of non-dominated (efficient, Pareto optimal) solutions, that is, feasible solutions for which no improvement in all objective functions is possible simultaneously; in order to improve an objective function, it is necessary to accept worsening at least another objective function value. In real-world problems, a high number of non-dominated solutions are likely to exist. Figure 6 illustrates this concept for a problem with two objective functions to be minimized. Although it is the essential concept in MOP, the concept of non-dominated solution is a poor one, in the sense that it lacks discriminative power for decision recommendation purposes. Non-dominated solutions are not comparable between them, so no solution naturally arises as the “final” one. The fact that multi-objective optimization enables the characterization of the non-dominated front and the trade-offs at stake between the objective functions is one of its advantages. However, it is then necessary to reach a final compromise solution for practical implementation of a reduced set of non-dominated solutions for further screening.

Pareto optimization was introduced in this area in the 1980s by Radford and Gero (1980a, b), Gero et al. (1983), D’cruz and Radford (1987), and it is now widely used in building design and less in retrofit optimization. It was used, for example, by Asadi et al. (2012a, b) to optimize the retrofit cost and energy savings

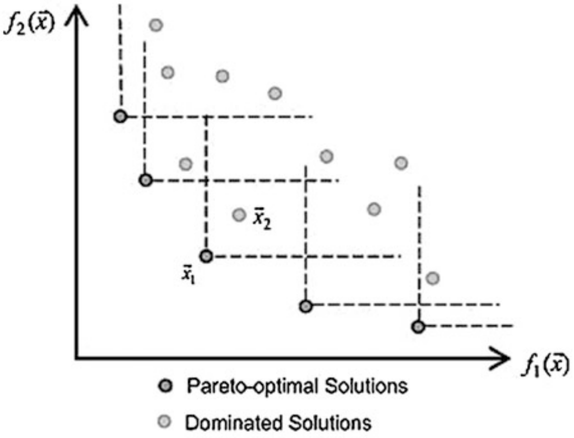

**Fig. 6** Example of a Pareto set

of a residential building. Diakaki et al. (2008) developed a MOP model to find alternative measures for improving energy efficiency in buildings. Hamdy et al. (2011) proposed a MOP approach based on genetic algorithm (GA) to tackle the problem of designing low-emission cost-effective dwellings. The proposed approach is used to minimize the carbon dioxide emissions and the investment cost for a two-story house and its HVAC system. Magnier et al. (2010) used a simulation-based artificial neural network (ANN) to characterize building behavior, and then combined ANN with multi-objective GA for optimization of thermal comfort and energy consumption in a residential house.

### *Multi-objective Programming (MOP) Approaches using GA*

The use of GA to deal with MOP models has gained an increasing relevance due to their ability to work with a population of individuals (solutions) that expectedly converges to the true non-dominated front (Deb 2001). GA are particularly suitable for tackling hard combinatorial and/or non-linear models, as they are less susceptible to the shape or continuity of the non-dominated front than the classical (mathematical programming) optimization methods. The rationale is that GA deals with a population of solutions, and the aim is generally the characterization of a non-dominated front. In this setting, GA-incorporating techniques to preserve the diversity of solutions (for a comprehensive depiction of that front, thus unveiling the trade-offs in different regions of the search space) possess advantages compared with the use of "scalarizing" functions, in which a surrogate scalar function aggregating the multiple objectives is optimized, as in traditional mathematical programming approaches. However, it must be noticed that, in real-world problems, this is, in general, "just" a potential non-dominated front (also known as Pareto front), classified as such because no other solutions dominating it could be found but no theoretical tools exist, which guarantees their true Pareto optimality.

GAs have been extensively used as search and optimization tools in several real-world problems, such as building energy efficiency problems, due to their flexibility and good performance in exploring the search space. Regarding building

**Fig. 7** Basic genetic algorithm pseudo-code

```
Begin
   INITIALIZE population with random candidate solutions;
   EVALUATE each candidate;
        REPEAT
                1 SELECT parents;
                2 RECOMBINE parents;
                3 MUTATE the resulting offspring;
                4 EVALUATE new candidates;
                5 SELECT individuals for the next generation
        UNTIL (TERMINATION CONDITION is satisfied)
END
```

applications, GA are frequently used for the optimization of building thermal system design (Wright et al. 2002), HVAC controls (Huang and Lam 1997; Lu et al. 2005), and chiller energy costs (Chow et al. 2002).

The pseudo-algorithm of GA is displayed in Fig. 7 and can be described with the following steps:

- First, a random population is created, where each individual represents a solution using some encoding scheme (for instance, binary).
- At each generation, couples of individuals (parents) produce new individuals by gene crossover and mutation (offspring).
- At the end of each generation, the candidate solutions to be included in the next generation are evaluated using a fitness evaluation function.
- The last two steps operate until the termination condition is met (generally based on the number of generations or on the stagnancy of population fitness).

As a gradient-free method, GA is able to deal with nonlinear functions and to find global optima without being trapped in local ones. Furthermore, it can handle real, discrete, or even discontinuous variables and can be applied to noisy objective functions (Wright et al. 2002; Huang and Lam 1997).

A main drawback of GA is the high burden whenever it is necessary to make a high number of calls to an evaluation function involving a high computational cost. In building applications, these evaluations are generally estimated by an external simulation program such as CFD or other simulation packages. If accurate results are required, each evaluation can be time consuming, and thus the complete computational process becomes extremely unattractive (Magnier 2008). For instance, for the two-objective optimization of building floor shape, Wang et al. (2006) used an evaluation tool where each evaluation took 24 s (CPU time). In that case, the total optimization time, which is mainly due to evaluations, was 68 h. Using simulation software where each evaluation would take several minutes, a similar optimization would result in a total optimization time of several months. This shortcoming should be dealt with before being able to take full advantage of GA in building energy efficiency problems.

Genetic algorithm integrating neural network (GAINN) is one of the solutions to the above-mentioned problem. The main idea of GAINN is to benefit from the

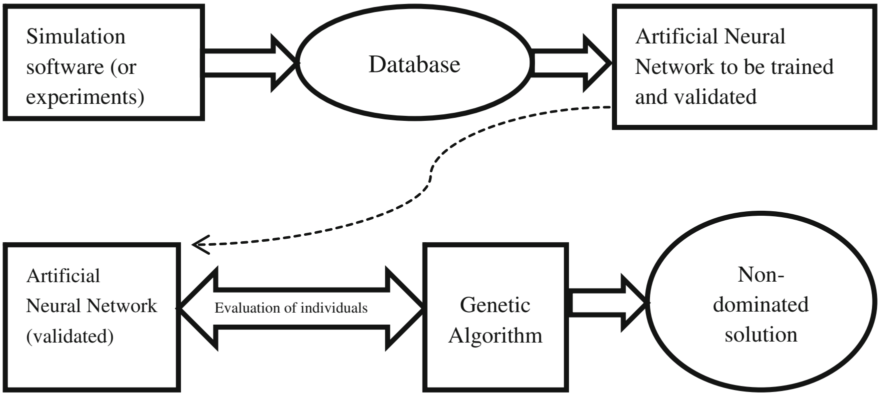

**Fig. 8** GAINN framework (Magnier and Haghighat 2010)

rapidity of evaluation provided by ANN as well as the optimization power of the GA. The procedure is to first use an ANN to approximate the system being studied, and then use this ANN within the GA as the objective function. The outcome is a drastic reduction in the simulation time, while keeping an acceptable quality and reliability in the solution process. The complete workflow of GAINN is illustrated in Fig. 8 and is divided into three steps. First, a base software or experimental setup is used to generate a database of cases. Once the database is created, it can be used to train and validate the ANN. The ANN is then integrated into the GA as the objective function, so the GA can run with almost instantaneous evaluation of individuals. The GA optimization finally provides the non-dominated solution set (Magnier and Haghighat 2010).

GAINN was first used in building engineering for the optimization of chillers control (Chow et al. 2002). This study introduced the methodology to the building field and proved its efficiency in terms of accuracy and reduction in the total optimization time. Later, GAINN has been successfully applied in other studies, such as Zhou (2007), combined with computational fluids dynamics, and Conraud (2008), combined with ESP-r.

Recently, this approach was used by Magnier et al. (2010) using a simulation-based ANN to characterize building behavior, and then the ANN model was combined with a multi-objective GA to optimize thermal comfort and energy consumption in a residential building.

According to the previous studies, the GAINN methodology can be very efficient for building application. Due to the ANN evaluation inside the GA, a significant amount of time can be saved, while keeping the optimization reliable. One main limitation of GAINN is that the optimization results rely on the ANN accuracy. If the ANN is not 100 % accurate, results could be affected and optimal solutions could be missed.

Another major drawback regarding how GAINN methodology has been applied so far is the handling of multiple objectives. In the great majority of previous studies, multiple objectives were handled by using an aggregate weighted-sum scalar function. This method suffers from many limitations, such as being dependent on stated assumptions and on the initial situation. It also provides no guarantee to reach the best compromise solution according to the underlying preferences associated with the specification of weights.

## 2.4 Discussion

In this chapter, an overview of recent research and development related to evaluation of different retrofit technologies for building applications is provided.

The major findings from previous studies are as follows:

- A large number of innovative technologies and energy efficiency measures for building retrofit exist. The main issue is to identify those that will prove to be the more effective and reliable in the long term.
- The building retrofit assessment procedure is an iterative procedure influenced by the objectives, the alternative actions, and the sets of constraints.
- The methodologies involving multiple evaluation aspects of potential solutions for decision support in the assessment of retrofit action may be distinguished into two main approaches: approaches in which alternatives are explicitly known a priori (MCDA) and approaches in which alternatives are implicitly defined within an optimization model (MOP).
- Appropriate problem structuring methods, selection of evaluation criteria, definition of representative alternative courses of action, and preference elicitation techniques are essential in MCDA approaches to select the most effective retrofit strategies.
- MCDA approaches consider that a list of predefined intervention solutions is given for which the performance in multiple (quantitative or qualitative) criteria is known at the outset. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the other hand, when a large number of solutions are defined, the required evaluation and selection processes may become extremely difficult to handle.
- Recently, more attention has been paid to the use of MOP techniques for the problem of improving energy efficiency in buildings. These approaches based on comprehensive mathematical models aim at providing a thorough characterization of the trade-offs between different objectives.
- The use of GA to deal with MOP models for building retrofit decision support has gained an increasing relevance due to its ability to deal with complex mathematical models and avoid being trapped in local non-dominated solutions.
- A major drawback of the application of GA in building efficiency improvement is the high number of calls to evaluation function associated with physical parameters that are generally estimated by an external simulation program such

as CFD or other simulation software. If accurate results are required, each evaluation can be time consuming, and thus the complete computational process becomes extremely unattractive.
- GAINN is one of the techniques to deal with this problem by approximating the system under study by an ANN whose results are then used within the GA.

## 3 Conclusion

In face of a large set of choices for retrofitting a building, the main issue is to identify those that prove to be the most effective in the long term. When choosing among a variety of proposed measures, the DM (the building expert) has to reconcile environmental, energy, financial, legal regulation, and social factors to reach the best possible compromise solution to satisfy the final occupant needs. Therefore, MCDA and MOP models are essential tools to assist the DM in rationalizing the comparison between non-dominated solutions and assess the trade-offs at stake between those distinct evaluations aspects.

Thus, there is a need for further development of decision-aid systems based on MCDA and MOP to support building experts in the application of their expertise and assist less-experienced decision makers (DM), while taking into account the continuous development of technological advances in energy-efficient solutions.

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## References

Alanne K (2004) Selection of renovation actions using multi-criteria “knapsack” model. Autom Constr 13:377–391

Alanne K, Salo A, Saari A, Gustafsson S (2007) Multi-criteria evaluation of residential energy supply systems. Energy Build 39:1218–1226

Asadi E, da Silva MG, Antunes CH, Dias L (2012a) Multi-objective optimization for building retrofit strategies: a model and an application. Energy Build 44:81–87

Asadi E, da Silva MG, Antunes CH, Dias L (2012b) A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. Build Environ 56:370–378

Becker R, Goldberger I, Paciuk M (2007) Improving energy performance of school buildings while ensuring indoor air quality ventilation. Build Environ 42:3261–3276

Blondeau P, Sperandio M, Allard F (2002) Multicriteria analysis of ventilation in summer period. Build Environ 37:165–176

Bluyssen PM, Cox C (2002) Indoor environment quality and upgrading of European office buildings. Energy Build 34:155–162

Bouchlaghem N (2000) Optimising the design of building envelopes for thermal performance. Autom Constr 10:101–112

Caccavelli D, Gugerli H (2002) TOBUS—a European diagnosis and decision-making tool for office building upgrading. Energy Build 34:113–119

CEN (1998) Ventilation for buildings—design criteria for the indoor environment

Chen Z, Clements-Croome D, Hong J, Li H, Xu Q (2006) A multi-criteria lifespan energy efficiency approach to intelligent building assessment. Energy Build 38:393–409

Chow TT, Zhang GQ, Lin Z, Song CL (2002) Global optimization of absorption chiller system by genetic algorithm and neural network. Energy Build 34:103–109

Conraud J (2008) A methodology for the optimization of building energy, thermal, and visual performance. Master, Concordia University

Crawley DB, Hand JW, Kummert M, Griffith BT (2008) Contrasting the capabilities of building energy performance simulation programs. Build Environ 43:661–673

D'cruz NA, Radford AD (1987) A multi-criteria model for building performance and design. Build Environ 22:167–179

Da Silva MCG (2002) Measurements of comfort in vehicles. Meas Sci Technol 13:41–60

Deb K (2001) Multi-objective optimization using evolutionary algorithms. Wiley, New York

Diakaki C, Grigoroudis E, Kolokotsa D (2008) Towards a multi-objective optimization approach for improving energy efficiency in buildings. Energy Build 40:1747–1754

Diakoulaki D, Antunes CH, Martins AG (2005) MCDA and energy planning. In: Figueira J, Erghott SGM (eds) State of the art of multiple criteria decision analysis. Springer

Doukas H, Patlitzianas KD, Iatropoulos K, Psarras J (2007) Intelligent building energy management system using rulesets. Build Environ 42:3562–3569

EC (2002) Directive 2002/91/EC of the European parliament and of the council of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities, Brussels, Belgium

EC (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Communities

Flourentzou F, Roulet CA (2002) Elaboration of retrofit scenarios. Energy Build 34:185–192

Gero JS, Dcruz N, Radford AD (1983) Energy in context—a multicriteria model for building design. Build Environ 18:99–107

Gholap AK, Khan JA (2007) Design and multi-objective optimization of heat exchangers for refrigerators. Appl Energy 84:1226–1239

Hamdy M, Hasan A, Siren K (2011) Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings. Build Environ 46:109–123

Horsley A, France C, Quatermass B (2003) Delivering energy efficient buildings: a design procedure to demonstrate environmental and economic benefits. Constr Manage Econ 21:345–356

Huang W, Lam HN (1997) Using genetic algorithms to optimize controller parameters for HVAC systems. Energy Build 26:277–282

ISO (2002) Lighting of indoor work places. Standard ISO 8995:2002. Geneva

ISO (2005) Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. ISO, Geneva

ISO (2007) Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and noise. ISO standard 15251-2007. Geneva

Jaggs M, Palmer J (2000) Energy performance indoor environmental quality retrofit—a European diagnosis and decision making method for building refurbishment. Energy Build 31:97–101

Juan Y-K, Kim JH, Roper K, Castro-Lacouture D (2009) GA-based decision support system for housing condition assessment and refurbishment strategies. Autom Constr 18:394–401

Kaklauskas A, Zavadskas E, Raslanas S (2005) Multivariant design and multiple criteria analysis of building refurbishments. Energy Build 37:361–372

Kolokotsa D, Diakaki C, Grigoroudis E, Stavrakakis G, Kalaitzakis K (2009) Decision support methodologies on the energy efficiency and energy management in buildings. Adv Build Energy Res 3:121–146

Krarti M (2000) Energy audit of building systems. CRC Press

Lu L, Cai WJ, Xie LH, Li SJ, Soh YC (2005) HVAC system optimization in building section. Energy Build 37:11–22

Ma Z, Cooper P, Daly D, Ledo L (2012) Existing building retrofits: methodology and state-of-the-art. Energy Build 55:889–902

Magnier L (2008) Multiobjective optimization of building design using artificial neural network and multiobjective evolutionary algorithms. Master of Applied Science Master of Science thesis, Concordia University

Magnier L, Haghighat F (2010) Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and artificial neural network. Build Environ 45:739–746

Martinaitis V, Rogoza A, Bikmaniene I (2004) Criterion to evaluate the "twofold benefit" of the renovation of buildings and their elements. Energy Build 36:2–8

Martinaitis V, Kazakevicius E, Vitkauskas A (2007) A two-factor method for appraising building renovation and energy efficiency improvement projects. Energy Policy 35:192–201

Radford AD, Gero JS (1980a) On optimization in computer-aided architectural design. Build Environ 15:73–80

Radford AD, Gero JS (1980b) Tradeoff diagrams for the integrated design of the physical-environment in buildings. Build Environ 15:3–15

Rey E (2004) Office building retrofitting strategies: multicriteria approach of an architectural and technical issue. Energy Build 36:367–372

Rosenfeld Y, Shohet IM (1999) Decision support model for semi-automated selection of renovation alternatives. Autom Constr 8:503–510

Roulet CA, Flourentzou F, Labben HH, Santamouris M, Koronaki I, Dascalaki E, Richalet V (2002) ORME: a multi-criteria rating methodology for buildings. Build Environ 37:579–586

Rutman E, Inard C, Bailly A, Allard F (2005) A global approach of indoor environment in an air-conditioned office room. Build Environ 40:29–37

Santamouris M, Pavlou C, Doukas P, Mihalakakou G, Synnefa A, Hatzibiros A, Patargias P (2007) Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens. Energy 32:1781–1788

Wang W, Zmeureanu R, Rivard H (2005) Applying multi-objective genetic algorithms in green building design optimization. Build Environ 40:1512–1525

Wang WM, Rivard H, Zmeureanu R (2006) Floor shape optimization for green building design. Adv Eng Inform 20:363–378

Whitehouse (2011) President Obama's plan to win the future by making American businesses more energy efficient through the "better buildings initiative". White House

Wright JA, Loosemore HA, Farmani R (2002) Optimization of building thermal design and control by multi-criterion genetic algorithm. Energy Build 34:959–972

Zhou L (2007) Optimization of ventilation system design and operation in office environment. Ph.D., Concordia University

Zhu Y (2006) Applying computer-based simulation energy auditing: a case study. Energy Build 38:421–428

Zmeureanu R, Fazio P, Depani R, Calla R (1999) Development of an energy rating system for existing houses. Energy Build 29:107–119

# Multiple-Criteria Analysis of Life Cycle of Energy-Efficient Built Environment

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**Abstract** For a broader application of the life cycle of energy-efficient built environment in the practice of various countries, more attention needs to be paid not only on the selected most rational processes and solutions, the interest level of the stakeholders, but also on the micro-, meso- and macro-level factors. The authors of this article developed the life cycle of energy-efficient built environment model and different decision support systems over the course of two international projects (IDES-EDU and LEAN CC). Based on this model, professionals involved in design and realization of life cycle of energy-efficient built environment can develop a lot of the alternatives as well as assessing them and making the final choice of the most efficient variant. The model and two systems (Energy Efficient House DSS for cooling and decision support system for assessment of energy generation technologies) are briefly described in this chapter.

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# 1 Introduction

Built environment can be defined in several ways:

- all the structures people have built when considered as separate from the natural environment (the British English definition),
- artificial or man-made surroundings built to serve for a particular purpose, e.g., human activities ranging from the large-scale civic surroundings to the personal places (Biology-Online.org),
- all the structures people have built when considered as separate from the natural environment (the American English definition),
- the term built environment refers to the human-made surroundings that provide the setting for human activity, ranging in scale from buildings and parks or green space to neighbourhoods and cities that can often include their supporting infrastructure, such as water supply, or energy networks. The built environment is a material, spatial and cultural product of human labour that combines physical elements and energy in forms for living, working and playing. It has been defined as "the human-made space in which people live, work and recreate on a day-to-day basis" (Linked in),
- the "built environment encompasses places and spaces created or modified by people including buildings, parks and transportation systems". In recent years, public health research has expanded the definition of "built environment" to include healthy food access, community gardens, "walkabilty" and "bikeability" (http://www.ieltsinternational.com/).

A built environment is developed in order to satisfy residents' requirements. Human needs can be physiological or social and are related to security, respect and self-expression. People want their built environment to be aesthetically attractive and to be in an accessible place with a well-developed infrastructure, convenient communication access and good roads, and the dwelling should also be comparatively cheap, comfortable, with low maintenance costs and have sound and thermal insulation of walls. People are also interested in ecologically clean and almost noiseless environments, with sufficient options for relaxation, shopping, fast access to work or other destinations and good relationships with neighbours.

It must be admitted that the most serious problems of built environments, e.g., unemployment, vandalism, lack of education, robberies, are not always related to the direct physical structure of housing. Increasing investment into the development of social and recreational centres, such as athletic clubs, physical fitness centres, and family entertainment centres, the infrastructure, a good neighbourhood and better education of young people, can solve such problems. Investment, purchase and sale of a property and its registration have related legal issues. The legal system of a country aims to reflect its existing social, economic, political and technical state and the requirements of the market economy.

The built environment is not constructed in an empty space. During the built environment life cycle—brief, designing, construction, maintenance, facility management, renovation, demolition and utilization—built environment is affected by various micro-, meso- and macro-level factors.

It is estimated that about 20 % of the US population suffers from asthma, emphysema, bronchitis, diabetes or cardiovascular diseases and are thus especially susceptible to external air pollution (American Lung Association 2005). Outdoor air quality plays an important role in maintaining good human health. Air pollution causes large increases in medical expenses and morbidity and is estimated to cause about 800,000 annual premature deaths globally (Cohen et al. 2005). Much research, digital maps and standards on the health effects (respiratory and cardiovascular effects, cancer, infection, etc.) of outdoor air pollution, a premise's microclimate and property valuation, have been published in the last decade. These and other problems are related to a built environment's air pollution, a premise's microclimate, health effects and real estate market value.

The imperative to reduce atmospheric carbon is well documented and one significant area of production is from the built form which is responsible for up to 40 % of global energy consumption and 30 % of the world's carbon emissions. Over the full life cycle of buildings, which includes construction and demolition, 80–90 % of this energy is used during the operational phase to heat, cool, ventilate, light and run appliances. The balance of 10–20 % represents the embodied energy and is consumed during the building process of construction and production of the raw materials themselves. The need for the transport of goods and services, delivery of water and waste services to and from buildings adds further to account of emissions that the built form is responsible for and the total can be described as the carbon footprint (Goodfield et al. 2011).

Next, we present a few examples of components that comprise energy-efficient built environment (energy carrier networks, pedestrian pavements in cities, trees and the open green spaces).

Employing different energy carrier networks in connection with distributed renewable energy generation is an attractive way to improve energy sustainability in urban areas. An effective option to increase local renewable energy production is to convert surplus electricity into, e.g., thermal energy (Niemi et al. 2012).

Mendoza et al. (2012) examine the relevance of incorporating comprehensive life cycle environmental data into the design and management of pedestrian pavements to minimize the impact on the built environment. The overall primary energy demand and global-warming potential of concrete, asphalt and granite sidewalks are assessed. A design with a long functional lifetime reduces its overall primary energy demand and global-warming potential due to lower maintenance and repair requirements. However, long-lived construction solutions do not ensure a lower life cycle primary energy demand and global-warming potential than for shorter-lived designs; these values depend on the environmental suitability of the materials chosen for paving. Asphalt sidewalks reduce long-term global-warming potential under exposure conditions where the functional lifetime of the pavements is less than 15 years. In places where it is known that a concrete sidewalk can have a life of at least 40 years, a concrete sidewalk is the best for minimizing both long-term primary energy demand and global-warming potential. Granite sidewalks are

**Fig. 1** Life cycle of energy-efficient built environment quantitative and qualitative analyses aspects

the largest energy consumers and greenhouse gas (GHG) contributors (Mendoza et al. 2012).

The trees and the open green spaces have multiple uses and their presence in the outdoors makes a major contribution to the saving of energy inside the buildings as well as to the improvement of the microclimate in the urban spaces adjacent to buildings and in urban subareas. The amount of energy needed for heating and cooling is decreased considerably by the suitable placement of trees around buildings, so that there is much shading from the sun during the summer and as little as possible during the winter (Georgi and Dimitriou 2010). Life cycle of energy-efficient built environment quantitative and qualitative analyses aspects and application areas are presented in Figs. 1 and 2.

The problem is how to define a life cycle of energy-efficient built environment when a lot of various parties are involved, the alternatives come to hundreds thousand and the efficiency changes with the alterations in the environment

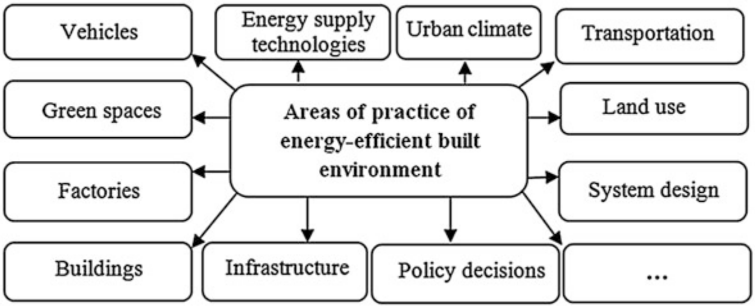


**Fig. 2** Areas of practice of energy-efficient built environment

conditions and the constituent parts of the process in question. Moreover, the realization of some objectives seems more rational from the economic perspective thought from the other perspectives they have various significance. Therefore, it is considered that the rationality of life cycle of energy-efficient built environment depends on the rationality of its composite parts as well as on the ability to satisfy the needs of the interested parties and the rational character of environment conditions. Our research object is life cycle of energy-efficient built environment, interested parties striving to attain their goals and micro-, meso- and macro-environment making an integral whole.

The structure of this chapter is as follows: Sect. 2, which follows this introduction, describes the multiple-criteria decision-making. Section 3 analyses the model for a complex analysis of life cycle of energy-efficient built environment. Sections 4 and 5 contain case studies. Certain concluding remarks appear in Sect 6.

## 2 Multiple-Criteria Decision-Making

A thorough energy-efficient built environment multiple-criteria analysis is quite difficult to undertake, because a building and its environment are complex systems (technical, technological, environment, ecological, social, economical, comfort, esthetical, etc.), where all subsystems influence the total efficiency performance and where the interdependence between subsystems play a significant role. Many multiple-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) methods have been developed in the world for solving the above-mentioned and other problems as follows: AHP method (Kablan 2004; Nigim et al. 2004; Jaber et al. 2008; Alanne et al. 2007), COPRAS (Kaklauskas et al. 2005, 2006), Data envelopment analysis, Decision EXpert, Disaggregation approach (Diakoulaki et al. 1999), Displaced Ideal (Mirasgedis and Diakoulaki 1997), Dominance-based rough set approach, ELECTRE (Georgopoulou et al. 1997; Beccali et al. 1998, 2003; Thiel and Mroz 2001), Evidential reasoning approach, Fuzzy sets (Beccali et al. 1998; Cavallaro and Ciraolo 2005; Gamboa and Munda 2007; Jaber et al. 2008; Alanne et al. 2007), Genetic algorithm (Juan et al. 2009; Wright et al. 2002), Goal programming, Grey relational analysis, Information deficiency method (Afgan and Carvalho 2002), Inner product of vectors, MACBETH, Multi-attribute-utility analysis (Renn 2003), PAPRIKA, PROMETHEE (Goumas et al. 1999; Haralambopoulos and Polatidis 2003; Cavallaro 2005), SIR method, TOPSIS, Value analysis, Value engineering, Value tree method (Renn 2003), VIKOR, Weighted product model, Weighted sum model, PAIRS (Salo and Hämäläinen 1992).

The aforesaid methods were used to solve various problems of energy-efficient built environment:

- ELECTRE (Georgopoulou et al. 1997; Beccali et al. 1998, 2003; Thiel and Mroz 2001): regional energy planning, evaluation of renewable energy options, renewable energy diffusion strategies, renewable energy technologies, selecting a heating system for a historical building.

- Disaggregation Approach (UTADIS: Diakoulaki et al. 1999): energy analysis and policy making.
- Value tree method (Renn 2003): evaluation of energy scenarios, waste energy utilization.
- Multi-attribute utility analysis (Renn 2003): selection of energy scenarios, waste energy utilization.
- PROMETHEE (Georgopoulou et al. 1998; Goumas et al. 1999; Haralambopoulos and Polatidis 2003; Cavallaro 2005): promotion, planning and assessment of renewable energy sources; geothermal and renewable energy projects; "scenarios" for geothermal resources; renewable energy plants.
- fuzzy sets (Zadeh 1965) (Beccali et al. 1998; Cavallaro and Ciraolo 2005; Gamboa and Munda 2007; Jaber et al. 2008; Alanne et al. 2007): technologies of energy conversion and heating distribution, renewable energy diffusion strategies, wind energy plants, locating wind turbines.
- PAIRS (Salo and Hämäläinen 1992): residential heating systems and the handling of uncertainties related to the actual preferences of decision-makers for type heating systems.
- Displaced Ideal (Mirasgedis and Diakoulaki 1997): electricity generation systems.
- Information deficiency method (Afgan and Carvalho 2002): new and renewable energy technologies (power plants).
- AHP (Saaty 2001) method (Kablan 2004, Nigim et al. 2004; Jaber et al. 2008; Alanne et al. 2007): evaluation of conventional and renewable energy sources for household heating, prioritization of policy instruments, prefeasibility ranking of alternative renewable energy sources.

MCDM is the most well-known branch of decision-making. It is a branch of a general class of operations research (OR) models which deal with decision problems under the presence of a number of decision criteria. According to many authors MCDM is divided into multi-objective decision-making (MODM) and multi-attribute decision-making (MADM) (Triantaphyllou et al. 1998). Different authors have different names for the concept of MODM such as multiple-criteria design, multiple objective mathematical programming or multi-objective optimization. MODM methods (Diakaki et al. 2010; Asadi et al. 2012a; Diakaki et al. 2008; Wright et al. 2002) and MADM methods (Gero et al. 1983; Jaggs and Palmar 2000; Flourentzou and Roulet 2002; Rey 2004; Kaklauskas et al. 2006; Kaklauskas and Zavadskas 2007; Sliogeriene et al. 2009; Alanne et al. 2007; Diakaki et al. 2010) are widely used in analyses of energy-efficient built environment.

MODM studies decision problems in which the decision space is continuous. A typical example is mathematical programming problems with multiple objective functions. The first reference to this problem is also known as the "*vector-maximum*" problem (Triantaphyllou et al. 1998). The alternatives in this class of problems are not explicitly known, they are either infinite and not countable or typically very large if countable. MODM methods sometimes using interactive computer methods to involve the analyst explicitly in the process also directly seek to specify what the definition of the best option should be. The question is essentially one of identifying an optimal design for the option, guided by MODM methods. Almost always, the optimization is subject to specific constraints, for example on cost or technical specification (Multi-criteria analysis 2009).

The problem faced by the decision-maker is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives, the decision space consisting in a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and constraints that should be taken into account. Therefore, it is not necessary to enumerate the set of actions to be considered (Diakaki et al. 2010).

A number of MODM methods has been used to analyse different areas of energy-efficient built environment such as design of building envelopes (Diakaki et al. 2008), selection of heating systems (Wright et al. 2002), optimal thickness of insulation (Malckzewski 1999), retrofit actions aimed at minimizing energy use in a cost-effective manner (Asadi et al. 2012b), and improving energy efficiency in buildings (Diakaki et al. 2010).

MADM methods often have alternative names, too (e.g. multiple-criteria evaluation).

There are many ways one can classify MADM methods. One way is to classify them according to the type of the data they use. That is, we have deterministic, stochastic or fuzzy MADM methods (for an overview of fuzzy MADM methods (Chen and Hwang 1992). However, there may be situations which involve combinations of all the above (such as stochastic and fuzzy data) data types. Another way of classifying MADM methods is according to the number of decision-makers involved in the decision process. Hence, we have decision-maker MADM methods and group decision-making MADM (Triantaphyllou et al. 1998).

MADM concentrates on problems with discrete decision spaces. In these problems, the set of decision alternatives has been predetermined (Triantaphyllou et al. 1998). In MADM problems with a finite number of options, each of which is assessed in terms of a given number of criteria. For each option, with respect to each criterion, this performance information needs to be collected. Most decisions concern choices between a finite number of options, the details of which have already been predetermined before they are subject to MADM. It is concerned simply to assess the strengths and weaknesses of options as they stand and find the best alternative (a set of good alternatives) for a decision-maker (Multi-criteria analysis 2009). In a number of countries, scientists used MADM methods to solve miscellaneous problems of energy-efficient built environment:

- local energy systems involving several energy resources (Løken 2007);
- selection process (Malckzewski 1999);
- selecting a heating system for a historical building (Thiel and Mroz 2001);
- design of building envelope and refurbishment problems; selecting contractors for public buildings (Kaklauskas et al. 2005, 2006);
- evaluation of conventional and renewable energy sources for household heating (Jaber et al. 2008; Alanne et al. 2007);

- energy conversion and heating distribution technologies (Nagesha and Balachandra 2006);
- residential heating systems and the handling of uncertainties related to the actual preferences of decision-makers for type heating systems (Salo and Hämäläinen 1992);
- building design (Gero et al. 1983);
- evaluation of retrofitting scenarios (Jaggs and Palmar 2000; Flourentzou and Roulet 2002; Rey 2004);
- multi-variate design and multiple-criteria analysis for building retrofitting (Kaklauskas et al. 2005, 2006);
- selection of the most feasible retrofit actions in the conceptual phase of a retrofit project (Alanne 2004);
- housing condition assessment to suggest optimal retrofit actions considering the trade-off between cost and quality (Juan et al. 2009).

A few brief examples follow, as a quick illustration of the aforementioned MCDM methods applied in some areas of energy-efficient built environment.

Diakaki et al. (2010) investigated the feasibility of applying multi-objective optimization techniques to the problem of improving energy efficiency in buildings, considering a simplified model for building thermal simulation.

Due to growing limitations on land use and awareness of sustainability concerns, the building retrofit market has faced increasing opportunities worldwide. Several technological/constructive options are available to improve energy efficiency and indoor environmental quality in buildings. The identification of the most appropriate retrofitting options is a topic of outstanding importance given the potential costs and impacts involved (Asadi et al. 2012b). Asadi et al. (2012b) present a multi-objective optimization model and method to assist stakeholders in the definition of intervention measures aimed at minimizing the energy use in the building in a cost-effective manner, while satisfying the occupant needs and requirements. An existing house needing refurbishment is taken as a case study to demonstrate the feasibility of the proposed multi-objective model in a real-world situation. The results corroborate the practicability of this approach and highlight potential problems that may arise (Asadi et al. 2012b).

Coherent and efficient retrofit scenarios are commonly built on the basis of the knowledge of the degradation state of the building and its obsolescence. The architect or building engineer prepares a list of refurbishment works required on the basis of the building audit, his experience and the available budget (Flourentzou and Roulet 2002). Flourentzou and Roulet (2002) describe a systematic method, based on multiple-criteria analysis and a constructivist approach, which helps an expert in designing retrofit scenarios. This approach includes several steps and follows an iterative process. The associated computer tool takes charge of tedious tasks such as calculating the associated costs, performing an energy balance and checking for coherence between actions and presents various viewpoints to the expert. It also helps the user in quickly creating various scenarios. The expert can then interact with this information and makes the decision for selecting the final scenario. This interactive approach brings together expert intuition and rational systematic verification (Flourentzou and Roulet 2002).

As one can see, the above-mentioned research has enabled the authors to solve a majority of problems in a complex way as far as energy-efficient built environment's MCDM is concerned. However, one of the weakest aspects of the above research was the formation and multiple-criteria analysis of alternative variants of the whole energy-efficient built environment. The authors of this chapter have developed methods of multi-variant design and multiple-criteria analysis of energy-efficient built environment to tackle these problems.

## 3 Model for a Complex Analysis of Life Cycle of Energy-Efficient Built Environment

In order to develop a high-quality built environment, it is necessary to take care of its efficiency from the brief to the end of service life. The entire process must be planned and executed with consideration of goals aspired by participating stakeholders and micro-, meso- and macro-level environment. In order to realize the above purposes, an original model of a complex analysis of life cycle of energy-efficient built environment (see Fig. 3) was developed enabling to analyse life cycle of energy-efficient built environment, the parties involved as well as its micro- and macro-environment as one complete entity.

A model was being developed step by step as follows (see Fig. 3): a comprehensive quantitative and conceptual description of a research object; multi-variant design of life cycle of energy-efficient built environment; multiple-criteria analysis of life cycle of energy-efficient built environment; selection of the most rational version of life cycle of energy-efficient built environment; and development of rational micro-, meso- and macro-level environment. The above model will be now described in more detail.

For more comprehensive study of a research object and methods and ways of its assessment, major constituent parts of the above object will be briefly analysed. They are as follows: life cycle of energy-efficient built environment, the parties involved and micro- and macro-environment having a particular impact on it.

Life cycle of energy-efficient built environment in turn consists of seven closely interrelated stages, such as brief, design, construction, maintenance, facilities management, demolition and utilization.

At the stage of brief, the stakeholders state major requirements and limitations regarding the energy-efficient built environment in question.

Energy-efficient built environment is being designed with account of the stakeholders' needs as well as the possibilities of designers, constructors, suppliers, facilities managers, etc. At the design stage, life cycle of energy-efficient built environment multi-variant design and multiple-criteria analysis should be carried out taking into account the experience gained in realizing similar projects and

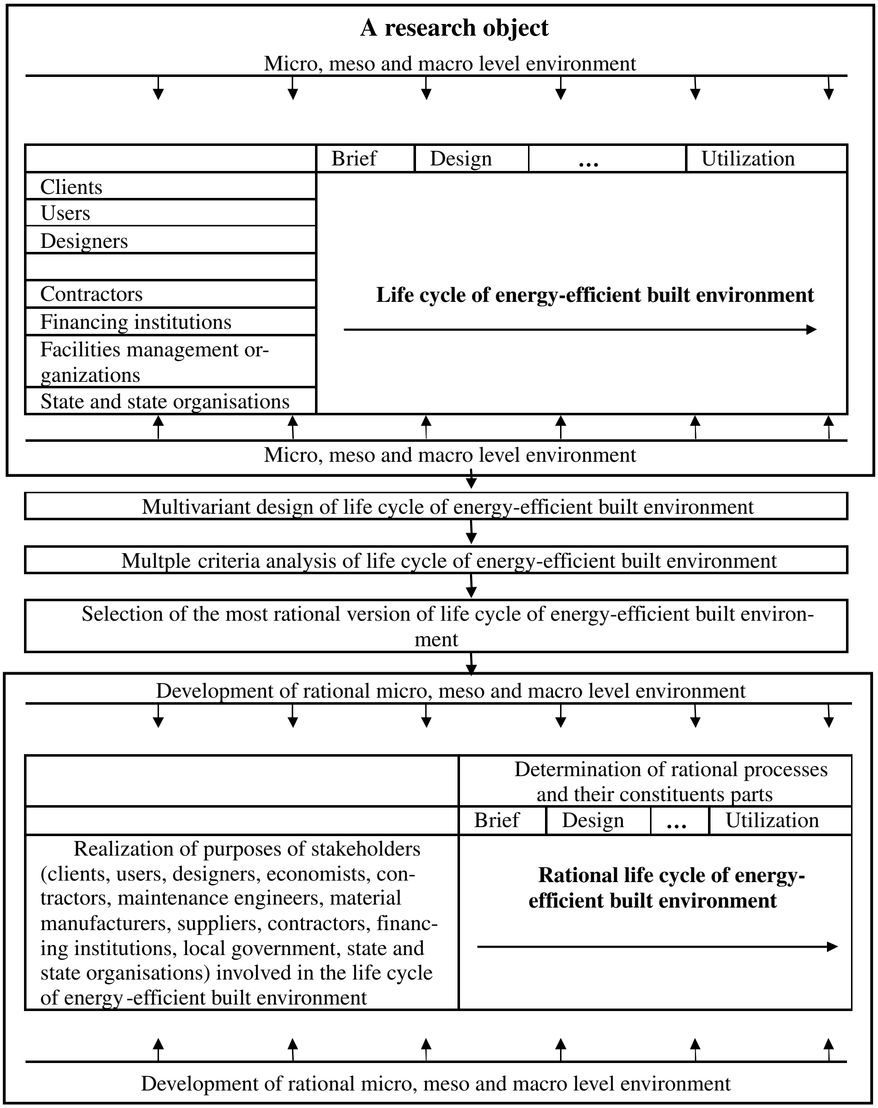


**Fig. 3** A model of a complex analysis of life cycle of energy-efficient built environment

seeking to harmonize the activities of various stakeholders. At a design stage, the strategy and means of its realization related to maintenance, facilities management, demolition and utilization should be defined.

These should ensure that maintenance, facilities management, demolition and utilization problems are continually dealt with, starting from the brief stage.

Since the rationality of various aspects of project often depends on a particular interested party, only complex design of a life cycle process of energy-efficient built environment involving close collaboration of major stakeholders can lead to good results. Various parties are involved in the brief, design, construction, maintenance, facilities management, demolition and utilization of energy-efficient built environment, their cooperation taking rather long period of time.

Passive systems are the last technical components in each energy chain. Examples of passive systems include a car (excluding the engine) which delivers transport, or a house (without the boiler or lighting device) which provides thermal comfort and illumination (Cullen and Allwood 2010). Cullen and Allwood (2010) describe passive energy systems within three broad categories (vehicles, factories and building):

*Vehicle*: car (light-duty vehicle: car, mini-van, SUV, pick-up), truck (heavy-duty vehicle: urban delivery, long-haul, bus), plane (aircraft: jet engine, propeller), ship (ocean, lake and river craft: ship, barge, ferry), train (rail vehicle: diesel, diesel–electric, electric, steam)
*Factory*: driven system (system refrigerator, air compressor, conveyor and pump), steam system (medium temperature application: petrochemical cracker, reaction vessel and cleaning facility),
*Furnace* (high temperature application: blast furnace, arc furnace, smelter, oven)
*Building*: hot water system (fuel and electric immersion boilers), heated/cooled space (residential/commercial indoor space), appliance (refrigerator, cooker, washer, dryer, dishwasher, electronic devices), illuminated space (residential/commercial indoor space, outdoor space).

Demand-side energy-conservation measures include improving the energy-out/energy-in efficiency of end uses (e.g. with more efficient vehicles, more efficient lighting, better insulation in homes, and the use of heat-exchange and filtration systems), directing demand to low-energy-use modes (e.g. using public transit or telecommuting instead of driving), large-scale planning to reduce energy demand without compromising economic activity or comfort (e.g. designing cities to facilitate greater use of non-motorized transport and to have better matching of origins and destinations, thereby reducing the need for travel), and designing buildings to use solar energy directly (e.g. with more daylighting, solar hot water heating, and improved passive solar heating in winter and cooling in summer) (Jacobson and Delucchi 2011).

Keirstead et al. (2012) first presented a definition of urban energy systems, as the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area. This set the context and scope for a review of 219 papers, covering five distinct areas of practice (Keirstead et al. 2012):

- *Technology design*: The studies focused on energy supply technologies including the design and performance of urban wind turbines; solar energy systems including PV, hot water and cooling; other heating or cooling technologies, including fuel cells; vehicle performance under urban load cycles; waste-to-energy systems.

- *Building design:* Broadly speaking, the studies might be classified as dealing with building design and renovation, energy demand estimation in the built environment, urban climate as it directly affects buildings, urban planning and policy, and transport. They represent a range of spatial scales, from single buildings to groups of buildings in a street or district or the whole city, and the behaviour of individuals.
- *Urban climate:* The studies operated at two main spatial scales. The first group looked at the effect of urban climate and heat island effects on buildings and the second looked at a larger district scale, including street cross sections or raster grid of several hundred metres.
- *System design:* These studies are characterized primarily by their use of optimization techniques. The typical problem definition in these studies is, for an exogenously specified pattern of energy service demands, to determine the combinations of capital equipment and operating patterns to meet some objective subject to constraints (e.g. what is the lowest cost system that satisfies heat and power demands subject to a carbon emissions reduction target?).
- *Policy assessment:* This cluster representing studies of the whole city and how its energy performance might be shaped by policy decisions.
- *Transportation and land use:* Within this field of transportation and land-use research, integrated land-use-transport models are most relevant. These are large complex, generally econometric, model systems which seek to capture the major dynamics of urban processes such as land-use change and transportation use.

Almost one-third of energy is attributed to the production of materials and goods in industry (Cullen and Allwood 2010). Allwood et al. (2010) analysed options for reducing energy use in material production (improving material efficiency through substituting less energy-intensive materials, light-weighting products, designing for reuse and recycling, etc.).

Nakicenovic et al. (1993) introduce the term "service efficiency", defined as "the provision of a given task with less useful energy (the output from conversion devices) without loss of 'service' quality". The effect is to separate out efficiency measures, for example using a more fuel-efficient car, from conservation measures, such as improving the flow of traffic (Nakicenovic et al. 1993).

Hence, life cycle efficiency of energy-efficient built environment depends to a very great extent not only on the selected most rational processes and solutions, the interest level of the concerned parties involved in the project, expressed as the effectiveness of their participation in the process, but also on the micro-, meso- and macro-level factors. As can be seen from Fig. 3, the object of investigation is rather complicated involving not only life cycle of energy-efficient built environment and its stages but also including stakeholders and micro- and macro-environment factors having impact on the former. To select a rational alternative, a new model of a complex analysis of life cycle of energy-efficient built environment was developed. Based on this model, professionals involved in design and realization of life cycle of energy-efficient built environment can develop a lot of the alternative versions as well as assessing them and making the final choice

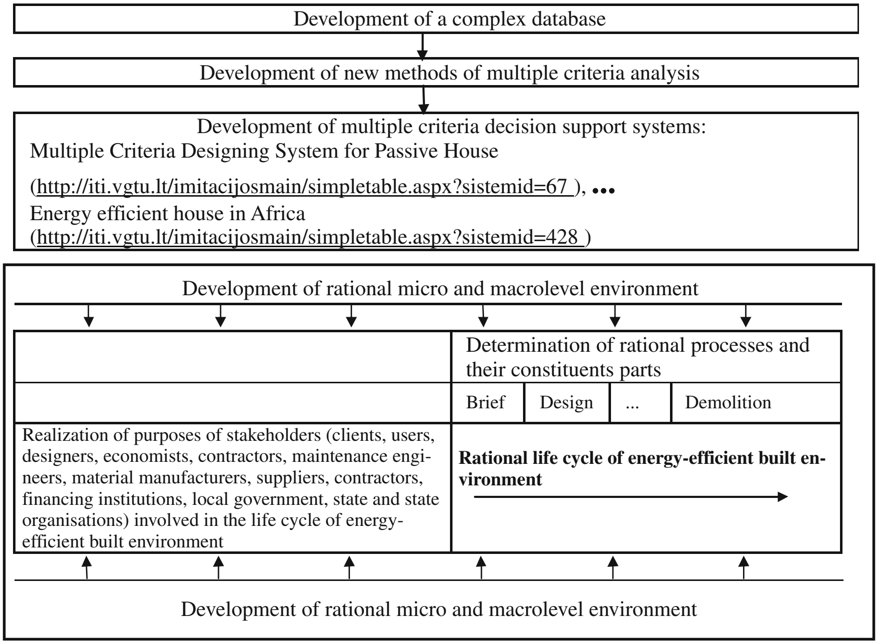


**Fig. 4** Practical realization of a model of a complex analysis of life cycle of energy-efficient built environment

of the most efficient variant. A practical realization of a model is presented in Fig. 4.

## 4 Case Study 1: Choice of Energy Generation Technologies Using DSS

Access to modern energy services will require a combination of electricity and modern fuels and technologies. At the global level, the energy system—supply, transformation, delivery and use—is the dominant contributor to climate change, representing around 60 % of total current GHG emissions. Current patterns of energy production and consumption are unsustainable and threaten the environment on both local and global scales. Emissions from the combustion of fossil fuels are major contributors to the unpredictable effects of climate change, and to urban air pollution and acidification of land and water. Reducing the carbon intensity of energy is a key objective in reaching long-term climate goals.

The huge potential for conserving energy resources, and also protecting the environment, can be tapped through efficient energy consumption in households and public buildings. The International Energy Agency reckons that up to 29 % of global energy consumption in households goes to heating, 17 % to cooling, 14 %

to hot water preparation, 12 % to lighting and 15 % to other needs. In Lithuania, however, the share of heating amounts to as many as 47 % of all energy consumed. Hence, when we consider such consumer group as households, any measure that helps conserve energy resources and choose the most efficient solutions is important. Households may conserve energy in two ways, which are innovative products and technological solutions, and changed behaviours. The prices of natural resources are growing, people are realizing the scale of environmental issues, and renewable energy generation technologies are advancing; these are the reasons why ever more households adopt advanced energy supply systems based on renewable resources.

To formulate a real-life multiple-criteria analysis problem, energy generation technologies employing different primary and traditional energy sources—wind plus electricity, geothermal plus electricity, solar plus electricity, biomass plus electricity, solar, wind plus electricity, and solar biomass plus electricity—have been selected. These types of energy generation technologies are the most suitable in the sector of private housing. Such combinations of technologies are suitable in the climate zones where the most important types of energy in buildings are heating and hot water preparation (the Baltic states, for instance).

When a set of criteria must describe certain alternatives, quantifiable criteria are not enough. A need is growing to consider how the alternatives comply with environmental goals, the principles of sustainable development and public expectations. Adding qualitative criteria makes it possible to develop a more flexible system that makes an integrated analysis of changing environment (Sliogeriene et al. 2012).

The set of criteria in the EGT-PH-DSS comprises five quantitative criteria expressed by quantitative measuring units ("Investments in energy supply sources", "Heating cost", "Payback time", "Share of renewable resources in the system", and "Durability of system") and seven qualitative criteria assessed in points ("Compliance with the natural conditions", "Treatment of used batteries, fuel waste", "Risk of accidents", "Innovativeness", "Acceptability of the environmental aspect", "Acceptability of the social dimension", and "User-friendliness, comfortable fit of system"). These criteria define four main aspects of environment and secure system's effectiveness. Figure 5 gives a possible set of criteria for the assessment of energy technologies.

The weights of importance of the criteria groups (technological, economic, social and environment protection) were determined during the study, based on Lithuanian case. According to the evaluation results, the economical and social criteria of the energy sector are assigned with the maximum weight of importance. The results are provided in Fig. 6.

The decision support system includes a database and a database management system, a model base and a model base management system, and a user interface. The model base includes a multiple-criteria analysis model, a model of utility degree and priority, and a recommender model. The model base management system lets the user choose any required model. The system is designed in such way that the results of calculations in one model are used as the input data in other

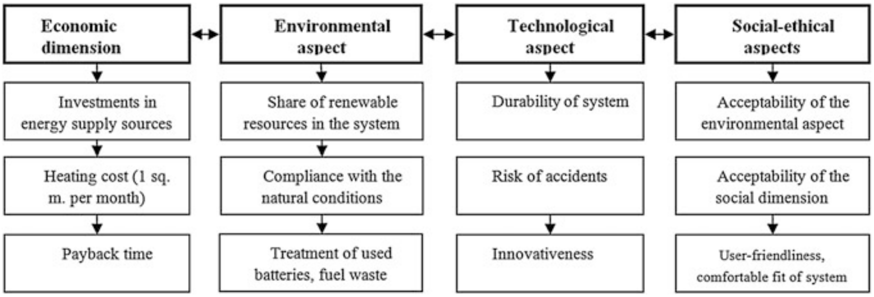
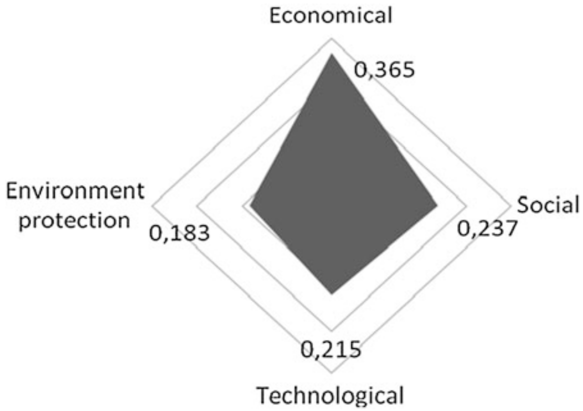


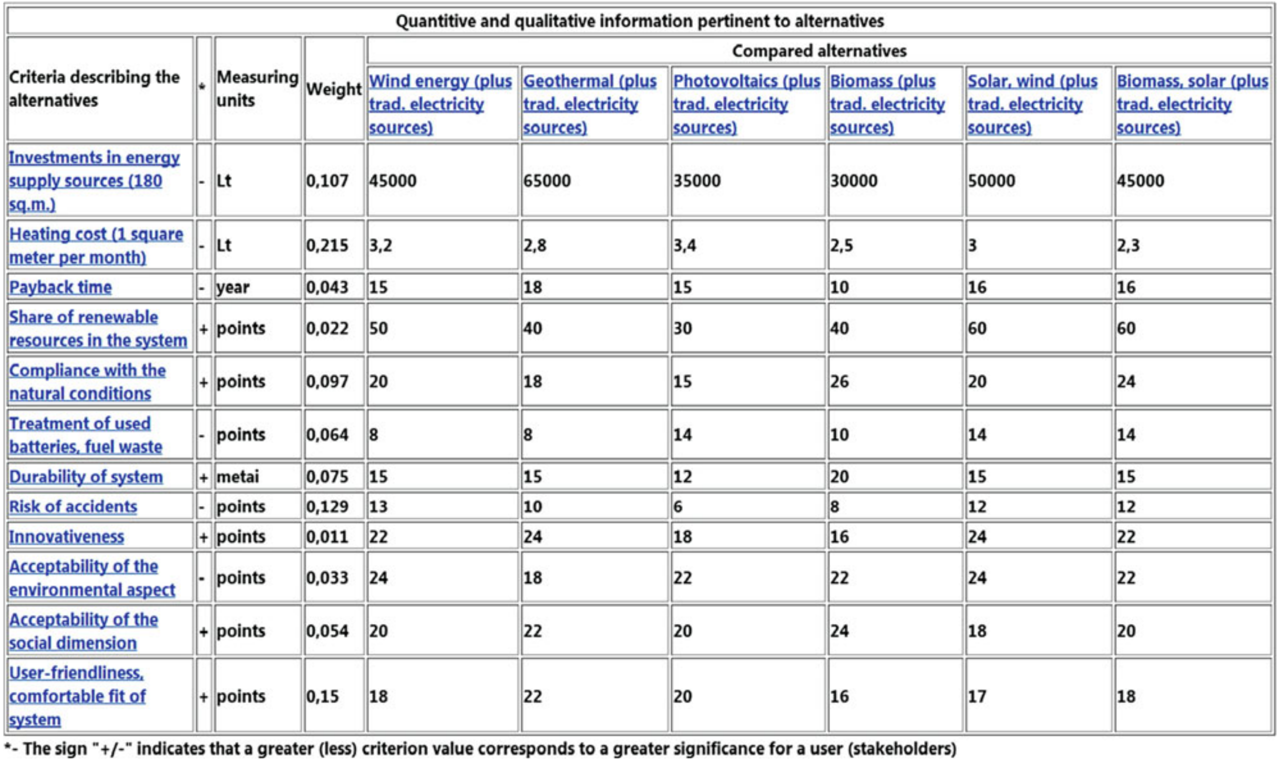
**Fig. 5** The set of criteria in the *EGT-PH-DSS*

**Fig. 6** Weight of criteria groups



models, which, in turn, return results which become the input data for yet other models. The decision support system *EGT-PH-DSS* enables processing of large amounts of data and monitoring of changes of all criteria in question. The system may be supplemented with new objects and data about them. A significant advantage is that the system displays the intermediate results, which reflect the impact of each criterion on the utility and value. The decision support system *EGTAV-DSS* is available online at the address http://iti.vgtu.lt/imitacijosmain. The opening screen is shown in Fig. 7.

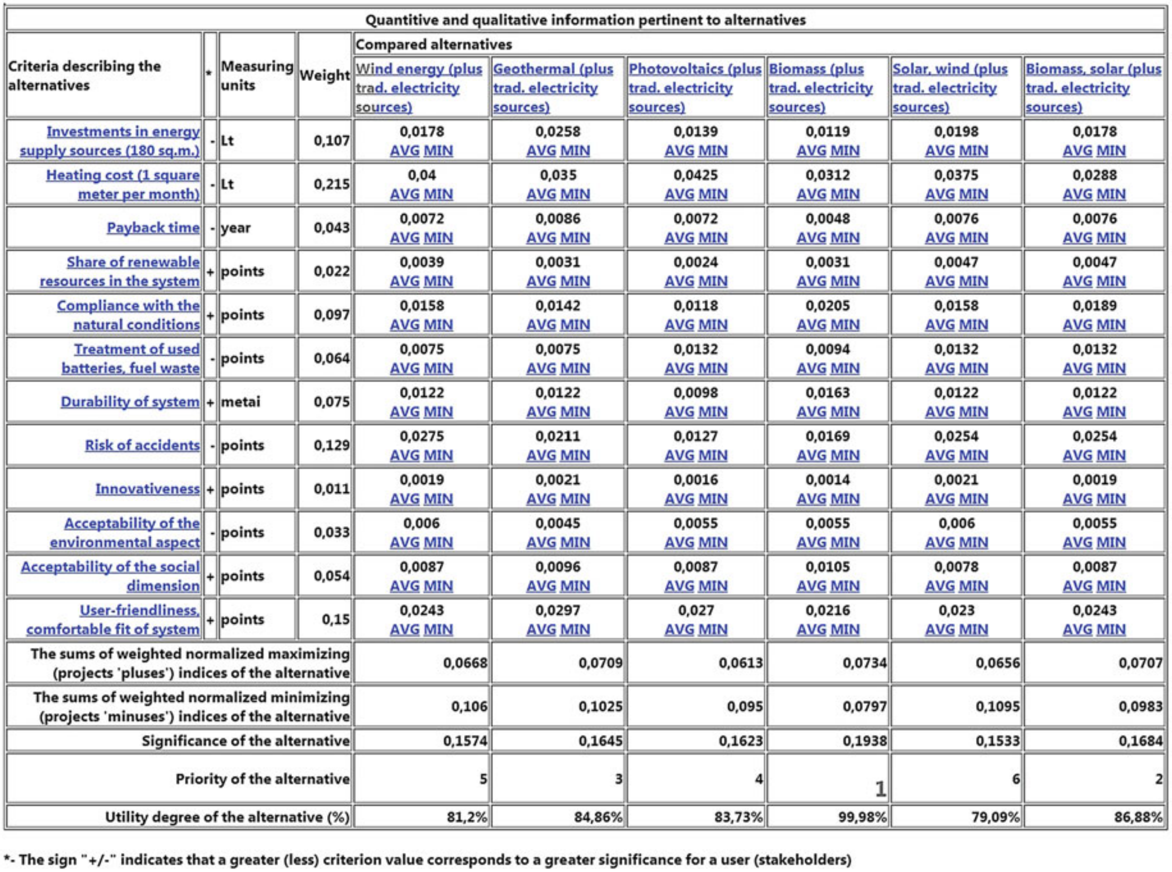
Use of the *EGT-PH-DSS* is simple, but the system performs a thorough analysis and presents a lot of useful information. The system's advantage is the analysis of the weights of all criteria used in research. The weights of criteria are analysed in the module's window "Results of multiple-criteria evaluation of the alternatives". A click on the value of any selected criterion in a matrix cell on the links AVG, MN displays the value of each selected criterion in percentage compared to the same criterion of other objects (see Fig. 8). The result also shows the increase in the percentage that would raise the value of the object in question. The same screen of the model can display the effect of environmental factors determined



| Quantitive and qualitative information pertinent to alternatives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Compared alternatives | | | | | |
| Criteria describing the alternatives | * | Measuring units | Weight | Wind energy (plus trad. electricity sources) | Geothermal (plus trad. electricity sources) | Photovoltaics (plus trad. electricity sources) | Biomass (plus trad. electricity sources) | Solar, wind (plus trad. electricity sources) | Biomass, solar (plus trad. electricity sources) |
| Investments in energy supply sources (180 sq.m.) | - | Lt | 0,107 | 45000 | 65000 | 35000 | 30000 | 50000 | 45000 |
| Heating cost (1 square meter per month) | - | Lt | 0,215 | 3,2 | 2,8 | 3,4 | 2,5 | 3 | 2,3 |
| Payback time | - | year | 0,043 | 15 | 18 | 15 | 10 | 16 | 16 |
| Share of renewable resources in the system | + | points | 0,022 | 50 | 40 | 30 | 40 | 60 | 60 |
| Compliance with the natural conditions | + | points | 0,097 | 20 | 18 | 15 | 26 | 20 | 24 |
| Treatment of used batteries, fuel waste | - | points | 0,064 | 8 | 8 | 14 | 10 | 14 | 14 |
| Durability of system | + | metai | 0,075 | 15 | 15 | 12 | 20 | 15 | 15 |
| Risk of accidents | - | points | 0,129 | 13 | 10 | 6 | 8 | 12 | 12 |
| Innovativeness | + | points | 0,011 | 22 | 24 | 18 | 16 | 24 | 22 |
| Acceptability of the environmental aspect | - | points | 0,033 | 24 | 18 | 22 | 22 | 24 | 22 |
| Acceptability of the social dimension | + | points | 0,054 | 20 | 22 | 20 | 24 | 18 | 20 |
| User-friendliness, comfortable fit of system | + | points | 0,15 | 18 | 22 | 20 | 16 | 17 | 18 |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

**Fig. 7** Qualitative and quantitative description of the alternatives



| Quantitive and qualitative information pertinent to alternatives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Compared alternatives | | | | | |
| Criteria describing the alternatives | * | Measuring units | Weight | Wind energy (plus trad. electricity sources) | Geothermal (plus trad. electricity sources) | Photovoltaics (plus trad. electricity sources) | Biomass (plus trad. electricity sources) | Solar, wind (plus trad. electricity sources) | Biomass, solar (plus trad. electricity sources) |
| Investments in energy supply sources (180 sq.m.) | - | Lt | 0,107 | 0,0178<br>AVG MIN | 0,0258<br>AVG MIN | 0,0139<br>AVG MIN | 0,0119<br>AVG MIN | 0,0198<br>AVG MIN | 0,0178<br>AVG MIN |
| Heating cost (1 square meter per month) | - | Lt | 0,215 | 0,04<br>AVG MIN | 0,035<br>AVG MIN | 0,0425<br>AVG MIN | 0,0312<br>AVG MIN | 0,0375<br>AVG MIN | 0,0288<br>AVG MIN |
| Payback time | - | year | 0,043 | 0,0072<br>AVG MIN | 0,0086<br>AVG MIN | 0,0072<br>AVG MIN | 0,0048<br>AVG MIN | 0,0076<br>AVG MIN | 0,0076<br>AVG MIN |
| Share of renewable resources in the system | + | points | 0,022 | 0,0039<br>AVG MIN | 0,0031<br>AVG MIN | 0,0024<br>AVG MIN | 0,0031<br>AVG MIN | 0,0047<br>AVG MIN | 0,0047<br>AVG MIN |
| Compliance with the natural conditions | + | points | 0,097 | 0,0158<br>AVG MIN | 0,0142<br>AVG MIN | 0,0118<br>AVG MIN | 0,0205<br>AVG MIN | 0,0158<br>AVG MIN | 0,0189<br>AVG MIN |
| Treatment of used batteries, fuel waste | - | points | 0,064 | 0,0075<br>AVG MIN | 0,0075<br>AVG MIN | 0,0132<br>AVG MIN | 0,0094<br>AVG MIN | 0,0132<br>AVG MIN | 0,0132<br>AVG MIN |
| Durability of system | + | metai | 0,075 | 0,0122<br>AVG MIN | 0,0122<br>AVG MIN | 0,0098<br>AVG MIN | 0,0163<br>AVG MIN | 0,0122<br>AVG MIN | 0,0122<br>AVG MIN |
| Risk of accidents | - | points | 0,129 | 0,0275<br>AVG MIN | 0,0211<br>AVG MIN | 0,0127<br>AVG MIN | 0,0169<br>AVG MIN | 0,0254<br>AVG MIN | 0,0254<br>AVG MIN |
| Innovativeness | + | points | 0,011 | 0,0019<br>AVG MIN | 0,0021<br>AVG MIN | 0,0016<br>AVG MIN | 0,0014<br>AVG MIN | 0,0021<br>AVG MIN | 0,0019<br>AVG MIN |
| Acceptability of the environmental aspect | - | points | 0,033 | 0,006<br>AVG MIN | 0,0045<br>AVG MIN | 0,0055<br>AVG MIN | 0,0055<br>AVG MIN | 0,006<br>AVG MIN | 0,0055<br>AVG MIN |
| Acceptability of the social dimension | + | points | 0,054 | 0,0087<br>AVG MIN | 0,0096<br>AVG MIN | 0,0087<br>AVG MIN | 0,0105<br>AVG MIN | 0,0078<br>AVG MIN | 0,0087<br>AVG MIN |
| User-friendliness, comfortable fit of system | + | points | 0,15 | 0,0243<br>AVG MIN | 0,0297<br>AVG MIN | 0,027<br>AVG MIN | 0,0216<br>AVG MIN | 0,023<br>AVG MIN | 0,0243<br>AVG MIN |
| The sums of weighted normalized maximizing (projects 'pluses') indices of the alternative | | | | 0,0668 | 0,0709 | 0,0613 | 0,0734 | 0,0656 | 0,0707 |
| The sums of weighted normalized minimizing (projects 'minuses') indices of the alternative | | | | 0,106 | 0,1025 | 0,095 | 0,0797 | 0,1095 | 0,0983 |
| Significance of the alternative | | | | 0,1574 | 0,1645 | 0,1623 | 0,1938 | 0,1533 | 0,1684 |
| Priority of the alternative | | | | 5 | 3 | 4 | 1 | 6 | 2 |
| Utility degree of the alternative (%) | | | | 81,2% | 84,86% | 83,73% | 99,98% | 79,09% | 86,88% |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

**Fig. 8** Results of multiple-criteria evaluation of the alternatives

considering quantitative and qualitative criteria, the priority of the object in question and the utility degree.

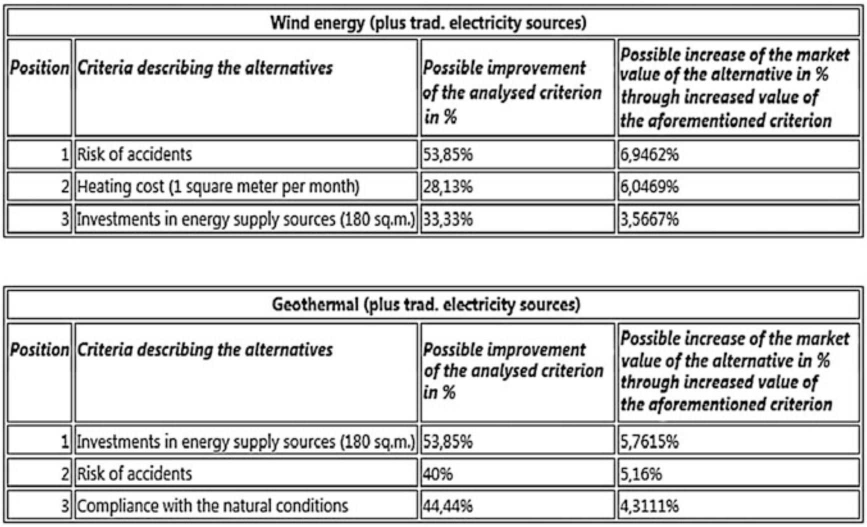
Having processed the expert evaluation data, the system returned the following results:

1. the highest utility was attributed to “biomass plus electricity” technologies;
2. the second priority was attributed to the “solar, biomass plus electricity” alternative;
3. the third priority was attributed to the “geothermal plus electricity” technologies;
4. the “Solar, wind plus electricity” technologies is ranked as the worst priority.

The main advantage of the *EGTAV-DSS*, which distinguishes it among other decision support systems, is recommendations to user. The model analyses all alternatives using the entire set of criteria. The system automatically analyses each criterion, determines its effect, compares it among alternatives and assesses its potential to change the end result in the assessment of alternatives. The system calculates the level of influence each criterion can have on the priority and utility of an object and provides visual recommendations (Sliogeriene et al. 2009).

The recommender model selects and displays three most significant criteria, which determine the utility of each alternative in question (see Fig. 9).

The decision support system for assessment of energy generation technologies *EGT-PH-DSS* facilitates the decision-maker to extract from its database versatile and thorough quantitative and qualitative information about the effect of environment and to use the model base for flexible analysis of these factors and for decision-making. The *EGT-PH-DSS* provides logical and informative results about the utility of the technologies in question and the effect of environmental factors on their value; it also gives recommendations for each criterion and helps avoid errors and partiality. In summary, the developed decision support system *EGT-PH-DSS* enables unbiased results, which can be used in assessment of a range of



Wind energy (plus trad. electricity sources)

| *Position* | *Criteria describing the alternatives* | *Possible improvement of the analysed criterion in %* | *Possible increase of the market value of the alternative in % through increased value of the aforementioned criterion* |
|---|---|---|---|
| 1 | Risk of accidents | 53,85% | 6,9462% |
| 2 | Heating cost (1 square meter per month) | 28,13% | 6,0469% |
| 3 | Investments in energy supply sources (180 sq.m.) | 33,33% | 3,5667% |

Geothermal (plus trad. electricity sources)

| *Position* | *Criteria describing the alternatives* | *Possible improvement of the analysed criterion in %* | *Possible increase of the market value of the alternative in % through increased value of the aforementioned criterion* |
|---|---|---|---|
| 1 | Investments in energy supply sources (180 sq.m.) | 53,85% | 5,7615% |
| 2 | Risk of accidents | 40% | 5,16% |
| 3 | Compliance with the natural conditions | 44,44% | 4,3111% |

**Fig. 9** Example of the recommendation module

energy generation technologies, their utility and the efficiency; in other analyses as well.

The renewable energy technologies were assessed based on several critical sustainability indicators. The selected indicators were price of generated electricity, GHG emissions during the full life cycle of the technology, availability of renewable sources, efficiency of energy conversion and social impacts. Each indicator was assumed to have equal importance to sustainable development and used to rank the renewable energy technologies against their impacts.

The expert assessment of the effect of environmental factors on the value of energy generation technologies has shown that such technologies must be analysed from a much broader perspective than just their technical or economic properties.

## 5 Case Study 2: Energy Efficient House DSS for Cooling

A building design based on energy-saving criteria reduces economic costs throughout the useful life of the building because of its lower energy consumption, and this more than compensates for the greater initial investment. Since there are also fewer $CO_2$ emissions into the atmosphere throughout the building's life cycle, this benefits society as well (Pacheco et al. 2012).

This is the reason, why the early stage building design and the use of optimization tools here are highly important. The building should be optimized according to not only quantitative (energetic, environmental, economic), but also qualitative (aesthetics, comfort) criteria.

As they start planning to build a house, clients often face a problem: how to choose the best wall structures and windows, or how, in countries with hot climates, to keep more heat out. Not less important are the climate change factors, due to structure materials or fuels used. We, therefore, develop an Energy Efficient House DSS for Cooling that will make it possible to pick, by quantitative and qualitative criteria, the best option from a range of available alternatives. It is a universal system and the example discussed below is, therefore, tailored specifically for Johannesburg in South Africa.

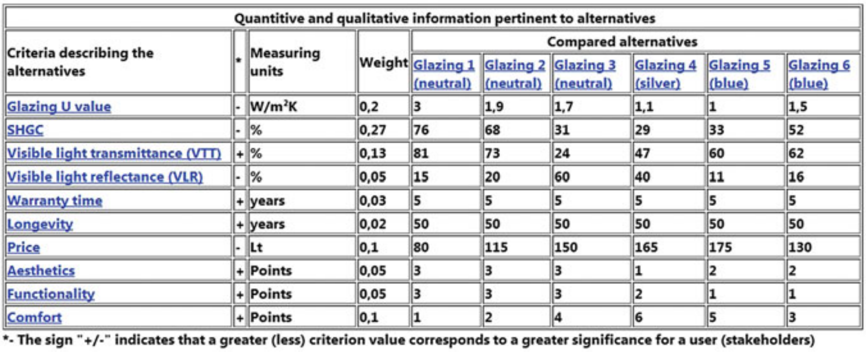
To make proper assessment of the key properties of building envelope, all decisions were based on actual estimates done with Swegon's Proclim. The example in question is a model of a single-zone building (7 × 5 × 2.6 m) with all its walls external; the window-to-wall ratio (WWR%) in the main façade makes up 10 %. The walls have the same properties as "Exterior Wall 1", the glazing has the same properties as "Glazing 1". The main façade (with glazing) looks north. This model is used as a reference in comparisons of alternatives. Johannesburg, a city in South Africa, has been picked from the Climate Data Library. All walls have their properties complying with South African National Standard (SANS) 204:2010, energy efficiency in buildings. The assessment trends of insulation criteria (both of walls and windows) and glazing criteria in our system conform to the energy-efficiency requirements laid out in SAFIERA (South Africa Fenestration and Insulation Energy Rating Association).

The research from a life cycle perspective was made using SimaPro software. The determination of carbon footprint was based on IPCC 2007 method, developed by the Intergovernmental Panel on Climate Change. It contains the climate change factors of IPCC with a time frame of 100 years. The determination of cumulative energy demand (renewable and non-renewable) was based on Cumulative energy demand (CED) method. The decision-making matrix includes alternative options of external-wall structures (5), glazed units (6), the orientation of glazing (4), the area of glazing (8) and the shading devices (4).

The group of glazed units comprises of six alternatives with ten quantitative and qualitative criteria for their assessment (Fig. 10). Each criterion has its own weight that shows its impact on the choice of alternatives and the indicator "±" that shows that either higher or lower value of the criterion is better. Quantitative criteria include thermal transmittance (U value), solar heat gain coefficient (SGHC), visible light transmittance (VLT), visible light reflectance (VLR), price, warranty time and longevity. Qualitative include aesthetics, functionality and comfort.

The presented alternatives of glazing include standard, sun protecting, reflecting glass unit, with neutral, silver or blue tinned glass. Their U value ranges from 1 to 3 W/m$^2$K, and SGHC from 29 to 76 %. These parameters are the key indicators in our case. Lower SHGC cuts heat gains (and cooling demands)—a feature most significant in countries with hot climates. Lower heat transmittance (U value) shows greater resistance to heat flow. In order to pick the best alternative from all glazed units, they all must be assessed by all other criteria, one by one.

The group of external-wall structures comprises of five alternatives with fifteen quantitative and qualitative criteria (see external wall: http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=428) (Fig. 11) include thermo-physical properties, economic and life cycle calculation results of walls materials.

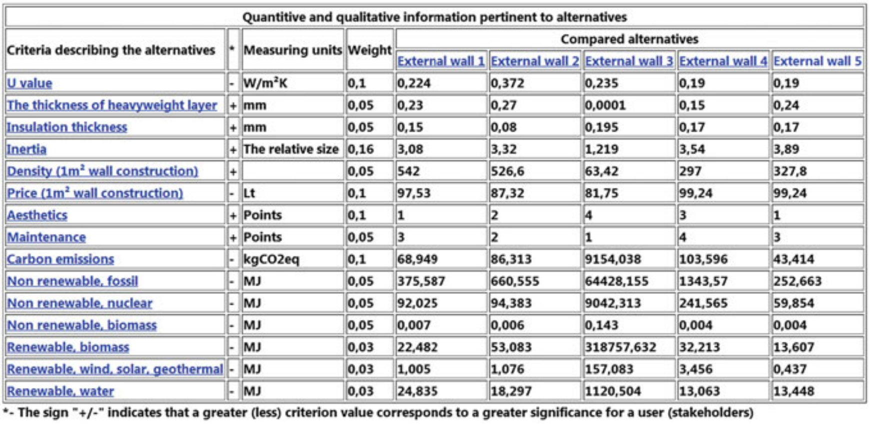


**Quantitive and qualitative information pertinent to alternatives**

| Criteria describing the alternatives | * | Measuring units | Weight | Compared alternatives | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Glazing 1 (neutral) | Glazing 2 (neutral) | Glazing 3 (neutral) | Glazing 4 (silver) | Glazing 5 (blue) | Glazing 6 (blue) |
| Glazing U value | - | W/m²K | 0,2 | 3 | 1,9 | 1,7 | 1,1 | 1 | 1,5 |
| SHGC | - | % | 0,27 | 76 | 68 | 31 | 29 | 33 | 52 |
| Visible light transmittance (VTT) | + | % | 0,13 | 81 | 73 | 24 | 47 | 60 | 62 |
| Visible light reflectance (VLR) | - | % | 0,05 | 15 | 20 | 60 | 40 | 11 | 16 |
| Warranty time | + | years | 0,03 | 5 | 5 | 5 | 5 | 5 | 5 |
| Longevity | + | years | 0,02 | 50 | 50 | 50 | 50 | 50 | 50 |
| Price | - | Lt | 0,1 | 80 | 115 | 150 | 165 | 175 | 130 |
| Aesthetics | + | Points | 0,05 | 3 | 3 | 3 | 1 | 2 | 2 |
| Functionality | + | Points | 0,05 | 3 | 3 | 3 | 2 | 1 | 1 |
| Comfort | + | Points | 0,1 | 1 | 2 | 4 | 6 | 5 | 3 |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

**Fig. 10** Initial data of glazing multiple-criteria analysis



| Quantitive and qualitative information pertinent to alternatives | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Criteria describing the alternatives | * | Measuring units | Weight | Compared alternatives | | | | |
| | | | | External wall 1 | External wall 2 | External wall 3 | External wall 4 | External wall 5 |
| U value | - | $W/m^2K$ | 0,1 | 0,224 | 0,372 | 0,235 | 0,19 | 0,19 |
| The thickness of heavyweight layer | + | mm | 0,05 | 0,23 | 0,27 | 0,0001 | 0,15 | 0,24 |
| Insulation thickness | + | mm | 0,05 | 0,15 | 0,08 | 0,195 | 0,17 | 0,17 |
| Inertia | + | The relative size | 0,16 | 3,08 | 3,32 | 1,219 | 3,54 | 3,89 |
| Density ($1m^2$ wall construction) | + | | 0,05 | 542 | 526,6 | 63,42 | 297 | 327,8 |
| Price ($1m^2$ wall construction) | - | Lt | 0,1 | 97,53 | 87,32 | 81,75 | 99,24 | 99,24 |
| Aesthetics | + | Points | 0,1 | 1 | 2 | 4 | 3 | 1 |
| Maintenance | + | Points | 0,05 | 3 | 2 | 1 | 4 | 3 |
| Carbon emissions | - | kgCO2eq | 0,1 | 68,949 | 86,313 | 9154,038 | 103,596 | 43,414 |
| Non renewable, fossil | - | MJ | 0,05 | 375,587 | 660,555 | 64428,155 | 1343,57 | 252,663 |
| Non renewable, nuclear | - | MJ | 0,05 | 92,025 | 94,383 | 9042,313 | 241,565 | 59,854 |
| Non renewable, biomass | - | MJ | 0,05 | 0,007 | 0,006 | 0,143 | 0,004 | 0,004 |
| Renewable, biomass | - | MJ | 0,03 | 22,482 | 53,083 | 318757,632 | 32,213 | 13,607 |
| Renewable, wind, solar, geothermal | - | MJ | 0,03 | 1,005 | 1,076 | 157,083 | 3,456 | 0,437 |
| Renewable, water | - | MJ | 0,03 | 24,835 | 18,297 | 1120,504 | 13,063 | 13,448 |

*- The sign "+/-" indicates that a greater (less) criterion value corresponds to a greater significance for a user (stakeholders)

**Fig. 11** Initial data of external-wall multiple-criteria analysis

The presented alternatives include different concrete and wood wall construction (different insulation and concrete thickness, external decoration materials).

The criteria according to their significance are as follows: inertia (0,16), U value (0,1), carbon emission (during manufacturing phase) (0,1), price (0,1), the thickness of heavyweight layer (0,05), insulation thickness (0,05), density (0,05), maintenance and the cumulative energy demand (results from SimaPro): non-renewable, fossil (0,05), non-renewable, nuclear (0,05), non-renewable, biomass (0,05), renewable, biomass (0,03), renewable, wind, solar, geothermal (0,03), and renewable, water (0,03).

Here, thermal inertia is the key property, as it shows slowed reaction to temperature variations and, as suggested by our estimates, contributes to lower heat gains. This criterion has, therefore, the highest weight (0.16). The benefits of an energy-efficient building design should be evaluated for the entire life cycle of the building (Pacheco et al. 2012). In this case, they are as follows: carbon footprint (kg $CO_2$ eq) and cumulative energy demand (renewable and non-renewable), for wall materials in the manufacturing phase.

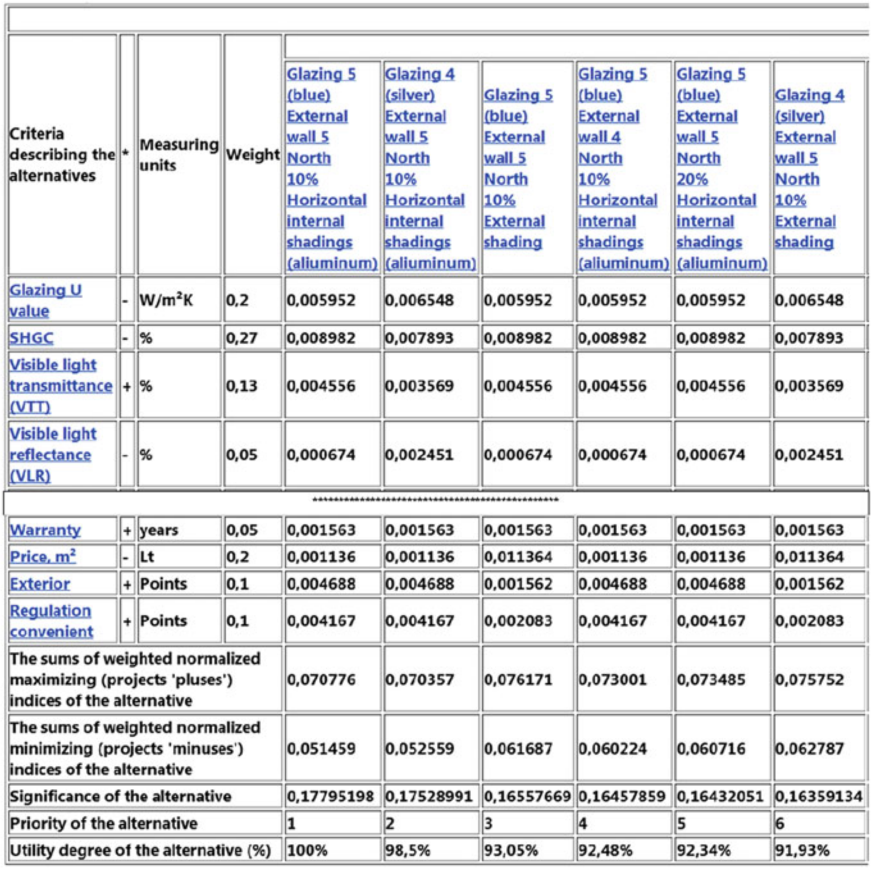
Among the parameters that intervene in the passive solar design of buildings, orientation is the most important and the one that has been most frequently studied. (Morrissey et al. 2011). According to (Pacheco et al. 2012), the benefits derived from optimal building orientation are the following:

- It is a low-cost measure that is applicable in the initial stages of project design.
- It reduces the energy demand.
- It reduces the use of more sophisticated passive systems.
- It increases the performance of other complex passive techniques.
- It increases the quantity of daylight, reduces the energy demand for artificial light, and contributes less to the internal heating load of the building.

That is why, next two groups of objects are the orientation of glazing and window-to-wall ratio (WWR%). In the considered alternatives (WWR%) ranges from 10 to 80 % for 4 orientation—north, south, west, and east, it includes both qualitative criteria and quantitative criteria.

In the group dealing with facade orientation, we assess two criteria—comfort and daily heat gain, which in our case are equally important.

In the group dealing with the area of glazing, we assess more criteria: heat gains (0,3), comfort (0,2), price for glazing (0,15), aesthetics (0,15), price for wall construction (0,1) and maintenance (0,1). The variation of heat gains shows which orientation and area of glazing will produce the highest heat gains. Here, qualitative criteria are very important—comfort in particular, the sense of well-being at higher or lower solar exposure.



| Criteria describing the alternatives | * | Measuring units | Weight | Glazing 5 (blue) External wall 5 North 10% Horizontal internal shadings (aliuminum) | Glazing 4 (silver) External wall 5 North 10% Horizontal internal shadings (aliuminum) | Glazing 5 (blue) External wall 5 North 10% External shading | Glazing 5 (blue) External wall 4 North 10% Horizontal internal shadings (aliuminum) | Glazing 5 (blue) External wall 5 North 20% Horizontal internal shadings (aliuminum) | Glazing 4 (silver) External wall 5 North 10% External shading |
|---|---|---|---|---|---|---|---|---|---|
| Glazing U value | - | W/m²K | 0,2 | 0,005952 | 0,006548 | 0,005952 | 0,005952 | 0,005952 | 0,006548 |
| SHGC | - | % | 0,27 | 0,008982 | 0,007893 | 0,008982 | 0,008982 | 0,008982 | 0,007893 |
| Visible light transmittance (VTT) | + | % | 0,13 | 0,004556 | 0,003569 | 0,004556 | 0,004556 | 0,004556 | 0,003569 |
| Visible light reflectance (VLR) | - | % | 0,05 | 0,000674 | 0,002451 | 0,000674 | 0,000674 | 0,000674 | 0,002451 |
| ********************************************** | | | | | | | | | |
| Warranty | + | years | 0,05 | 0,001563 | 0,001563 | 0,001563 | 0,001563 | 0,001563 | 0,001563 |
| Price, m² | - | Lt | 0,2 | 0,001136 | 0,001136 | 0,011364 | 0,001136 | 0,001136 | 0,011364 |
| Exterior | + | Points | 0,1 | 0,004688 | 0,004688 | 0,001562 | 0,004688 | 0,004688 | 0,001562 |
| Regulation convenient | + | Points | 0,1 | 0,004167 | 0,004167 | 0,002083 | 0,004167 | 0,004167 | 0,002083 |
| The sums of weighted normalized maximizing (projects 'pluses') indices of the alternative | | | | 0,070776 | 0,070357 | 0,076171 | 0,073001 | 0,073485 | 0,075752 |
| The sums of weighted normalized minimizing (projects 'minuses') indices of the alternative | | | | 0,051459 | 0,052559 | 0,061687 | 0,060224 | 0,060716 | 0,062787 |
| Significance of the alternative | | | | 0,17795198 | 0,17528991 | 0,16557669 | 0,16457859 | 0,16432051 | 0,16359134 |
| Priority of the alternative | | | | 1 | 2 | 3 | 4 | 5 | 6 |
| Utility degree of the alternative (%) | | | | 100% | 98,5% | 93,05% | 92,48% | 92,34% | 91,93% |

**Fig. 12** Fragment of computer-aided development of the alternatives of energy-efficient house in Africa

The use of shading devices is essential in hot climates countries. Shading on building facade elements controls the amount of solar radiation received by the building. This strategy provides positive results when actions are performed on the building facade cavities since these are the elements that transmit the highest level of radiation to the inside of the building (Pacheco et al. 2012). The control of shading elements, lighting as well as heating and cooling components could significantly reduce peak cooling load and energy consumption for lighting and cooling, while maintaining suitable heating and lighting conditions (Tzempelikos et al. 2007).

The quantitative and qualitative information related to shading devices (see shading: http://iti.vgtu.lt/imitacijosmain/simpletable.aspx?sistemid=428). The alternatives include external shading, vertical plastic louver, horizontal aluminium and wood louvers. The criteria according to their significance are as follow: efficiency (0,3), price (0,2), control options (0,15), range of colours (0,1), regulation convenient (0,1), exterior (0,1) and warranty time (0,05).

Once the multiple-criteria analysis is completed on glazing, external walls, orientation, window-to-wall ratio, shading, the best alternative combinations are provided (see computer-aided development of the feasible alternatives: http://iti.vgtu.lt/imitacijosmain/daugvar.aspx?sistemid=428) (Fig. 12). After the activation of the item “Multiple-criteria analysis of the developed feasible alternatives”, the multiple-criteria analysis of the feasible alternatives is performed.

## 6 Conclusion

Designing and realizing an efficient life cycle of energy-efficient built environment requires an exhaustive investigation of all solutions that form it. The efficiency of a specific energy-efficient built environment depends on a great number of factors such as cost, energy saving, tentative payback period, adverse health effects of the materials used, aesthetics, maintenance properties, functionality, comfort, sound insulation and longevity. Solutions based on alternatives allow a more rational and realistic assessment of traditions and of energy-related, economic, ecological, legislative, climatic, social and political conditions. They also help meet customer requirements better. Multi-variant design and multiple-criteria analysis of energy-efficient built environment came to mean processing and evaluation of loads of data. The number of feasible alternatives could be in the range of millions. With such enormous amounts of information, multi-variant design and multiple-criteria analysis of alternative options have become problematic. To address these issues, the authors have developed the life cycle model of energy-efficient built environment and two systems. To demonstrate the developed method, the chapter presents two case studies.

## References

Afgan NH, Carvalho MG (2002) Multi-criteria assessment of new and renewable energy power plants. Energy 27:739–755

Alanne K, Salo A, Saari A, Gustafsson SI (2007) Multicriteria evaluation of residential energy supply systems. Energy Buildings 39(12):1218–1226

Allwood JM, Cullen JM, Milford RL (2010) Options for achieving a 50 % cut in industrial carbon emissions by 2050. Environ Sci Technol 44(6):1888–1894

American Lung Association (2005) State of the air, American Lung Association. Available from: http://www.lung.org/assets/documents/publications/stateof-the-air/stateof-the-air-report-2005.pdf

Asadi E, Silva MG, Antunes CH, Dias L (2012a) A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. Building Environ 56:370–378

Asadi E, Silva MG, Antunes CH, Dias L (2012b) Multi-objective optimization for building retrofit strategies: a model and an application. Energy Buildings 44:81–87

Beccali M, Cellura M, Ardente D (1998) Decision making in energy planning: the ELECTRE multicriteria decision analysis approach compared to a fuzzy-sets methodology. Energy Convers Manage 39(16–18):1869–1881

Beccali M, Cellura M, Mistretta M (2003) Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy technology. Renew Energy 28(13):2063–2087

Cavallaro F (2005) An integrated multi-criteria system to assess sustainable energy options: An application of the PROMETHEE method. Fondazione Eni Enrico Mattei, Nota di Lavaro, University of Molise, Campobasso

Cavallaro F, Ciraolo L (2005) A multicriteria approach to evaluate wind energy plants on an Italian island. Energy Policy 33:235–244

Chen SJ, Hwang CL (1992) Fuzzy multiple attribute decision making: methods and applications. Lecture notes in economics and mathematical systems, No. 375, Sringer, Berlin, Germany

Cohen AJ, Ross AH, Ostro B et al (2005) The global burden of disease due to outdoor air pollution. J Toxicol Environ Health A. 68:1301–1307

Cullen JM, Allwood JM (2010) The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy 38(1):75–81

Diakaki C, Grigoroudis E, Kolokotsa D (2008) Towards a multi-objective optimization approach for improving energy efficiency in buildings. Energy Buildings 40(9):1747–1754

Diakaki C, Grigoroudis E, Kabelis N, Kololotsa D, Kalaitzakis K (2010) A multi-objective decision model for the improvement of energy efficiency in buildings. Energy 35:5483–5496

Diakoulaki D, Zopounidis C, Mavrotas G, Doumpos M (1999) The use of a preference disaggregation method in energy analysis and policy making. Energy Int J 24:157–166

Flourentzou F, Roulet C-A (2002) Elaboration of retrofit scenarios. Energy Buildings 34:185–192

Gamboa G, Munda G (2007) The problem of windfarm location: a social multicriteria evaluation framework. Energy Policy 35:1564–1583

Georgi JN, Dimitriou D (2010) The contribution of urban green spaces to the improvement of environment in cities: case study of Chania, Greece. Building Environ 45(6):1401–1414

Georgopoulou E, Lalas D, Papagiannakis L (1997) A multicriteria decision aid approach for energy planning problems: the case of renewable energy option. Eur J Oper Res 103:38–54

Gero JS, Neville DC, Radford AD (1983) Energy in context: a multi-criteria model for building design. Building Environ 18(3):99–107

Goodfield D, Anda M, Ho G (2011) Carbon neutral mine site accommodation village: developing the model. In: MODSIM 2011—19th international congress on modelling and simulation—sustaining our future: understanding and living with uncertainty. pp 3038–3044

Goumas MG, Lygerou VA, Papayannakis LE (1999) Computational methods for planning and evaluation geothermal energy projects. Energy Policy 27:147–154

Haralambopoulos DA, Polatidis H (2003) Renewable energy projects: structuring a multi-criteria group decision-making framework. Renew Energy 28:961–973

Jaber JO, Jaber QM, Sawalha SA, Mohsen MS (2008) Evaluation of conventional and renewable energy sources for space heating in the household sector. Renew Sustain Energy Rev 12(1):278–289

Jaggs M, Palmar J (2000) Energy performance indoor environmental quality retrofit–a European diagnosis and decision making method for building refurbishment. Energy Buildings 31:97–101

Juan Y-K, Kim JH, Roper K, Lacouture DC (2009) GA-based decision support system for housing condition assessment and refurbishment strategies. Automat Constr 18:394–401

Kablan MM (2004) Decision support for energy conservation promotion: an analytic hierarchy process approach. Energy Policy 32:1151–1158

Kaklauskas A, Zavadskas EK (2007) Decision support system for innovation with a special emphasis on pollution. Int J Environ Pollut 30(3–4):518–528

Kaklauskas A, Zavadskas EK, Raslanas S (2005) Multivariant design and multiple criteria analysis of building refurbishments. Energy Buildings 37(4):361–372

Kaklauskas A, Zavadskas EK, Raslanas S, Ginevicius R, Komka A, Malinauskas P (2006) Selection of low-e windows in retrofit of public buildings by applying multiple criteria method COPRAS: a Lithuanian case. Energy Buildings 38(5):454–462

Keirstead J, Jennings M, Sivakumar A (2012) A review of urban energy system models: approaches, challenges and opportunities. Renew Sustain Energy Rev 16(6):3847–3866

Løken E (2007) Use of multicriteria decision analysis methods for energy planning problems. Renew Sustain Energy Rev 11(7):1584–1595

Malckzewski J (1999) GIS and multicriteria decision analysis. Wiley, New York

Jacobson MZ, Delucchi MA (2011) Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 39(3):1154–1169

Mendoza JMF, Oliver-Solà J, Gabarrell X, Rieradevall J, Josa A (2012) Planning strategies for promoting environmentally suitable pedestrian pavements in cities. Transp Res Part D: Transp Environ 17(6):442–450

Mirasgedis S, Diakoulaki D (1997) Multicriteria analysis vs. externalities assessment for the comparative evaluation of electricity generation systems. Eur J Oper Res 102:364–379

Morrissey J, Moore T, Horne RE (2011) Affordable passive solar design in a temperate climate: an experiment in residential building orientation. Renew Energy 36:568–577

Multi-criteria analysis (2009) A manual. Department for Communities and Local Government, London. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf

Nagesha N, Balachandra P (2006) Barriers to energy efficiency in small industry clusters: multi-criteria-based prioritization using the analytic hierarchy process. Energy 31(12):1969–1983

Nakicenovic N, Grubler A, Inaba A, Messner S, Nilsson S, Nishimura Y, Rogner H-H, Schafer A, Schrattenholzer L, Strubegger M, Swisher J, Victor D, Wilson D (1993) Long-term strategies for mitigating global warming. Energy 18(5):401–609

Niemi R, Mikkola J, Lund PD (2012) Urban energy systems with smart multi-carrier energy networks and renewable energy generation. Renew Energy 48:524–536

Nigim K, Munier N, Green J (2004) Pre-feasibility MCDM tools to aid communities in prioritizing local viable renewable energy sources. Renew Energy 29:1775–1791

Pacheco R, Ordóñez J, Martínez G (2012) Energy efficient design of building: a review. Renew Sustain Energy Rev 16(6):3559–3573

Renn O (2003) Social assessment of waste energy utilization scenarios. Energy Int J 28:1345–1357

Rey E (2004) Office building retrofitting strategies: multicriteria approach of an architectural and technical issue. Energ Buildings 36:367–372

Saaty TL (2001) Fundamentals of decision making and priority theory with the analytic hierarchy process. RWS Publications, Pittsburgh

Salo AA, Hämäläinen RP (1992) Preference assessment by imprecise ratio statements. Oper Res 40(6):1053–1061

Sliogeriene J, Kaklauskas A, Zavadskas EK, Bivainis J, Seniut M (2009) Environment factors of energy companies and their effect on value: analysis model and applied methods. Technol Econ Dev Econ 15(3):490–521

Sliogeriene J, Kaklauskas A, Streimikiene D, Bianchi M (2012) Multiple criteria decision support system for the assessment of energy generation technologies considering the dimension of values. Int J Strateg Property Manage 16(4):370–391

Thiel T, Mroz T (2001) Application of multi-criterion decision aid method in designing heating systems for museum buildings. Informatica 12(1):133–146

Triantaphyllou E, Shu B, Sanchez SN, Ray T (1998) Multi-criteria decision making: an operations research approach. In: Webster JG (ed) Encyclopedia of electrical and electronics engineering, vol 15. Wiley, New York, pp 175–186

Tzempelikos A, Athienitis AK, Karava P (2007) Simulation of façade and envelope design options for a new institutional building. Sol Energy 81(9):1088–1103

Wright JA, Loosemore HA, Farmani R (2002) Optimization of building thermal design and control by multi-criterion genetic algorithm. Energy Buildings 34(9):959–972

Zadeh LA (1965) Fuzzy sets. Inf Control 8:338–353

# Toxicity Issues: Indoor Air Quality

**Maite de Blas**

**Abstract** Indoor air quality (IAQ) has become an issue of interest, since people spend most of the time indoors. This chapter reviews main indoor pollutants and their sources. Considering existing World Health Organisation (WHO) guidelines for IAQ and toxicity, the pollutants considered here are asbestos, biological pollutants, benzene, carbon monoxide (CO), formaldehyde, naphthalene, nitrogen dioxide ($NO_2$), particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), radon, tetrachloroethylene and trichloroethylene. As key factors for the improvement of IAQ, management of indoor emissions and ventilation improvement in buildings are discussed.

## 1 Indoor Air Quality

### 1.1 Background

Historically, the field of atmospheric pollution has been concerned about outdoor air pollution. Scientific community has widely studied air quality outdoors and most of the legislation and regulatory programs worldwide have been focused on ambient air quality (Godish 2004). Indoor air quality (IAQ) began to be considered a problem in the late 1960s and, first studies were performed about 10 years later (Jones 1999). Since then, building materials, consumer products, and personal habits indoors have changed and, therefore, many chemicals present indoors now were not there in the past (Weschler 2009). IAQ is nowadays a main issue for researchers motivated by the time that humans spend indoors, the wide range of

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pollutants present in indoor air, their concentration and toxicity and, the higher indoor concentrations with respect to outdoor ones.

In developed countries, humans spend most of their time in indoor environments, and hence, several respiratory diseases may be associated with exposure to indoor air pollutants (WHO 2011). Allergic and asthmatic diseases are two of the largest current problems for public health in industrialised countries, especially for susceptible collectives such as children, elderly people, and those with health problems. Less susceptible collectives may not develop respiratory diseases, but poor IAQ can cause discomfort, stress, absenteeism, or lost of productivity (Guardino 1998). World Health Organisation (WHO) refers to those acute health and comfort effects as sick building syndrome (SBS) (WHO 1983).

SBS symptoms may be associated with dampness and mould as well as with the presence of indoor pollutants, personality trait, work stress, gender or low ventilation rates (Zhang et al. 2012). A review of studies in several European countries, Canada and the United States reported that at least 20 % of buildings have dampness problems or visible mould (Institute of Medicine, US 2004). Children are also a vulnerable group to dampness and mould exposure, since there is an association between respiratory and allergic and living in a damp and mouldy environment. The exposure to biologic pollutants in early life was reported to protect children from allergic health disorders, but genetic factors also play an important role (Tischer and Heinrich 2013).

In developing countries, biomass in the form of wood, dung and crop residues is frequently used as source of household heating and cooking fuel. These materials are burnt in simple stoves or open fireplaces leading to incomplete combustion (Bruce et al. 2000). Women and their children spend most of their time indoors, so they are exposed to high indoor air pollution levels, which increase the risk of adverse respiratory problems, especially in children (Franklin 2007).

## *1.2 Studies on Indoor Air Quality*

First studies on indoor air pollution where performed in industrial workplaces, such as the investigations about deaths of building trade insulation workers caused by exposure to high levels of asbestos (Selikoff et al. 1964). Air quality in industrial environments is assessed considering the exposure to the particular pollutants released by the industrial process concerned in order to establish regulations and protect workers' health. The term IAQ is usually applied to non-industrial indoor air such as residential buildings, offices, schools, hospitals, restaurants, theatres, etc., where the concentration of pollutants is frequently lower with respect to industrial environments. During the last 30 years, a number of studies in the USA and in Europe were performed to assess human exposure to indoor pollutants at indoor environments. Some of them are summarised in Table 1, which measure inorganic pollutants such as CO, $CO_2$, radon and metals; mixtures of inorganic pollutants such as particulate matter (PM), and organic pollutants such as VOCs, SVOCs and PAHs. Studies focused exclusively on biologic pollutants were not included in Table 1, but some epidemiological studies investigating associations between dampness and mould and asthma were reviewed by Sahakian et al. (2008).

### 1.3 Multidisciplinary Approach of IAQ Assessment

IAQ problems depend on a number of factors such as the existing indoor pollutants, their concentration, and their adverse effects on human health. Therefore, the investigation of IAQ requires multidisciplinary groups of experts in heating, ventilating, and air conditioning (HVAC), IAQ control, epidemiology, toxicology and exposure assessment among others. The number of indoor pollutants and their concentration depend on several factors, such as indoor sources, features of the building and the accumulation processes of pollutants (de Blas et al. 2012; Uhde and Salthammer 2007). The type and number of indoor sources determine both the pollutants emitted and their emission rates; chemical transformation and indoor accumulation will depend on each individual species and, hence, on indoor chemistry (Weschler 2011).

When an existing building undergoes a major renovation, it should satisfy the minimum energy performance requirements in order to fulfil nearly zero energy refurbishment. Besides, IAQ should be maintained to ensure the welfare of the occupants; it should be improved whenever possible. There is a general trend of using low-polluting materials, but those materials should be certified and labelled. Ventilation rates should be adjusted to certify acceptable IAQ levels, but it is not beneficial to increase them at any rate, since they would lead to energy loss. Considering all those factors affecting IAQ assessment, the sections of this book chapter are organised as follows:

- Section 2 describes the main indoor pollutants individually, selected for their hazardousness with respect to health effects. Major indoor sources, indoor and outdoor concentrations, and health effects are described.
- Section 3 describes ventilation and infiltration processes in buildings, which determine the effectiveness of removing pollutants from indoor air and the intrusion of outdoor pollutants.
- Section 4 discusses the control measures to be applied for the improvement of IAQ using a multidisciplinary approach.

**Table 1** Summary of studies on indoor air quality

| Study | Years | Location | Pollutants | Samples | References |
|---|---|---|---|---|---|
| Total exposure assessment methodology (TEAM) | 1980–1987 | 750 homes and 10 buildings in USA | VOCs, SVOCs, metals, PAHs | Personal air, outdoor air, drinking water, breath | Final report (Wallace 1987) |
| Building assessment survey and evaluation (BASE) | 1994–1998 | 100 public and commercial buildings in cities of the USA with populations greater than one hundred thousand inhabitants | $PM_{10}$, $PM_{2.5}$, VOCs, bioaerosols, radon, $CO_2$, CO | Indoor | Publications and related resources (US EPA 2013a) |
| National human exposure assessment survey (NHEXAS) | 1995–1997 | More than 400 homes in the USA | Toxic chemicals: metals, pesticides, VOCs, PAHs | Breathe; food, drinking water, and other beverages; soil and dust around homes; biological samples (blood, urine) | Results published in Journal of Exposure Analysis and Environmental Epidemiology 9, number 1 (1999) |
| EXPOLIS (Air Pollution Exposure Distributions of Adult Urban Populations in Europe) | 1996–2000 | At least 50 representatives in 7 European cities | $PM_{2.5}$, VOCs, CO, $NO_2$ | Home (indoor and outdoor), workplaces and personal air | Final report (Jantunen et al. 1999) EXPOLIS Database (Hänninen et al. 2002) |
| Relationship of indoor, outdoor and personal air (RIOPA) | 2001–2002 | 100 homes and 150 individuals (100 adults and 50 children) in three urban centres in USA | VOCs, aldehydes, $PM_{2.5}$ | Indoor, outdoor and personal air | Research report (Weisel et al. 2005) |
| AIRMEX (European Indoor Air Monitoring and Exposure Assessment Project) | 2003–2008 | 182 public buildings, schools and kindergartens; 103 private home places; 148 samples from individuals | VOCs | Indoor, outdoor and personal air | Geiss et al. (2011)<br>Kotzias et al. (2009) |

## 2 Main Indoor Air Pollutants, Toxicity and Sources

In order to protect human health from the adverse effects caused by pollutants commonly present in indoor air WHO has developed its WHO guidelines for IAQ. These guidelines do not include workplaces, where specific sources can be present. Therefore, occupational exposure is not assessed. The first series of the guidelines for IAQ: dampness and mould (WHO 2009) is focused on avoiding microbial and biological indoor pollution. The second series is focused on selected pollutants (WHO 2010) which have indoor sources and pose a risk for the health of the building occupants: CO, $NO_2$ , PM, polycyclic aromatic hydrocarbons (PAHs, especially benzo-[a]-pyrene), radon, and some VOCs (benzene, formaldehyde, naphthalene, trichloroethylene, and tetrachloroethylene).

Apart from the indoor pollutants included on the second guideline, WHO working group stated that current evidence was uncertain or not sufficient for guidelines on the following pollutants: acetaldehyde, asbestos, biocides, pesticides, flame retardants, glycol ethers, hexane, nitric oxide (NO), ozone, phthalates, styrene, toluene and xylenes. Asbestos is included in this chapter for two reasons: it was widely used in construction, now requiring building refurbishments, and the International Agency for Research on Cancer (IARC) classified asbestos as a carcinogen for humans.

Indoor pollutants covered in this chapter are shown in Table 2, together with their WHO guideline values and a summary of their effects on human health. Guideline and reference values are established depending on toxicological, epidemiological, and statistical criteria, considering short-term and long-term effects on human health. Quantitative guideline values for dampness and mould are not provided by WHO because the response to dampness, microbial exposure, and health effects cannot be precisely quantified.

Other indoor pollutants have been considered by researchers and regulatory programs. For example, environmental tobacco smoke (ETS) is considered one of the major contributors to indoor air pollution, but it has been eliminated from most indoor spaces, so it is not included in WHO guidelines for IAQ. Most scientific literature considers ETS as a pollutant itself, but it is a mixture of multiple components such as CO, nitrogen oxides, sulphur oxides, VOCs, PAHs, ammonia, and PM (Rando et al. 1997). Out of these, more than 20 substances are known to be carcinogens (Hecht 1999).

Some indoor pollutants, namely CO, PM, $SO_2$, $NO_2$, $O_3$, and VOCs are both indoor and outdoor pollutants. Nevertheless, due to infiltration, accumulation, and indoor sources their indoor concentration could be higher than outdoors. Other pollutants, such as radon, asbestos, and some biologic pollutants can be considered exclusively indoor pollutants. Moulds and bacteria may emit microbial volatile organic compounds are (MVOCs) when growing on building materials and, hence, they are considered indoor pollutants and their indoor concentration is usually higher indoors (Sahlberg et al. 2013). Consequently, some MVOCs may be used as markers of dampness and mould such as 3-methylfuran, emitted by fungi

**Table 2** Indoor pollutants covered in the chapter, WHO guideline values and acute and long-term effects on human health (ATSDR 2013a; IARC 2013; WHO 2009 and 2010)

| Indoor pollutant | Guideline value (WHO) | Acute effect | Long-term effect | IARC group |
|---|---|---|---|---|
| Asbestos | – | – | Lung cancer, larynx cancer, ovary cancer mesothelioma, asbestosis | 1 |
| Biological pollutants | – | Sneezing, watery eyes, coughing, shortness of breath, dizziness, lethargy, fever, digestive problems | Allergic reactions, asthma | – |
| Benzene | UR[1] of leukaemia per 1 μg/m$^3$: 6 × $10^{-6}$. ELR[2]: 17, 1.7 and 0.17 μg/m$^3$ (1/10.000, 1/100.000 and 1/1.000.000 respectively) | Mildly irritation of the skin, eyes and respiratory tract. Depression of the central nervous system and arrhythmias | Anaemia, alterations to the immune system, myeloid leukaemia, genotoxicity | 1 |
| Carbon monoxide | 100 mg/m$^3$ (15 min), 35 mg/m$^3$ (1 h), 10 mg/m$^3$ (8 h) and 7 mg/m$^3$ (24 h) | Reduction of exercise tolerance. Increase in symptoms of ischaemic heart attack | Cardiovascular diseases | – |
| Formaldehyde | 0.01 mg/m$^3$ (30 min) | Irritation of the skin, eyes and respiratory tract | Nasopharyngeal cancer, leukaemia | 1 |
| Naphthalene | 0.01 mg/m$^3$ (annual average) | Respiratory tract lesions leading to inflammation and malignancy (animal studies) | No reliable human data for long-term inhalation toxicity | 2B |
| Nitrogen dioxide | 200 g/m$^3$ (1 h), 40 g/m$^3$ (annual average) | Inflammation of the airways | Bronchitis in asthmatic children and reduction of the lung function | – |
| Particulate matter | $PM_{2.5}$: 10 μg/m$^3$ (annual average) and 25 μg/m$^3$ (24 h), $PM_{10}$: 20 μg/m$^3$ (annual average) and 50 μg/m$^3$ (24-hours) | Reduced lung function, chronic bronchitis | Development of respiratory diseases (asthma, bronchitis and infections), cardiovascular diseases (heart attacks and arrhythmias) and lung cancer | – |

(continued)

**Table 2** (continued)

| Indoor pollutant | Guideline value (WHO) | Acute effect | Long-term effect | IARC group |
|---|---|---|---|---|
| PAHs (benzo[a]pyrene) | UR of lung cancer: $8.7 \times 10^{-5}$ per ng/$m^3$ of B[α]P ELR: 1.2, 0.12 and 0.012 ng/$m^3$ (1/10.000, 1/100.000 and 1/1.000.000 respectively) | Low acute toxicity | Lung cancer | 1[3] |
| Radon | ELR, for current smokers 1,670 and 167 Bq/$m^3$ (1/100 and 1/1,000 respectively) and for lifelong non-smokers 67 and 6.7 Bq/$m^3$ (1/100 and 1/1,000 respectively) | – | Lung cancer | 1 |
| Trichloroethylene | UR: $4.3 \times 10^{-}5$ per g/$m^3$. ELR: 230, 23 and 2.3 g/$m^3$ (1/10.000, 1/100.000 and 1/1.000.000 respectively) | Central nervous system depression and drowsiness, neurological, liver and kidney damage | Carcinogenicity (liver, kidney, bile duct and non-Hodgkin's lymphoma), genotoxicity | 1 |
| Tetrachloroethylene | 0.25 mg/m3 (annual average) | – | Early renal disease and impaired performance of the kidney | 2A |

[1] UR = unit risk

[2] ELR = excess lifetime risk: 1/10.000, 1/100.000 and 1/100.000 benchmark are included

[3] See Table 5 for IARC classification of specific PAH

**Table 3** Indoor pollutants covered in this chapter and their main sources (Zhang and Smith 2003; Bernstein et al. 2008)

| Type of pollutant | Indoor pollutant | | Main indoor sources |
|---|---|---|---|
| Inorganic pollutants | Asbestos | | Construction materials |
| | Carbon monoxide | | Fuel combustion, ETS |
| | Nitrogen dioxide | | Fuel combustion for heating and cooking |
| | Radon | | Soil surrounding building, construction materials |
| Mixture of inorganic and organic pollutants | Particulate matter | | Fuel combustion, cleaning operations, cooking, ETS |
| Organic pollutants | PAHs | | Fuel combustion, ETS, cooking |
| | VOCs | Benzene | Adhesives, sealants, ETS, printers, copiers |
| | | Formaldehyde | Smoking, combustion processes, millwork, office furniture, textiles, cooking |
| | | Naphthalene | ETS, combustion processes, mothballs, building materials wall covering, window shades |
| | | Trichloroethylene | Solvents, drinking water, consumer products |
| | | Tetrachloroethlylene | Solvents, dry-cleaned clothes from the building occupants. |
| Biologic pollutants | Dampness and mould | | Damp conditions indoors |

(Sahlberg et al. 2013) and 2-ethyl-1-hexanol, emitted from floor dampness (Zhang et al. 2012). Nevertheless, the use of MVOCs as markers of dampness and moulds exposure is controversial as they may also be emitted from other sources such as ETS or building materials. Other authors reported that $C_8$ MVOCs may be reliable indicators of fungal growth, which may be use to detect dampness and mould problems and, hence, IAQ problems indoors (Ryan and Beaucham 2013).

As well as outdoors, the presence of a chemical and its concentration in indoor air will depend on its sources. Main indoor sources of air pollutants are the occupants of the building, materials used in the construction and furnishings, and the activity inside the building; including the use of products containing pollutants (cleaning products, insecticides, disinfectants, etc.) or combustion gases (heating, kitchens, etc.). Table 3 shows indoor pollutants covered in this chapter organised by pollutant type and – described in detail in the following sections – and a summary of their main individual sources.

## 2.1 *Asbestos*

Asbestos is a group of six naturally occurring impure hydrated silicate minerals: chrysotile, actinolite, amosite, anthophyllite, crocidolite and tremolite. Asbestos fibres exhibit high tensile strength, resistance to heat and to chemical attack. Due to these special characteristics, it has been widely used in a variety of manufactured goods, such as building materials (roofing shingles, ceiling and floor tiles, water supply lines), automobile clutches and brakes, and electrical and thermal insulating materials among others (Virta 2006).

Asbestos can be emitted by both natural sources, by erosion of asbestos or asbestiform rocks, and anthropogenic sources, such as unsealed hazardous waste landfills, and deterioration of building materials or car clutches and brakes (Bourdès et al. 2000). Asbestos fibres are neither volatile nor soluble, but they can occur in suspension both in air and in water and, being very stable, they may remain suspended for long periods and, hence, small quantities of asbestos are ubiquitous in the air (ATSDR 2013b).

Concentrations of asbestos fibres outdoors are variable (see Fig. 1), as well as indoors, depending on the presence of asbestos-containing building materials and their condition. Indoor concentrations of (WHO 2010) asbestos are generally greater than outdoors. High concentrations of asbestos can be found when released from building materials. Over time asbestos-containing materials may lose their adhesion and may be damaged, increasing the probability of releasing asbestos fibres to the environment, especially when during renovation and even after renovation (Hoppe et al. 2012).

Although asbestos was not included in the last WHO guideline for IAQ (2010), because there was no sufficient evidence for IAQ guidelines, it was included in the Air Quality guidelines for Europe (WHO 2000) developed to assess risk of air pollution in Europe. There is no evidence of acute effects of exposure to asbestos, but it has been reported that long-term exposure to asbestos can cause respiratory diseases, such as lung cancer, mesothelioma – a rare form of cancer that involves the proliferation of mesothelial cells – and asbestosis – progressive and long-term

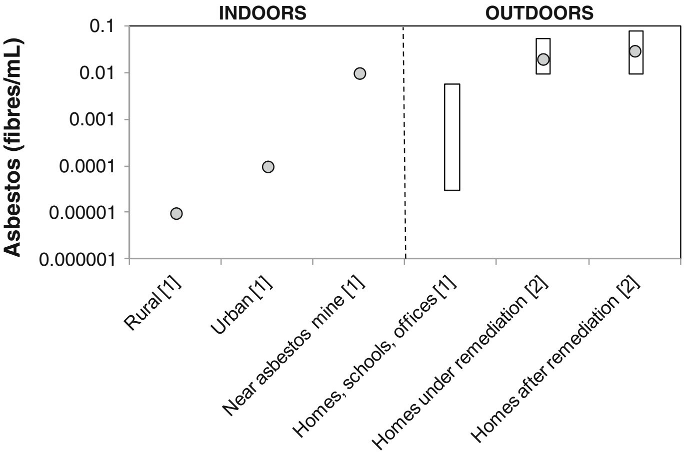


**Fig. 1** Asbestos average concentrations in different outdoor and indoor environments. Boxes represent the range of average concentrations: (1) ATSDR (2013b), (2) Hoppe et al. 2012

lung fibrosis – (ATSDR 2013b). The latency period since the exposure and the manifestation of the asbestos-related disease is between 20 and 50 years (Bolton et al. 2002). Shorter latency periods may be considered when exposure occurs during home maintenance and renovation involving asbestos-containing products, since there is evidence that it increases the incidence of malignant mesothelioma (Olsen et al. 2011).

Iceland was the first country to ban most forms of asbestos in 1983 and, since then, efforts have been made to ban asbestos-containing products elsewhere (Haynes 2010). Commercialisation and use of asbestos products were banned in the European Union in 1999 (Directive 99/77/EEC) and, the extraction, manufacture, and processing of asbestos-containing products were banned in 2003 (Directive 2003/18/EC). Manufacture, importation, processing, and distribution of most asbestos-containing products were banned in United States in 1989, but the regulation was overturn in 1991. Nowadays, asbestos-containing products are not totally banned in USA (US EPA 2013b). After the World Trade Centre disaster in 2001 and the resulting exposure to asbestos, especially among cleanup workers and volunteers, the regulatory policies on asbestos in the United States were reconsidered (Lange 2001). A limit value of 0.1 fibres/cm$^3$ for the protection of workers was established in Europe (Directive 2009/148/EC), which is the same limit in force in USA. Indoor concentrations of asbestos in different microenvironments are usually below that limit, even when refurbishment is performed (see Fig. 1).

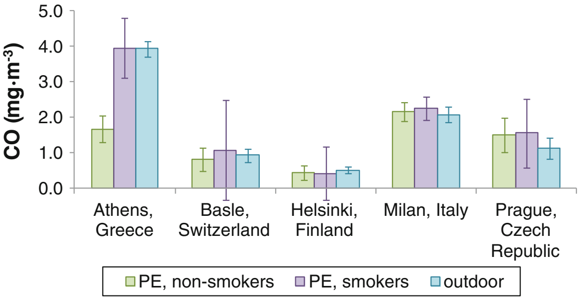
## 2.2 *Carbon Monoxide*

Carbon monoxide (CO) is a colourless, odourless and tasteless toxic gas. The toxicity of CO is mainly related with its reactivity with haemoglobin to form carboxihaemoglobin (COHb), which decreases the oxygen-carrying capacity of the blood. Exposure to dangerous levels of CO occurs mainly indoors, where CO lethal levels lead each year to a number of deaths worldwide (Raub et al. 2000).

The main indoor CO source is the incomplete combustion of carbon-containing fuels used for cooking and heating purposes. Poorly adjusted and maintained or unvented boilers, stoves, and heaters can be a significant source of CO indoors, as well as tobacco smoke. High indoor CO levels may also be found due to the contribution of vehicle-exhaust outdoor air masses coming from parking areas or garages (US EPA 2013c). CO is also emitted in low quantities by the endogenous metabolism of the building occupants (Wu and Wang 2005). In the absence of indoor sources, indoor concentrations of CO can be lower than outdoors. Dangerous levels of CO may be reached indoors when malfunctioning or unvented combustion devices are used (Jones 1999).

Natural background concentrations of CO in remote areas were reported to be between 0.06 and 0.14 mg/m$^3$, while in traffic-affected areas and poorly ventilated indoor spaces CO may range between 20 and 60 mg/m$^3$ (Georgoulis et al. 2002). A recent review reported that typical concentrations of CO in public buildings

**Fig. 2** Personal 48-h exposure to CO (PE) for non-smokers and smokers, and ambient concentrations of CO in five European cities (Georgoulis et al. 2002). *Bars* indicate standard errors



ranged between 0.01 and 10 mg/m$^3$, with maximum values of 100 mg/m$^3$ in traffic-affected buildings (Kolarik 2012). Similar values were found in the residences in the EXPOLIS study (Georgoulis et al. 2002). Mean personal exposure at homes for non-smokers and for smokers, and outdoor concentrations of CO were reported (see Fig. 2). Exposure and ambient concentrations differ significantly between cities, due to differences in size and socio-economic characteristics. The higher values were reported in Athens and Milan, and the lowest in Helsinki. Generally, ETS increased the short-term exposure to CO, but it was also reported that cooking with gas leads to higher CO concentrations. Ambient concentrations had also a large influence on personal exposure.

Inhalation is the only exposure route to CO for humans. CO rapidly enters blood, brain, hearth and muscles, causing severe short- and long-term effects. CO is eliminated from the body mainly by exhalation (ATSDR 2013b). Symptoms from acute exposure include headache, weakness or lethargy, dizziness, nausea or vomiting, and difficulties with memory or confusion (Weaver et al. 2002), being more vulnerable people suffering respiratory or cardiovascular diseases. In order to address short-term CO exposure, WHO considered 15 min, 1 h, and 8 h guideline values, shown in Table 2. Long-term exposure can cause cardiovascular diseases (WHO 2010) and is addressed by the 24-h guideline value.

## *2.3 Nitrogen Dioxide*

In atmospheric chemistry, the term $NO_X$ means the total concentration of nitric oxide (NO) and nitrogen dioxide ($NO_2$). They are produced in combustion processes, when nitrogen and oxygen react, especially at high temperatures. Typically, more than 90 % of the nitrogen oxides are emitted as NO, which in ambient air is oxidised with ozone to form $NO_2$ (Derwent and Hertel 1999). $NO_X$ are tropospheric ozone precursors and react to produce acid rain, and, hence, they are limited under Directive 2008/50/EC. WHO guidelines for IAQ include $NO_2$, but not NO because there is no sufficient evidence for it (WHO 2010).

Inhalation is the main route of exposure to $NO_2$ at room temperature, even at temperatures below 21 °C it exists as a liquid and, if ingested, it can cause gastrointestinal irritation or burns. Being poorly soluble in water, approximately 80–90 % of the inhaled $NO_2$ is absorbed in the respiratory system (Sandstrom 1995). Short-term exposure to $NO_2$ can cause irritation of the eyes, nose, throat, and respiratory tract, being population with asthma and respiratory diseases more susceptible (Hesterberg et al. 2009).

In the absence of indoor sources, indoor concentration of $NO_2$ is lower than outdoors, even though outdoor sources such as road traffic or industry contribute to indoor $NO_2$ (Pegas et al. 2012). Main indoor sources are tobacco smoke and poorly maintained or unvented combustion devices used for heating and cooking purposes, where coal, oil, kerosene or natural gas are burned (WHO 2010). Incense burning and candles can also emit $NO_2$ as well as NO (Loupa et al. 2006).

Figure 3 summarises $NO_2$ geometric mean concentration values in indoor workplaces, and residential indoor and outdoor values in four European cities taken from EXPOLIS study. Indoor residential $NO_2$ concentrations were the lowest in all cities except in Prague, where lowest concentrations were detected in workplaces (Kousa et al. 2001; Lai et al. 2004). The study also reported that outdoor concentrations of $NO_2$, the use of gas for cooking and workplace location strongly influence the $NO_2$ exposure, even though smoking is not a strong determinant.

Similar results were concluded in other works. Uhde and Salthammer (2007) reported higher $NO_2$ concentrations in kitchens were gas was used (300–3,000 μg/m$^3$) with respect to living spaces in residences (10–200 μg/m$^3$). Typical $NO_2$ range in public buildings is between 1 and 200 μg/m$^3$, but concentrations of up to 1.000 μg/m$^3$ may be found in traffic-related buildings or with very strong indoor sources (Kolarik et al. 2012), where the 1-h guideline value of 200 μg/m$^3$ may be exceed (WHO 2010).

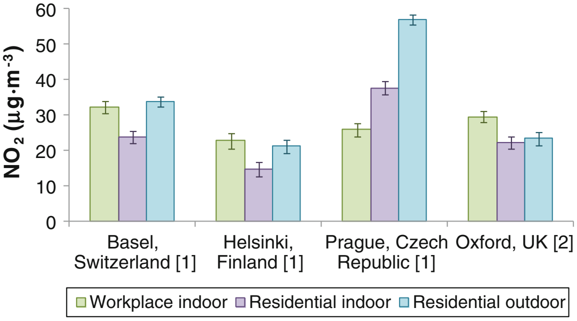


**Fig. 3** Nitrogen dioxide geometric mean concentration indoors (workplace and homes) and outdoors (residential) from EXPOLIS study: (1) Basel, Helsinki and Prague (Kousa et al. 2001) and (2) Oxford (Lai et al. 2004). *Bars* indicate geometric standard deviation

## 2.4 Radon

Radon is covered in "Toxicity Issues: Radon". Hence, this section provides a brief description of radon concerning IAQ, health effects and its main sources. Exposure to common environmental radon levels causes no acute health effects (ATSDR 2013a), but radon is nowadays classified as carcinogenic to humans by the IARC. The main source of radon is the soil subjacent to the building, which may enter by infiltration though openings, joints, and cracks (Mäkeläinen et al. 2001). Water supplies and granitic construction and decorative materials inside the building may be considered minor sources of radon, so geological factors are decisive to indoor radon concentrations (US EPA 2013d). Radon is easily dispersed outdoors, but it tends to accumulate indoors, especially in inadequately ventilated small spaces (US EPA 2013c). Hence, radon could be a problem of concern regarding energy saving in the construction of new buildings and in the refurbishment of existing ones (Pacheco-Torgal 2012).

## 2.5 Particulate Matter

PM is a complex mixture of solid particles and liquid droplets, made of organic and inorganic compounds. Indoor PM includes dust, smoke and biologic-related particles or bioaerosols, such as pollen, dust mites, mould, bacteria and viruses (Goyal and Khare 2010). The size of the particles is directly linked with their adverse health effects. Hence, PM is frequently classified as inhalable coarse particles $PM_{10}$ (particles less than 10 μm in aerodynamic diameter), fine particles $PM_{2.5}$ (particles less than 2.5 μm in aerodynamic diameter) and ultrafine particles $PM_{0.1}$ (particles less than 0.1 μm in aerodynamic diameter). $PM_{10}$ and $PM_{2.5}$ are used for compliance monitoring, while $PM_{0.1}$ standardised measurement programmes have not yet been widely implemented (WHO 2005).

When indoor sources are present, the concentration of PM indoors is frequently higher than outdoors. Particularly, in developing countries indoor exposure to PM from combustion of wood, charcoal and coal among others for heating and cooking purposes exposes the population to high concentration of PM (Bruce et al. 2000). Other indoor activities emitting PM and their particle size characterisation are shown in Table 4. Although indoor PM concentrations are mainly affected by indoor activities, particles penetrating by infiltration and ventilation may be considered as an important contribution (Kopperud et al. 2004).

$PM_{2.5}$ may be a better indicator of particle pollution than $PM_{10}$, being a better marker of both risk to human health and anthropogenic suspended PM (WHO 2005). Figure 4 shows $PM_{2.5}$ concentrations inside buildings, homes and outdoors from selected studies in the USA and Europe. In general, indoor concentrations are higher than outdoors, except in the studies performed in Boston (Abt et al. 2000) and Oxford (Lai et al. 2004), where indoor activities such as cooking, cleaning and

**Table 4** Particulate matter and main indoor sources

| Source | | PM size | References |
|---|---|---|---|
| Fossil fuels and biomass combustion | | $PM_{10}$, $PM_{2.5}$ | Pekey et al. (2010) |
| Cleaning: vacuuming and sweeping | | $PM_{10}$, $PM_{2.5}$ | Corsi et al. (2008) |
| Cooking | Oven cooking, toasting, barbecuing | $PM_{2.5}$ | Abt et al. (2000), Jones et al. (2000) |
| | Sautéing | $PM_{10}$ | Abt et al. (2000) |
| | Frying | $PM_{10}PM_{2.5}$ | Abt et al. (2000) |
| Movement of people | | $PM_{10}$ | Abt et al. (2000) |
| Environmental tobacco smoke | | $PM_{2.5}$ | Jones et al. (2000) |
| Construction and demolition activities | | $PM_{10}$ | Latif et al. (2011) |

smoking were reported. In the EXPOLIS study, personal exposure concentrations were also measured and reported to be even higher than indoor concentrations (Kruize et al. 2003; Lai et al. 2004).

A study performed in the USA reported similar $PM_{2.5}$ concentrations in 10 schools (Ligman et al. 1999). A recent review on indoor pollutants and their concentration reported that typical concentrations of $PM_{2.5}$ in public buildings ranged between 1 and 150 μg/m$^3$, with maximum values of 500 μg/m$^3$ in buildings located in places with high-traffic density or where indoor potential sources were present, such as tobacco smoking (Kolarik et al. 2012). Mean values of the studies summarised in Fig. 4 are in that ranges.

WHO guidelines for IAQ (WHO 2010) reported that there is no convincing evidence of a more hazardous nature of PM from indoor sources with respect to the

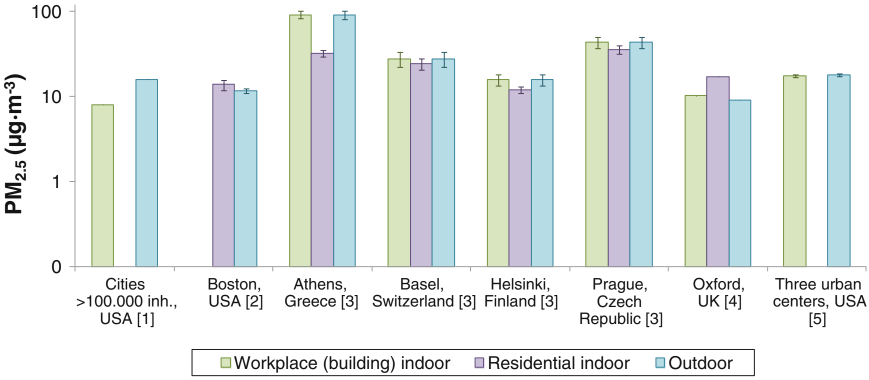


**Fig. 4** Indoor and outdoor $PM_{2.5}$ mean concentration values from selected studies performed in the USA and Europe: (1) BASE study: Ligman et al. 1999, (2) Abt et al., 2000, (3) EXPOLIS study in Athens, Basel, Helsinki and Prague (Kruize et al., 2003) (4) EXPOLIS study in Oxford (Lai et al. 2004) (5) RIOPA study: Weisel et al. 2005 (5). For the BASE study, geometric mean values are shown. All outdoor mean values correspond to residences except (1) and (5). *Bars* indicate standard error

outdoor ones, so WHO guidelines for Air Quality (WHO 2005) recommendations are applicable. There is little evidence to establish a safe threshold value below which there is no adverse health effect derived from the exposure to PM. The report of the US EPA on PM Health Effects (Lippmann et al. 2003) suggests that effects are different depending on the particle size and chemical composition. The values set by the WHO guidelines were shown in Table 2, for long-term effects as annual means and short-term effects as 24-h mean values. Concentrations in Fig. 4 correspond to average values of the overall sampling period, but it may be stated that guideline values for $PM_{2.5}$ (annual average of 10 μg/$m^3$ and daily mean average of 25 μg/$m^3$) are frequently exceed indoors. Otherwise, in developing countries, PM concentrations are approximately 10–20 times higher than the values quoted in WHO IAQ guidelines, as a result of the use of open fires for cooking and heating purposes (WHO 2005).

## *2.6 Polycyclic Aromatic Hydrocarbons*

Polycyclic aromatic hydrocarbons (PAHs) are a group of over 100 chemicals containing two or more fused aromatic rings. Lighter PAHs, with two and three rings, occur in the air predominantly in vapour phase, whereas heavier PAHs, with five rings or more, are mainly bound to particles (WHO 2010). The majority of particle-bound PAHs are found on small particles ($PM_{2.5}$). Benzo[a]pyrene (B[a]P), classified as carcinogenic to humans by the IARC, is used as a marker for total exposure to PAHs.

Different health effects of each PAH complicate the estimation of the total exposure risk, which is measured in terms of contribution of B[a]P to the carcinogenic potential of the mixture. PAHs are not limited in indoor air, and in Europe, benzo[a]pyrene is the only PAH regulated in ambient air under Directive 2004/107/EC. Table 5 shows the IARC classification of some PAH, selected from European and US EPA lists and their IARC classification. In addition to individual PAHs, IARC has also classified some activities emitting PAHs as carcinogenic to humans, such as emissions from household combustion of coal (IARC 2013).

PAHs are formed during incomplete combustion of carbon-containing matter at high temperature (Nikolau et al. 1984). ETS (Liu et al. 2001) and fireplaces using wood (Delgado-Saborit et al. 2011) have been reported to be the main contributor to PAHs indoors. Other indoor sources of PAHs are cooking, and incense and candle emissions (Levy et al. 2002; Ott and Siegmann 2006). Indoor activities are the main factor affecting indoor concentrations of PAHs, but sorption on building materials and re-emission have been reported, and outdoor contribution may also be considered (Li et al. 2005). Main outdoor sources of PAHs are related to motor vehicle emissions, domestic heating and industrial emissions such as power generation plants, waste incinerators and open burning (Ravindra et al. 2008).

Fluoranthene, pyrene and phenanthrene, all of them not classifiable as carcinogenic to human, are the most abundant PAHs in ambient air, but the one

**Table 5** IARC classification of selected polycyclic aromatic hydrocarbons

| Group 1: Carcinogenic to humans | Group 2A: Probably carcinogenic to humans | Group 2B Possibly carcinogenic to humans | Group 3 Not classifiable as carcinogenic to humans | Not classified by IARC |
|---|---|---|---|---|
| Benzo[a]pyrene | Cyclopenta[cd]pyrene | Benz[a]anthracene | Acenaphthene | Acenaphthylene |
| | Dibenzo[a,h]anthracene | Benzo[b]fluoranthene | Anthracene | |
| | Dibenzo[a,l]pyrene | Benzo[j]fluoranthene | Benzo[c]fluorine | |
| | | Benzo[k]fluoranthene | Benzo[ghi]perylene | |
| | | Chrysene | Dibenzo[a,e]pyrene | |
| | | Dibenzo[a,h]pyrene | Fluoranthene | |
| | | Dibenzo[a,i]pyrene | Fluorene | |
| | | Indeno[1,2,3-cd]pyrene | Pyrene | |
| | | 5-Methylchrysene | Phenanthrene | |
| | | Naphthalene | | |

contributing most to the total carcinogenity of the mixture is another PAH, benzo[a]pyrene (B[a]P), which confirms its suitability as a marker (Delgado-Saborit 2011). Figure 5 shows (B[a]P) indoor and outdoor concentrations in different environments in the United Kingdom. Indoor concentrations of PAHs are generally lower than outdoor ones, bar locations away from traffic emissions, such as parks. Maximum (B[a]P) were measured in pubs where ETS was present (4.91 ng/m$^3$), followed by traffic-affected roadsides (2.52 ng/m$^3$), and homes where wood was burned in a fireplace (2.40 ng/m$^3$). The study performed by Delgado-Saborit et al. (2010) highlights the importance of the exposure to PAHs mixtures, especially in indoor environments where specific PAHs sources may be present.

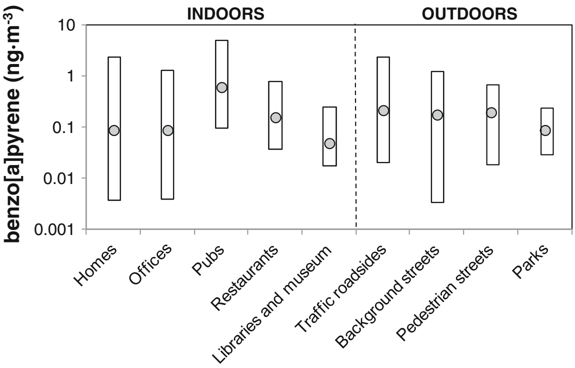


**Fig. 5** Benzo[a]pyrene geometric mean concentration values in indoor and outdoor environments (Delgado-Saborit et al. 2011). Boxes represent range of concentration. Values below the method detection limit (MDL) of 0.008 ng/m$^3$ (Delgado-Saborit et al. 2010) were assumed to be as MDL/2, following the US EPA criteria (US EPA 1991)

## 2.7 Volatile Organic Compounds

Different definitions of the term volatile organic compound (VOC) are provided by national and international organisations based on volatility, photochemical reactivity or toxicity (Directive 2008/50/CE; California Environmental Protection Agency 2009). Simply, the term VOC comprises a wide variety of carbon-containing chemicals with low-boiling points. The boiling points of the VOCs considered in this chapter ranges from −19 °C for formaldehyde, to 218 °C for naphthalene. This last compound can also be considered as a semi-volatile organic compound (SVOC), partitioned between the gas phase and solid phase and, being formed by two fused benzene rings, it is also the simplest PAH (see Sect. 2.6).

Major indoor sources of VOCs are building materials and furnishings, leading to higher concentrations in newly constructed buildings or on those where refurbishment or redecoration has recently taken place (Jones 1999; Liu et al. 2012; Shin and Jo 2012). Other indoor sources and activities emitting VOCs are smoking, pesticides, consumer products, burning devices and cooking (Barro et al. 2009; Jia et al. 2008). Human beings may also significantly emit organic pollutants, such as isoprene, acetone, ethanol, methanol and other alcohols (Fenske and Paulson 1999, Vereb et al. 2011).

Apart from potential indoor sources, accumulation and formation processes driven by indoor organic chemistry may affect VOCs' concentrations (Morrison 2009). A variety of VOCs may be emitted when cleaning agents and fresheners are used, but they may also be produced secondary pollutants when indoor reactions occur (Nazaroff and Weschler 2004). VOCs' concentration may also be affected by sink effect, being adsorbed by building materials and furnishings and reemitted later. Materials such as carpets, vinyl floor tiles, painted drywalls and ceiling tiles tend to adsorb VOCs (An et al. 1999).

Due to the presence of numerous indoor sources and accumulation and formation processes, concentrations of VOCs indoors are very frequently higher than outdoors (Edwards et al. 2001; Ohura et al. 2006). Organic pollutants are present indoors as complex mixtures of many compounds at low concentrations, making difficult the estimation of the risk associated with the exposure of VOCs. In the past, the term total volatile organic compounds (TVOC) were used as an indicator of the exposure to mixtures of VOCs (Bernstein et al. 2008). Nevertheless, considering the differences in health effects regarding toxicity and carcinogenity (see Table 2), individual VOC should be considered separately (Mølhave and Nielsen 1992).

### 2.7.1 Benzene

The molecule of benzene, $C_6H_6$, contains six atoms of carbon forming a ring with alternate double and single bonds, namely three conjugated bonds, making the molecule more stable than expected. Benzene is the simplest aromatic hydrocarbon and it may be present in the air, water and soil. Inhalation is the main pathway of exposure to benzene, being intake from food and water consumption negligible (MacLeod and Mackay 1999). Short-term exposure to benzene via inhalation may cause drowsiness, dizziness, delirium, loss of consciousness, respiratory arrest and even death. Benzene is a known clastogen, and its long-term exposure may cause anaemia and leukaemia (Chilcott 2007). WHO reported that no safe level of exposure can be recommended for benzene (WHO 2010).

In the absence of indoor sources of benzene, indoor concentrations are determined by outdoor ones. Major outdoor sources of benzene are traffic and industrial activities such as petrochemical industry, oil refineries, coal and coke manufacturing, rubber industry, shoe manufacturing and laboratories (ATSDR 2013b). Main indoor sources of benzene are ETS, stored fuels, paint supplies and solvents, attached garages, heating and cooking systems, cleaning products, and printers and copiers (Lai et al. 2007). Indoor benzene may also be emitted from building materials and furniture, including carpets, chipboard and PVC flooring, and plywood (Yu et al. 2002).

Figure 6 shows indoor and outdoor concentrations of benzene from selected studies. Indoor concentrations of benzene in both buildings and residences are generally greater than outdoor ones, with some exceptions on the EXPOLIS study performed in Oxford (Lai et al. 2004) and Milan (not shown in Fig. 6, Lai et al. 2007), and the AIRMEX study performed in 11 European cities (Geiss et al. 2011). For the remaining EXPOLIS cities (not shown in Fig. 6), Athens, Basel and Prague, greater benzene concentrations were found indoors with respect to outdoor ones. Outdoor benzene concentrations, outdoor temperature, outdoor wind speed and ETS strongly influence indoor benzene concentration (Lai et al. 2007).

**Fig. 6** Indoor building, residential and outdoor average concentrations of benzene from selected studies: (1) BASE (US EPA 2013a), (2) NHEXAS (Gordon et al. 1999), (3) EXPOLIS, Helsinki (Edwards et al. 2001), (4) EXPOLIS Oxford (Lai et al. 2004), (5) MNCPES (Adgate et al. 2004), (6) Serrano-Trespalacios et al. (2004), (7) RIOPA (Weisel et al. 2005), (8) AIRMEX (Geiss et al. 2011), (9) de Blas et al. 2012. *Bars* indicate standard errors

In the study performed by de Blas et al. (2012) in an urban building, benzene was found to have both indoor and outdoor origin. Some benzene peaks were related to outdoor traffic and industrial emissions, others were related to indoor activities, but some peaks occurred during weekends, when there was no activity in the building, emitted by building materials or products used in the refurbishment of the building. A recent review also reported that a high benzene indoor concentration may be found were in public buildings located nearby traffic sources or when strong indoor benzene sources are present, such as building materials (Kolarik et al. 2012).

### 2.7.2 Formaldehyde

Formaldehyde, $CH_2O$, is the simplest and the most widespread aldehyde found in the environment. At room temperature, formaldehyde is a colourless gas with a characteristic pungent and irritating odour. Inhalation is the main exposure path, causing irritation of the respiratory tract and eyes. Dermal exposure can also result in skin irritation (Jones 1999). Formaldehyde is classified as carcinogenic to humans by the IARC, since it causes nasopharyngeal cancer in humans. New epidemiological findings concluded that occupational exposure to formaldehyde causes leukaemia, but there is limited evidence for sinonasal cancer.

The main use of formaldehyde is the fabrication of urea–formaldehyde, a component of resins added to foam insulation materials and to adhesives used to manufacture particleboards, furniture or plywood. The emission rate of formaldehyde from those materials has been reported to increase with temperature, wood moisture content, humidity and the age of the material (Theodore and Theodore 2009). Also, many consumer products, ornaments and appliances contain formaldehyde: antiseptics, cleaning agents, carpets and permanent press fabrics, cigarettes, cosmetics, fertilisers, wiring and appliances, paints and varnishes and preserved foods (ATSDR 2013b).

Apart from building materials and household products, other additional sources may contribute to indoor formaldehyde such as outdoor air, indoor chemical reactions, candles, cooking, gas heaters and so on (Salthammer et al. 2010). Main sources of formaldehyde in ambient air are combustion processes, such as emissions from motor vehicles, power plants and incinerators (ATSDR 2013b). Destaillats et al. (2006) reported that in the presence of ozone, formaldehyde is the major oxidation product of cleaners, degreasers, and fresheners, emitting a variety of VOCs such as terpenoids, alcohols and esters. Small amounts of formaldehyde may be naturally emitted by plants, animals and humans (ATSDR 2013b).

Figure 7 shows indoor and outdoor formaldehyde concentration values from selected studies. Indoor concentrations of formaldehyde are generally higher than outdoor ones. Concentrations at residences are higher with respect to buildings used as workplaces (Jurvelin et al. 2001; Geiss et al. 2011), due to the many sources at homes, and/or a better ventilation in workplaces. From the data in

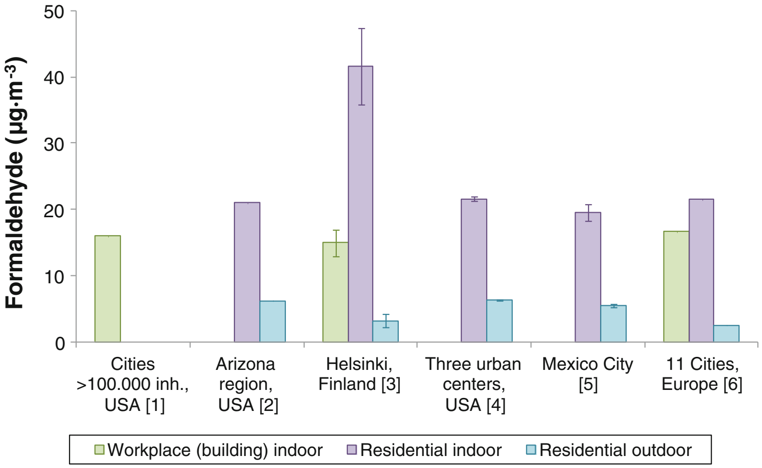


**Fig. 7** Indoor building, residential and outdoor average concentrations of formaldehyde from selected studies: (1) BASE (US EPA 2013a), (2) NHEXAS (Gordon et al. 1999), (3) EXPOLIS, Jurvelin et al. (2001), (4) RIOPA (Weisel et al. 2005), (5) Serrano-Trespalacios et al. (2004), (6) AIRMEX (Geiss et al. 2011). For NHXAS study median is showed instead of average. *Bars* indicate standard errors

Fig. 7, it may be deduced that outdoor air do not seem to contribute to indoor formaldehyde, a finding consistent with other studies (WHO 2010).

Besides the studies included in Fig. 7, other authors reviewed formaldehyde indoor concentrations worldwide and noticed similar concentrations to those in Fig. 7. Average indoor exposure to formaldehyde ranged between 20 and 40 µg/m$^3$ (Salthammer et al. 2010) and indoor concentration in public buildings ranged between 1 and 300 µg/m$^3$, with maximum values around 1.500 µg/m$^3$ (Kolarik et al. 2012) and where 30-min guideline value (10 mg/m$^3$) may be exceed (WHO 2010).

### 2.7.3 Naphthalene

Naphthalene, $C_8H_{10}$, is a two-ring aromatic hydrocarbon. It is considered both VOC and PAH and, hence, its concentration and exposure are poorly characterised with respect to other pollutants (Jia and Batterman 2010). The main exposure to naphthalene occurs via inhalation of its vapour, but dermal exposure should not be neglected as naphthalene may be absorbed from clothes (Guerrero and Corsi 2011). Exposure to naphthalene can cause a variety of short-term adverse effects such as haemolytic anaemia, liver and neurological damage and cataracts (US EPA 2013c). Naphthalene is classified as possible human carcinogen by the IARC. Other long-term effects of naphthalene exposure are similar to the ones observed for acute exposure, being children more susceptible than adults to haemolytic effects (Wakefield 2007).

Naphthalene is an ubiquitous pollutant in outdoor and indoor air. Being present in oil and coal, naphthalene may be emitted from combustion devices, indoors as well as outdoors (Batterman et al. 2012). Outdoor naphthalene emissions come primarily from chemical industries such as the production of phthalic anhydride and the manufacture of phthalate plasticisers, resins, dyes, leather tanning agents, and insect repellents (Jia and Batterman 2010). Naphthalene is emitted indoors by cigarette smoke, moth repellents and deodorisers. Naphthalene may also be emitted by building materials and furnishings, especially vinyl furniture and painted walls and ceilings, since naphthalene may be added as a chemical intermediate in the manufacture of such products (Kang et al. 2012). Sink effect of naphthalene may also be considered as Heroux et al. (2008) reported a decreasing in naphthalene concentrations in homes with furniture newer than 1 year.

Figure 8 shows average naphthalene indoor and outdoor concentrations obtained from selected studies. Indoor concentrations of naphthalene are higher than outdoors, both in residences and buildings (Batterman et al. 2012; de Blas et al. 2012). Naphthalene was found in 90 % of the buildings investigated in the BASE study (US EPA 2013a). In the EXPOLIS study, naphthalene was only found outdoors in 2 % of the samples in Helsinki (Edwards et al. 2001). In the same study in Oxford, naphthalene was only found in 8 % of the indoor samples and in 3 % of the outdoor samples (Lai et al. 2004). The EXPOLIS study also reported that long-term guideline value of 10 μg/m$^3$ was exceeded indoor and in personal exposure in Athens and Prague (Edwards et al. 2005).

Boxes represent the range of the average concentration of naphthalene from reviews on indoor pollutants. The first review reported typical average concentrations in urban buildings (Kolarik et al. 2012). A second review on naphthalene evaluated the literature published since 1990, considering nearly 150 studies and reporting the ranges represented in the figure as representative from non-smoker's homes and outdoors in urban areas (Jia and Batterman 2010). Naphthalene concentrations were within ranges reported in the reviews, except the one

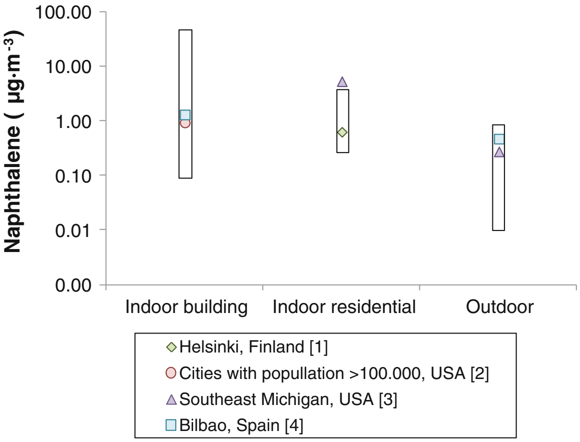


**Fig. 8** Indoor and outdoor average concentrations of naphthalene from selected studies: (1) EXPOLIS, Edwards et al. (2001), (2) BASE, US EPA (2013a) (3) Batterman et al. (2012), (4) de Blas et al. (2012). Boxes represent range of concentration from review works (Jia and Batterman 2010; Kolarik et al. 2012)

corresponding to indoor residencies in Southwest Michigan. In the residences object of that study, local naphthalene indoor sources were detected such as the use of consumer products, the presence of attached garages, naphthalene combustion products entering the houses and ETS to a smaller extent (Jia et al. 2010).

### 2.7.4 Trichloroethylene

Trichloroethylene ($C_2HCl_3$) otherwise abbreviated as TCE is a chlorinated solvent that can be found in air, water, soil, food and animal tissues (IARC 2013). The main route of exposure to TCE is inhalation. Nevertheless, other pathways such as water ingestion and dermal absorption of TCE when showering should be considered, particularly if drinking water is highly polluted (Fan et al. 2009). The short-term exposure to TCE can lead to effects on the central nervous system, such as sleepiness, fatigue, headache, confusion and excitement. It can also cause nausea and vomiting followed by loss of coordination and drowsiness. Very prolonged exposures can lead to coma, cardiac arrhythmias and even death. TCE is classified as carcinogenic to humans, and it will be included in the IARC Monograph 106, which is in preparation (IARC 2013). Other long-term effects are neurological, liver and kidney damages (Foxall 2008a).

The main indoor source of TCE is the use of consumer products, as it is used as a solvent in wood stains, varnishes, finishes, lubricants, adhesives, typewriter correction fluids, paint removers and cleaners (US EPA 2001). It has been reported that TCE and tetrachloroethylene (PCE) later described, can be found indoors after cleaning with chlorine bleach containing products, even with the ones not containing TCE and PCE, so accumulation and formation processes should be also considered (Odabasi 2008). Even emitted intermittently, indoor concentration of TCE may remain higher than background values in relatively long periods, being less reactive than other VOCs considered in this chapter such as benzene (Atkinson et al. 2008).

Industrial emissions of TCE can affect to indoor concentrations in certain areas and soil vapour intrusion can also occur though cracks in the foundations, especially at sites with historic use of TCE (McHugh et al. 2011). In the past, the main use of TCE was as a solvent for metal surface cleaning and degreasing, but due to toxicity concerns that use decreased in the 60 s (Doherty 2000a). Nowadays, approximately 80 % of the TCE in Europe is used as feedstock in the production of fluorinated hydrocarbons and polymers. Other minor uses of TCE are the production of special adhesives, high-tech ceramic production, and wool scouring (European Chlorinated Solvent Association 2012).

Figure 9 shows TCE indoor and outdoor average concentrations obtained from various studies. In the literature reviewed, there were more studies with data on TCE, i.e., the EXPOLIS, but most of the values were below the detection limits: in Helsinki, 97 % of indoor data, not detected outdoors (Edwards 2001), and in Oxford, 95 % of indoor data and 87 % of outdoor data (Lai et al. 2004). In the BASE study, TCE was detected in 66 % of the buildings (US EPA 2013a). TCE

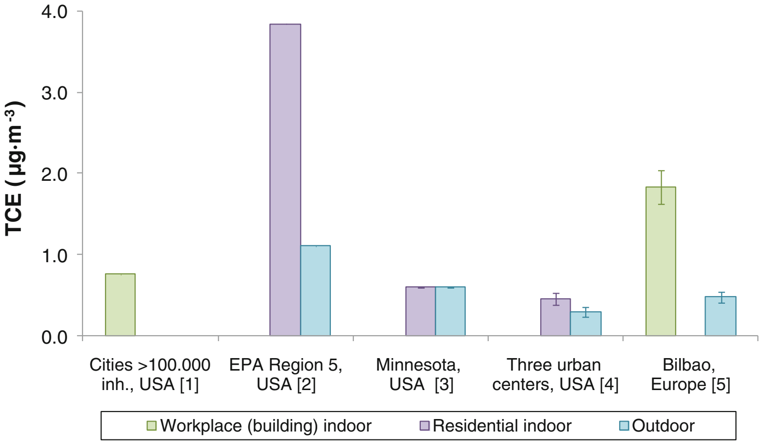


**Fig. 9** Selected indoor and outdoor average concentrations of TCE from various studies: (1) BASE study (US EPA 2013a), (2) NHEXAS (Clayton et al. 1999), (3) MNCPES (Adgate et al. 2004), (4) RIOPA (Weisel et al. 2005), (5) de Blas et al. (2012). *Bars* indicate standard errors

concentrations are generally higher than outdoor ones. The study performed in Bilbao reported that TCE may be generated indoors from the use of chlorine bleach containing products and even by refurbishment works (de Blas et al. 2012). Average indoor and outdoor TCE concentration in Minnesota homes was the 0.6 µg/m$^3$, but it was detected in more cases indoors (89 % of samples) than outdoors (70 % of samples) (Adgate et al. 2004). All indoor and outdoor values in Fig. 9 are below the concentrations associated with an excess lifetime cancer risk of 1:1.000.000 (2.3 µg/m$^3$) (WHO 2010), except the residential indoors reported in NHXAS study (Clayton et al. 1999).

### 2.7.5 Tetrachloroethylene

Tetrachloroethylene ($C_6H_3Cl_3$), otherwise abbreviated as PCE, is a chlorinated solvent. As well as TCE, it can be found in air, water, soil, food and animal tissues. The main path of exposure to PCE is inhalation, but in areas with highly polluted water, ingestion of drinking water may also be significant (IARC 2013). Main short-term effects of the exposure to PCE are dizziness, sleepiness and loss of coordination. Irritation of the nose and throat is observed when the exposition occurs via inhalation. Substantial exposures can lead to coma and even death (Foxall 2008b). PCE is classified as probably carcinogenic to humans, and it will be included in the IARC Monograph 106 in preparation (IARC 2013). Other long-term effects are neurological and kidney damage (Foxall 2008b).

The use of consumer products is a potential source of PCE indoors. A variety of household products may contain PCE, such as adhesives, water repellents, fabric finishers, stain removers, spot removers, wood cleaners, some inks, polishes, rug and upholstery cleaners, sealants and silicones (US EPA 2001). Polluted drinking water may be a source of indoor PCE, while taking a shower or washing dishes. Dry-cleaned clothes may also emit PCE in dwellings (WHO 2010).

Emissions of PCE have historically been related with its use as a solvent in dry cleaning (Doherty 2000b). Dry-cleaning machines recover the main part of PCE employed, but atmospheric emissions result from evaporation and leakages during the process (Hellweg et al. 2005). A study conducted in 196 dwellings has revealed that indoor concentrations of PCE increase with the proximity to dry-cleaning facilities, the use of consumer products containing PCE, aeration and ventilation, and the age of the building (Roda et al. 2013). Nowadays, main uses of PCE in Europe are as raw material to produce fluorinated hydrocarbons, fluorinated polymers, other fluorinated derivatives, and TCE. PCE is also industrially used for textile treatment, cleaning of metal surfaces and for catalyst regeneration in petrol industry (European Chlorinated Solvent Association 2012).

Figure 10 shows PCE indoor and outdoor concentrations obtained from the same studies as for TCE. Data suggest that generally indoor concentrations are greater than outdoors. Standard errors were of the same order of magnitude except in the MNCPES study, which reported high indoor standard error of the mean, due to the variability of PCE concentration indoors—the 95 % confidence interval on the mean ranges from 0.4 to 6.6 μg/m$^3$—(Clayton et al. 1999). Significant differences between indoor residential and outdoor concentrations of PCE were found in some studies (Clayton et al. 1999; Adgate et al. 2004; Weisel et al. 2005), indicating the existence of indoor sources at homes. Apart from the studies on Fig. 9, the EXPOLIS study reported that most PCE data were below the detection limits: in Helsinki 91 % of indoor data and 99 % of outdoor values (Edwards et al. 2001) and,

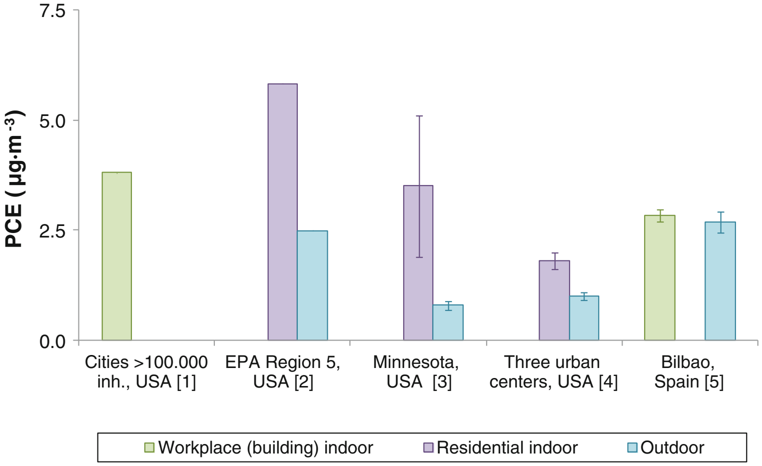


**Fig. 10** Selected indoor and outdoor average concentrations of PCE from various studies: (1) BASE study (US EPA 2013a), (2) NHEXAS (Clayton et al. 1999), (3) MNCPES (Adgate et al. 2004), (4) RIOPA (Weisel et al. 2005), (5) de Blas et al. (2012). *Bars* indicate standard errors

in Oxford 95 % of indoor data and 97 % of outdoor data (Lai et al. 2004). Otherwise, the BASE study reported that PCE was detected in all buildings sampled (US EPA 2013a).

## *2.8 Biological Pollutants: Dampness and Mould*

Indoor biological pollution is particularly caused by a complex mixture of live and dead microorganism, toxins, allergens, microbial VOCs and other chemicals growing indoors when sufficient moisture is available. Biological pollutants can be found in house dust, furniture surfaces, carpets and textiles among others (WHO 2009). A summary of dampness-related pollutants is provided in Table 6.

Main health effects associated with dampness and mould are adverse respiratory symptoms, allergies and asthma, as well as perturbation of the immune system (Mendell et al. 2011). Behavioural problems such as depressive symptoms in adults and poorer cognitive function in children (Casas et al. 2013) were also reported to be significantly associated with dampness and mould in dwellings and workplaces. These effects cannot be quantitatively quantified and, hence, WHO guidelines do not provide any threshold for biological pollutants. The general recommendation is to prevent or minimise persistent dampness and microbial growth on indoor surfaces and building structures, such as wallpapers, furniture and textiles and, hence, adequate building design, construction and maintenance are required (Schuchardt and Strube 2012). Building occupants are responsible for preventing and reducing indoor moisture, by providing correct ventilation. Therefore, public authorities may establish regulatory measures suitable housing and occupancy policies.

**Table 6** Summary of dampness-related indoor pollutants (WHO 2009)

| Indoor pollutant | Type of organism and most common species |
|---|---|
| House dust mite allergen | Small microscopic arachnids such as *Dermatophagoides, Pteronyssinus* and *Dermatophagoides farinae* |
| Fungal allergen | Eukaryotic organisms such as *Alternaria, Penicillium, Aspergillus,* and *Cladosporium* |
| Bacteria | Prokaryotic microorganisms such as *Streptomycetes* and mycobacteria |
| Endotoxins | Integral components of the bacteria cell, released after the destruction of the bacteria |
| Fungal (1 → 3)-$\beta$-D-glucans | Non-allergenic and water insoluble components of the structural cell-wall of most fungi, some bacteria, most higher plants and many lower plants |
| Mycotoxins | Fungal toxins or biomolecules with relatively low-molecular mass produced by fungi such as alcohols, aldehydes, ketones, terpenes, esters, aromatic compounds, amines and sulphur-containing compounds |
| Microbial and other VOCs | Volatile metabolites produced by fungi |
| Viruses | Infectious agents that can cause respiratory diseases |

## 3 Ventilation and Infiltration in Buildings

In order to prevent health problems of the occupants, an adequate design of the buildings' ventilation system is necessary to provide a good IAQ (Sundell et al. 2011). The indoor dilution capacity of pollutants is much lower than outdoors, making ventilation a critical issue. According to indoor ventilation standards, the rate of ventilation in a building must be set in order to achieve an acceptable IAQ (Olesen 2011). Due to the increasing need of saving energy in recent years, there is a tendency to decrease ventilation rates in buildings. The European HealthVent project aims the development of health-based ventilation guidelines for non-industrial buildings, considering both health and rational use of energy (HealthVent 2013).

The ventilation rate is the volumetric rate of outside air introduced to the building, which can be defined per person (L/s·person) or per area (L/s·m$^2$). The minimum ventilation rate per person is set concerning the pollution emitted from people occupying the space, such as odour and other bioeffluents, taking into account the number of expected visitors and occupants. Different criteria should be considered depending on the space to be ventilated: conference room, restaurant, office, apartment, etc. (Olesen 2011). The ventilation rate per floor area is set concerning other indoor sources than people such as furnishing, cleaning products, heating, ventilating and air-conditioning (HVAC) systems and ETS (US EPA 1990).

In addition to indoor sources, ventilation effectiveness is also affected by outdoor sources, season and climate. In buildings located in polluted areas, contaminated air could be introduced ventilation, resulting in the opposite effect that required (Fisk et al. 2012). That could occur in urban buildings located nearby high-traffic road or in buildings located in industrial areas (Pegas et al. 2012). Ventilation effectiveness can seasonally change, being ventilation more efficient in summer with respect to winter. Ventilation strategy varies with climate, being the dominating systems in Europe natural ventilation, uncontrolled air infiltration and window opening; bar northern Europe, where mechanical ventilation is frequently used due to colder climate (Dimitroulopoulou 2012).

Other causes of inadequate ventilation are infiltration and exfiltration and incomplete mixing and distribution of clean air with indoor air, which may be due to the inappropriate design of the filtration system. Infiltration is the air exchange from outside into the building that occurs mainly by uncontrolled air leakage across the building envelope, driven by wind, temperature difference and/or induced pressures (Lazaridis 2011). Infiltration and exfiltration may occur though openings, joints, cracks and porous materials in the building. The air exchange moving out of the building to outdoors is called exfiltration. Regarding IAQ, infiltration and exfiltration should be considered when infiltration of polluted air occurs (Wichmann et al. 2010) and when pollutants are transformed while air enters the building in some cases pollutants may be lost during infiltration (Liu and Nazaroff 2001). Air exchange rates between building zones in mixed-use buildings may lead to the migration of pollutants from their source in the work area to the major zones of exposure for the occupants of the building such as offices (Jia et al. 2010).

## 4 Prevention and Control of Indoor Pollution

Many IAQ problems have their origin in the design and construction of the building. Although these problems may be overcome by taking corrective measures, it may be more cost-effective to prevent and correct deficiencies when the building is designed or planned to be refurbished. A variety of approaches are available to prevent and control IAQ problems and even to improve IAQ. These can be classified as source management, ventilation and infiltration improvements, and contaminant control (Godish 2004).

### *4.1 Source Management*

Source control was not considered until the 90 s, since previously the only approach to achieve good IAQ was by means of appropriate ventilation (Bluyssen 2010)—see Sect. 4.2 in this chapter and "Ventilation: Thermal Efficiency and Health Aspects". Nevertheless, the most effective measure to reduce indoor pollution is to completely eliminate indoor sources, for example, by restricting smoking, or by eliminating the use of consumer products like solvents, varnishes, finishes, cleaning products, etc. (Godish 2004). Sometimes it is not possible to completely eliminate the sources, so IAQ problems may be overcome by reducing their emission (Wargocki et al. 2000). Furthermore, the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is regulated in Europe under the Regulation (EC) No 1907/2006. The main objective of REACH is to protect human health from the threat of chemicals by managing risk and providing safety information to users. Additionally, European Union takes additional restrictions for dangerous substances, such as asbestos, benzene or PAHs, all of them considered in this chapter.

Approximately, 40 % of the IAQ levels are caused by emissions from building materials (Missia et al. 2010) and, hence, during the planning of refurbishment works, building designers may select low-polluting materials (Zhang and Smith 2003). IAQ guidelines have been included into the design of new buildings to reduce the risk of the exposure to some indoor pollutants such as VOCs (Bernstein et al. 2008). Moreover, the European Construction Products Regulation (Regulation (EU) No 305/2011) requires to design construction works not to be a threat to workers, occupants or neighbours, during construction, use and demolition. Concerning IAQ, emission of toxic gases, dangerous substances (VOCs, greenhouse gases or PM) and radiation must be avoided, as well as dampness in parts of surfaces construction works.

For example, indoor formaldehyde can be kept at low levels by avoiding the use of formaldehyde-emitting materials, such as particleboard and plywood. Instead, softwood plywood and oriented-strand boards may be used (Godish 2004). Even though the tendency is to reduce or remove some VOCs from building products, building materials contain an increasing number of chemicals that can emit reactive compounds or lead to the production of secondary pollutants that contribute to poor IAQ (Uhde and Salthammer 2007). For instance, primary sources of formaldehyde may be completely removed but it may be found indoors, since formaldehyde is the major oxidation product of household products containing VOCs (Destaillats et al. 2006).

Emissions of VOCs from building materials are significant during the first six months. Carbonyls and ketones followed by aromatics are the compounds that mainly contribute to the indoor air concentrations (Missia et al. 2010). In order to prevent adverse health effects after decoration, refurbishment or renovation of a building, some authors recommend a wait period before using newly refurbished rooms in public buildings, especially for those used by risk groups like young children such as nurseries (Herbarth and Matysik 2010). Remediation of dampness and mould has been reported to reduce respiratory diseases, especially concerning adults since there is little evidence for children (WHO 2009).

Indoor sources can also be treated or modified. For example, formaldehyde-emitting surfaces can be treated with coatings, and asbestos-containing materials can be encapsulated to prevent fibre release. Emissions of combustion by-products, such as CO, $NO_2$, particles, PAHs and VOCs may be reduced by means of amending and replacing malfunctioning combustion devices used for cooking and heating purposes (Godish 2004).

## 4.2 Ventilation and Infiltration Improvements

The concentration of indoor air pollutants can be lowered by increasing the ventilation rate and its effectiveness. Ventilation is essential for maintaining comfortable, low-human-odour-building environments and helps to increase indoor air circulation. Apart from decreasing the concentration of indoor pollutants, increasing ventilation rates also reduces the time available for indoor chemical reactions, such as the ones between indoor ozone and VOCs which may produce substances that often are more irritating than their precursors (Weschler and Shields 1997). It is also advisable to increase ventilation rates during indoor activities such as painting, cooking, cleaning and smoking (US EPA 2013c).

The correct design of the infiltration system is a key factor in the control of some indoor pollutants such as radon. Measures include the sealing of foundation cracks and other openings, the depressurisation of the soil around the building, the installation of barriers and membranes and, finally the adequately ventilation of unoccupied and occupied spaces (Pacheco-Torgal, 2012).

### *4.3 Air Cleaning*

The most advisable approaches to prevent and control poor residential IAQ are the elimination of sources or the improvement of ventilation effectiveness. If those methods are insufficient, then air cleaning may be useful (US EPA 2013c). Air cleaning devices can be designed to remove PM, gaseous pollutants or both. Particle filters are used in most HVAC systems in order to protect mechanical equipment. Those devices are relatively effective in reducing indoor level of particles and mould spores.

Many cleaning devices for gaseous pollutants use sorbents such as activated carbon (Godish 2004). Sorption technology is effective for some chemicals reviewed in this chapter such as $NO_2$ and VOCs, but it may produce secondary pollutants if they react with ozone (Zhang et al. 2011). Other fan-driven technologies, such as ultraviolet germicidal irradiation (UVGI), photocatalytic oxidation (PCO), thermal catalytic oxidation (TCO), plasma, botanic air cleaners, ion generators, and electrostatic precipitators were reviewed and the conclusion was that the efficiency of each cleaner depends on the indoor air pollutants. Hence, air cleaners should be selected depending on the indoor pollutant to be removed and the degree of elimination needed (US EPA 2013c).

## 5 Conclusions and Perspectives

Indoor concentrations of the pollutants covered in this chapter are in general higher than outdoors, both in buildings used as workplaces and in residences. The guideline values set by WHO are frequently exceed indoors and, hence, IAQ regulation policies should be considered as well as outdoors. The elimination of indoor sources and the improvement of ventilation effectiveness are the most advisable methods to prevent and control poor IAQ, but if they result inadequate, then air cleaning may be useful.

Short-term and long-term effects of individual indoor air pollutants have been described. Nevertheless, there are significant gaps on long-term exposures to low concentrations and mixtures of different pollutants. Environmental factors may affect health simultaneously and synergistically, which makes complicate to estimate whether certain health effects are exclusively due to indoor air pollution. Even for the most comprehensive research on IAQ, it is complicated to establish a clear relationship between the characteristics and composition of indoor air and the health and welfare of the occupants. Further research on the field is need and, furthermore, multidisciplinary collaboration is required to address IAQ problems.

## References

Abt E, Suh HH, Allen G et al (2000) Characterization of indoor particle sources: a study conducted in the metropolitan Boston area. Environ Health Perspect 108:35–44

Adgate JL, Eberly LE, Stroebel C et al (2004) Personal, indoor, and outdoor VOC exposures in a probability sample of children. J Expo Anal Env Epid 14:S4–S13

Agency for Toxic Substances and Disease Registry, ATSDR (2013a) ToxGuides$^{TM}$. Available via: http://www.atsdr.cdc.gov/toxguides/index.asp. Cited 16 Jan 2013

Agency for Toxic Substances and Disease Registry, ATSDR (2013b) Toxicological profiles. Available via: http://www.atsdr.cdc.gov/ToxProfiles/index.asp. Cited 16 Jan 2013

An Y, Zhang JS, Shaw CY (1999) Measurements of VOC adsorption/desorption characteristics of typical interior building materials. HVAC&Res 5:297–316

Atkinson R, Baulch DL, Cox RA et al (2008) Evaluated kinetic and photochemical data for atmospheric chemistry: volume IV—gas phase reactions of organic halogen species. Atmos Chem Phys 8:4141–4496

Barro R, Regueiro J, Llompart M et al (2009) Analysis of industrial contaminants in indoor air: part 1. Volatile organic compounds, carbonyl compounds, polycyclic aromatic hydrocarbons and polychlorinated biphenyls. J Chromatogr A 1216:540–566

Batterman S, Chin JY, Jia C et al (2012) Sources, concentrations, and risks of naphthalene in indoor and outdoor air. Indoor Air 22:266–278

Bernstein JA, Alexis N, Bacchus H (2008) The health effects of nonindustrial indoor air pollution. J Allegy Clin Immun 121:585–591

Bluyssen PM (2010) Product policy and indoor air quality. Available via: http://www.conseil-dubienetreanimal.be/internet2Prd/groups/public/@public/@mixednews/documents/ie2divers/19062960_de.pdf. Cited 4 Mar 2013

Bolton C, Richards A, Ebden P (2002) Asbestos-related disease. Hosp Med 63:148–151

Bourdès V, Boffetta P, Pisani P (2000) Environmental exposure to asbestos and risk of pleural mesothelioma: review and meta-analysis. Environmental exposure to asbestos and mesothelioma. Eur J Epidemiol 16:411–417

Bruce N, Perez-Padilla R, Albalak R (2000) Indoor air pollution in developing countries: a major environmental and public health challenge. B World Health Organ 78:1078–1092

California Environmental Protection Agency (2009) Air resources board. Definitions of VOC and ROG (2009). Available via: http://www.arb.ca.gov/ei/speciate/voc_rog_dfn_1_09.pdf. Cited 29 Jan 2013

Casas L, Tiesler C, Thiering E et al (2013) Indoor factors and behavioural problems in children: the GINIplus and LISAplus birth cohort studies. Int J Hyg Envir Heal 216:146–154

Chilcott RP (2007) Benzene toxicological overview. health protection agency of United Kingdom. Available via: http://www.hpa.org.uk. Cited 2 Jan 2013

Clayton CA, Pellizzari ED, Whitmore RW et al (1999) National Human Exposure Assessment Survey (NHEXAS): distributions and associations of lead, arsenic and volatile organic compounds in EPA region 5. J Expo Anal Env Epid 9:381–392

Corsi RL, Siegel JA, Chianga C (2008) Particle resuspension during the use of vacuum cleaners on residential carpet. J Occup Environ Hyg 5:232–238

de Blas M, Navazo M, Alonso L et al (2012) Simultaneous indoor and outdoor on-line hourly monitoring of atmospheric volatile organic compounds in an urban building. The role of inside and outside sources. Sci Total Environ 426:327–335

Delgado-Saborit JM, Aquilina N, Baker S et al (2010) Determination of atmospheric particulate-phase polycyclic aromatic hydrocarbons from low volume air samples. Anal Methods 2:231–242

Delgado-Saborit JM, Stark C, Harrison RM (2011) Carcinogenic potential, levels and sources of polycyclic aromatic hydrocarbon mixtures in indoor and outdoor environments and their implications for air quality standards. Environ Int 37:383–392

Derwent RG, Hertel O (1999) Transformation of air pollutants. In: Fenger J, Hertel O, Palmgren F (eds) Urban air pollution—European aspects. Kluwer Academic Press, Dordrecht

Destaillats H, Lunden MM, Singer BC et al (2006) Indoor secondary pollutants from household product emissions in the presence of Ozone: a bench-scale chamber study. Environ Sci Technol 40:4421–4428

Dimitroulopoulou C (2012) Ventilation in European dwellings: a review. Build Environ 47:109–225

Doherty RE (2000a) A history of the production and use of carbon tetrachloride, tetrachloroethylene, trichloroethylene and 1,1,1-trichloroethane in the United States: part 2—trichloroethylene and 1,1,1-trichloroethane. Environ Forensics 1:83–93

Doherty RE (2000b) A history of the production and use of carbon tetrachloride, tetrachloroethylene, trichloroethylene and 1,1,1-trichloroethane in the United States: part 1—historical background; carbon tetrachloride and tetrachloroethylene. Environ Forensics 1:69–81

EC (1999) Commission Directive 1999/77/EC of 26 July 1999 adapting to technical progress for the sixth time Annex I to Council Directive 76/769/EEC on the approximation of the laws, regulations and administrative provisions of the Member States relating to restrictions on the marketing and use of certain dangerous substances and preparations (asbestos). Off J Eur Commun L207:18–20

EC (2003) Directive 2003/18/EC of the European Parliament and of the Council of 27 March 2003 amending Council Directive 83/477/EEC on the protection of workers from the risks related to exposure to asbestos at work. Off J Eur Un L97:48–52

EC (2004) Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. Off J Eur Un L23:3–16

EC (2006) Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. Off J Eur Un L136:3–280

EC (2008) Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. Off J Eur Un L152:1–44

EC (2009) Directive 2009/148/EC of the European Parliament and of the Council of 30 November 2009 on the protection of workers from the risks related to exposure to asbestos at work. Off J Eu Commun L330:18–36

EC (2011) Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. Off J Eur Commun L88:5–43

Edwards RD, Jurvelin J, Koistinen K et al (2001) VOC source identification from personal and residential indoor, outdoor and workplace microenvironment samples in EXPOLIS-Helsinki, Finland. Atmos Environ 35:4829–4841

Edwards RD, Schweizer C, Jantunen M et al (2005) Personal exposures to VOC in the upper end of the distribution—relationships to indoor, outdoor and workplace concentrations. Atmos Environ 39:2299–2307

European Chlorinated Solvent Association (2012). Available via http://www.eurochlor.org/. Cited 30 Jan 2013

Fan CH, Wang GS, Chen YC et al (2009) Risk assessment of exposure to volatile organic compounds in groundwater in Taiwan. Sci Total Environ 407:2165–2174

Fenske JD, Paulson SE (1999) Human breath emissions of VOCs. J Air Waste Manage 49:594–598

Fisk WJ, Black D, Brunner G (2012) Changing ventilation rates in U.S. offices: implications for health, work performance, energy, and associated economics. Build Environ 47:368–372

Foxall K (2008a) Trichloroethylene toxicological overview. Health Protection Agency of United Kingdom. Available via: http://www.hpa.org.uk. Cited 10 Jan 2013

Foxall K (2008b) Tetrachloroethylene toxicological overview. Health Protection Agency of United Kingdom. Available via: http://www.hpa.org.uk. Cited 11 Jan 2013

Franklin PJ (2007) Indoor air quality and respiratory health of children. Paediatr Respir Rev 8:281–286

Geiss O, Giannopoulos G, Tirendi S et al (2011) The AIRMEX study—VOC measurements in public buildings and schools/kindergartens in eleven European cities: Statistical analysis of the data. Atmos Environ 45:3676–3684

Georgoulis LB, Hänninen O, Samoli E et al (2002) Personal carbon monoxide exposure in five European cities and its determinants. Atmos Environ 36:963–974

Godish T (2004) Air quality, 4th edn. Lewis Publishers, Florida

Gordon SM, Callahan PJ, Nishioka MG et al (1999) Residential environmental measurements in the National Human Exposure Assessment Survey (NHEXAS) pilot study in Arizona: preliminary results for pesticides and VOCs. J Expo Anal Env Epid 9:456–470

Goyal R, Khare M (2010) Indoor air pollution and health effects. In: Gurjar BR, Molina LT, Ojha CSP (eds) Air pollution: health and environmental impacts. CRC Press, Boca Raton

Guardino X (1998) Indoor air quality: introduction. In: Stellman JM (ed) Encyclopaedia of occupational health and safety. International Labour Organization, Geneva

Guerrero PA, Corsi RL (2011) p-Dichlorobenzene (p-DCB) and Naphthalene Adsorption to Clothing. Indoor Air, Conference, Austin, TX, USA, June 5–10 2011

Hänninen O, Alm S, Kaarakainen E et al (2002) EXPOLIS databases. KTL, Department of Environmental Health. Kuopio, Finland

Haynes RC (2010) A Worn-out welcome renewed call for a global ban on asbestos. Environ Health Perspect 118:A298–A303

HealthVent (2013) Health-Based Ventilation Guidelines for Europe. Available via: http://www.healthvent.byg.dtu.dk/. Cited 21 Jan 2013

Hecht SS (1999) Tobacco smoke carcinogens and lung cancer. J Natl Cancer Inst 91:1194–1210

Hellweg S, Demou E, Scheringer M et al (2005) Confronting workplace exposure to chemicals with LCA: examples of trichloroethylene and perchloroethylene in metal degreasing and dry cleaning. Environ Sci Technol 39:7741–7748

Herbarth O, Matysik S (2010) Decreasing concentrations of volatile organic compounds (VOC) emitted following home renovations. Indoor Air 20:141–146

Heroux ME, Gauvin D, Gilbert NL et al (2008) Housing characteristics and indoor concentrations of selected volatile organic compounds (VOCs) in Quebec City, Canada. Indoor Built Environ 17:128–137

Hesterberg TW, Bunn WB, McClellan RO et al (2009) Critical review of the human data on short-term nitrogen dioxide ($NO_2$) exposures: evidence for $NO_2$ no-effect levels. Crit Rev Toxicol 39:743–781

Hoppe KA, Metwali N, Perry SS et al (2012) Assessment of airborne exposures and health in flooded homes undergoing renovation. Indoor Air 22:446–456

Institute of Medicine (US) (2004) Committee on damp indoor spaces. Damp indoor spaces and health. National Academy Press. Available from: http://www.nap.edu/catalog.php?record_id=11011. Cited 6 Mar 2013

International Agency for Research on Cancer, IARC (2013) Monographs and supplements available in PDF format. http://monographs.iarc.fr/ENG/Monographs/PDFs/index.php Cited 4 Jan 2013

Jantunen, M, Katsouyanni, K, Knöppel, H et al (1999). Air pollution exposure in European cities: the EXPOLIS study. Final report

Jia C, Batterman S (2010) A critical review of naphthalene sources and exposures relevant to indoor and outdoor air. Int J Environ Res Public Health 7:2903–2939

Jia C, Batterman S, Godwin C (2008) VOCs in industrial, urban and suburban neighborhoods, part 1: indoor and outdoor concentrations, variation, and risk drivers. Atmos Environ 42:2083–2100

Jia C, Batterman S, Godwin C et al (2010) Sources and migration of volatile organic compounds in mixed-use buildings. Indoor Air 20:357–369

Jones AP (1999) Indoor air quality and health. Atmos Environ 33:4535–4564

Jones NC, Thornton CA, Mark D, Harrison RM (2000) Indoor/outdoor relationships of particulate matter in domestic homes with roadside, urban and rural locations. Atmos Environ 34:2603–2612

Jurvelin J, Vartiainen M, Jantunen M et al (2001) Personal exposure levels and microenvironmental concentrations of formaldehyde and acetaldehyde in the Helsinki Metropolitan Area, Finland. J Air Waste Manage 51:17–24

Kang DH, Choi DH, Won D et al (2012) Household materials as emission sources of naphthalene in Canadian homes and their contribution to indoor air. Atmos Environ 50:79–87

Kolarik B, Gunnarsen L, Traberg-Borup S (2012) Design requirements for sensing and detoxification devices to be used in large public spaces. Literature review on typical pollutants and their concentrations. Indoor Built Environ 21(3):358–373

Kopperud RJ, Ferro AR, Hildemann LM (2004) Outdoor versus indoor contributions to indoor particulate matter (PM) determined by mass balance methods. J Air Waste Manage Assoc 54:1188–1196

Kotzias D, Geiss O, Tirendi S et al (2009) Exposure to multiple air contaminants in public buildings, schools and kindergartens: the European indoor air monitoring and exposure assessment (AIRMEX) study. Fresen Environ Bull 18:670–681

Kousa A, Monn C, Rotko T et al (2001) Personal exposures to $NO_2$ in the EXPOLIS-study: relation to residential indoor, outdoor and workplace concentrations in Basel, Helsinki and Prague. Atmos Environ 35:3405–3412

Kruize H, Hänninen O, Breugelmans O et al (2003) Description and demonstration of the EXPOLIS simulation model: two examples of modeling population exposure to particulate matter. J Expo Anal Environ Epidemiol 13:87–99

Lai HK, Kendall M, Ferrier H et al (2004) Personal exposures and microenvironment concentrations of $PM_{2.5}$, VOC, $NO_2$ and CO in Oxford,UK. Atmos Environ 38:6399–6410

Lai HK, Jantunen MJ, Künzli N et al (2007) Determinants of indoor benzene in Europe. Atmos Environ 41:9128–9135

Lange JH (2001) Has the World trade center tragedy established a new standard for asbestos? Indoor Built Environ 10:346–349

Latif MT, Baharudin NH, Velayutham P, Awang N, Hamdan H, Mohamad R, Mokhtar MB (2011) Composition of heavy metals and airborne fibers in the indoor environment of a building during renovation. Environ Monit Assess 181:479–489

Lazaridis M (2011) Indoor air pollution. In: First principles of meteorology and air pollution. Springer, Netherlands

Levy JI, Dumyahn T, Spengler JD (2002) Particulate matter and polycyclic aromatic hydrocarbon concentrations in indoor and outdoor microenvironments in Boston, Massachusetts. J Expo Anal Env Epid 12:104–114

Li A, Schoonover TM, Zou Q et al (2005) Polycyclic aromatic hydrocarbons in residential air of ten Chicago area homes: concentrations and influencing factors. Atmos Environ 39:3491–3501

Ligman B, Casey M, Braganza E et al (1999) Airborne Particulate matter within school environments in the United States. Available from: http://www.epa.gov/iaq/base/publications.html. Cited: 29 Jan 2013

Lippmann M, Frampton M, Schwartz J (2003) The U.S. Environmental Protection Agency Particulate Matter Health Effects Research Centers Program: a midcourse report of status, progress, and plans. Environ Health Persp 111:1074–1092

Liu DL, Nazaroff WW (2001) Modeling pollutant penetration across building envelopes. Atmos Environ 35:4451–4462

Liu Y, Zhu L, Shen X (2001) Polycyclic aromatic hydrocarbons (PAHs) in indoor and outdoor air of Hangzhou, China. Environ Sci Technol 35:840–844

Liu W, Zhang Y, Yao Y et al (2012) Indoor decorating and refurbishing materials and furniture volatile organic compounds emission labeling systems: a review. Chinese Sci Bull 57:2533–2543

Loupa G, Charpantidou E, Kioutsioukis I et al (2006) Indoor microclimate, ozone and nitrogen oxides in two medieval churches in Cyprus. Atmos Environ 40:7457–7466

MacLeod M, Mackay D (1999) An assessment of the environmental fate and exposure of benzene and the chlorobenzenes in Canada. Chemosphere 38:1777–1796

Mäkeläinen I, Arvela H, Voutilainen A et al (2001) Correlations between radon concentration and indoor gamma dose rate, soil permeability and dwelling substructure and ventilation. Sci Total Environ 272:283–289

McHugh T, Kuder T, Fiorenza S et al (2011) Application of CSIA to distinguish between vapor intrusion and indoor sources of VOCs. Environ Sci Technol 45:5952–5958

Mendell MJ, Mirer AG, Cheung K et al (2011) Respiratory and allergic health effects of dampness, mold, and dampness-related agents: a review of the epidemiologic evidence. Environ Health Perspect 119:748–756

Missia DA, Demetriou E, Michael N et al (2010) Indoor exposure from building materials: a field study. Atmos Environ 44:4388–4395

Mølhave L, Nielsen GD (1992) Interpretation and limitations of the concept "total volatile organic compounds" (TVOC) as an indicator of human responses to exposures of volatile organic compounds (VOC) in indoor air. Indoor Air 2:65–77

Morrison G (2009) Indoor organic chemistry. In: Salthammer T, Uhde K (ed) Organic indoor air pollutants occurrence, measurement, evaluation. WILEY-VCH, Weinheim, Federal Republic of Germany

Nazaroff WW, Weschler CJ (2004) Cleaning products and air fresheners: exposure to primary and secondary air pollutants. Atmos Environ 38:2841–2865

Nikolaou K, Masclet P, Mouvier G (1984) Sources and chemical-reactivity of polynuclear aromatic hydrocarbons in the atmosphere: a critical-review. Sci Total Environ 32:103–132

Odabasi M (2008) Halogenated volatile organic compounds from the use of chlorine-bleach containing household products. Environ Sci Technol 42:1445–1451

Ohura T, Amagai T, Senga Y et al (2006) Organic air pollutants inside and outside residences in Shimizu, Japan: levels, sources and risks. Sci Total Environ 366:485–499

Olesen BW (2011) Standards for Ventilation and Indoor Air Quality in relation to the EPBD. REHVA Eu HVAC J 28–32

Olsen NJ, Franklin PJ, Reid A et al (2011) Increasing incidence of malignant mesothelioma after exposure to asbestos during home maintenance and renovation. Med J Aust 195:271–274

Ott WR, Siegmann HC (2006) Using multiple continuous fine particle monitors to characterize tobacco, incense, candle, cooking, wood burning, and vehicular sources in indoor, outdoor, and in-transit settings. Atmos Environ 40:821–843

Pacheco-Torgal F (2012) Indoor radon: an overview on a perennial problem. Build Environ 58:270–277

Pegas PN, Nunes T, Alves CA et al (2012) Indoor and outdoor characterisation of organic and inorganic compounds in city centre and suburban elementary schools of Aveiro, Portugal. Atmos Environ 55:80–89

Pekey B, Bozkurt ZB, Pekey H et al (2010) Indoor/outdoor concentrations and elemental composition of $PM_{10}/PM_{2.5}$ in urban/industrial areas of Kocaeli City, Turkey. Indoor Air 20:112–125

Rando RJ, Simlote P, Salvaggio JE et al (1997) Environmental tobacco smoke: measurement and health effects of involuntary smoking. In: Bardana EJ, Montanaro A (eds) Indoor air pollution and health. Marcel Dekker, New York

Raub JA, Mathieu-Nolf M, Hampson NB et al (2000) Carbon monoxide poisoning: a public health perspective. Toxicology 145:1–14

Ravindra K, Sokhi R, Grieken RV (2008) Atmospheric polycyclic aromatic hydrocarbons: source attribution, emission factors and regulation. Atmos Environ 42:2895–2921

Roda C, Kousignian I, Ramond A et al (2013) Indoor tetrachloroethylene levels and determinants in Paris dwellings. Environ Res 120:1–6

Ryan TJ, Beaucham C (2013) Dominant microbial volatile organic compounds in 23 US homes. Chemosphere 90:977–985

Sahakian NM, Park JH, Cox-Ganser JM (2008) Dampness and mold in the indoor environment: implications for asthma. Immunol Allergy Clin 28:485–505

Sahlberg B, Gunnbjornsdottir M, Soon A et al (2013) Airborne molds and bacteria, microbial volatile organic compounds (MVOC), plasticizers and formaldehyde in dwellings in three North European cities in relation to sick building syndrome (SBS). Sci Total Environ 444:433–440

Salthammer T, Sibel M, Rainer M (2010) Formaldehyde in the indoor environment. Chem Rev 110:2536–2572

Sandstrom T (1995) Respiratory effects of air pollutants: experimental studies in humans. Eur Respir J 8:976–995

Schuchardt S, Strube A (2012) Microbial volatile organic compounds in moldy interiors: a long-term climate chamber study. J Basic Microb 52:1–7

Selikoff IJ, Churg J, Hammond EC (1964) Asbestos exposure and neoplasia. JAMA 188:142–146

Serrano-Trespalacios P, Ryan L, Spengler JD (2004) Ambient, indoor and personal exposure relationships of volatile organic compounds in Mexico City Metropolitan Area. J Exposure Analy Environ Epidemiol 14:S118–S132

Shin SH, Jo WK (2012) Volatile organic compound concentrations, emission rates, and source apportionment in newly-built apartments at pre-occupancy stage. Chemosphere 89:569–578

Sundell J, Levin H, Nazaroff WW et al (2011) Commemorating 20 Years of indoor air ventilation rates and health: multidisciplinary review of the scientific literature. Indoor Air 21:191–204

Theodore MK, Theodore L (2009) Introduction to environmental management. CRC Press, Boca Raton

Tischer CG, Heinrich J (2013) Exposure assessment of residential mould, fungi and microbial components in relation to children's health: Achievements and challenges. Int J Hyg Envir Heal 216:109–114

Uhde E, Salthammer T (2007) Impact of reaction products from building materials and furnishings on indoor air quality—a review of recent advances in indoor chemistry. Atmos Environ 41:3111–3128

United States Environmental Protection Agency, US EPA (1990) Ventilation and air quality in offices fact sheet. Available via: http://www.epa.gov/iaq/pdfs/ventilation_factsheet.pdf. Cited 24 Jan 2013

United States Environmental Protection Agency, US EPA (1991) Chemical concentration data near the detection limit. Available via: http://www.epa.gov/nscep/index.html. Cited 24 Jan 2013

United States Environmental Protection Agency, US EPA (2001) Sources, emission and exposures for trichloroethylene (TCE) and related chemicals. Available via: http://www.epa.gov/ncea/. Cited 12 Jan 2013

United States Environmental Protection Agency, US EPA (2013a) Building assessment survey and evaluation (BASE) Study. Publications. Available via: http://www.epa.gov/iaq/base/publications.html. Cited 12 Jan 2013

United States Environmental Protection Agency, US EPA (2013b) Asbestos laws and regulations. Available via: http://www.epa.gov/asbestos/lawsregs.html. Cited 30 Jan 2013

United States Environmental Protection Agency, US EPA (2013c) An introduction to indoor air quality (IAQ). Available via: http://www.epa.gov/iaq/ia-intro.html. Cited 16 Jan 2013

United States Environmental Protection Agency, US EPA (2013d) EPA map of radon zones. Available via: http://www.epa.gov/radon/zonemap.html. Cited 30 Jan 2013

Vereb H, Dietrich AM, Alfeeli B, Agah M (2011) The possibilities will take your breath away: breath analysis for assessing environmental exposure. Environ Sci Technol 45:8467–8475

Virta RL (2006) Worldwide asbestos supply and consumption trends from 1900 through 2003. US Geological Survery, Circular 1298, Reston, VA

Wakefield JC (2007) Naphthalene toxicological overview. Health Protection Agency of United Kingdom. Available via: http://www.hpa.org.uk. Cited 2 Jan 2013

Wallace LA (1987) The total exposure assessment methodology (TEAM) Study: summary and analysis, vol I. Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C. Available from: http://exposurescience.org/the-total-exposure-assessment-methodology-team-study. Cited 17 Jan 2013

Wargocki P, Wyon DP, Sundell J et al (2000) The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity. Indoor Air 10:222–236

Weaver LK, Hopkins RO, Chan KJ et al (2002) Hyperbaric oxygen for acute carbon monoxide poisoning. N Engl J Med 347:1057–1067

Weisel CP, Zhang J, Turpin BJ et al (2005) Relationships of indoor, outdoor, and personal air (RIOPA). Part I. Collection methods and descriptive analyses. Research report (Health Effects Institute) 130:1–107

Weschler CJ (2009) Changes in indoor pollutants since the 1950s. Atmos Environ 43:153–169

Weschler CJ (2011) Chemistry in indoor environments: 20 years of research. Indoor Air 21:205–218

Weschler CJ, Shields HC (1997) Potential reactions among indoor pollutants. Atmos Environ 31:3487–3495

Wichmann J, Lind T, Nilsson MA-M, Bellander T (2010) $PM_{2.5}$, soot and $NO_2$ indoor–outdoor relationships at homes, pre-schools and schools in Stockholm. Sweden Atmos Environ 44:4536–4544

World Health Organization, WHO (1983) Indoor air pollutants: exposure and health effects. World Health Organization, EURO Reports and Studies 1978, World Health Organisation, Copenhagen. Available via: http://whqlibdoc.who.int/euro/r&s/EURO_R&S_78.pdf. Cited 30 Jan 2013

World Health Organization, WHO (2000) Air quality guidelines for Europe. 2nd edn. Available via: http://www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf. Cited 30 Jan 2013

World Health Organization, WHO (2005) Air quality guidelines—global update 2005. Available via: http://www.who.int/phe/health_topics/outdoorair_aqg/en/. Cited 30 Jan 2013

World Health Organization, WHO (2009) WHO guidelines for indoor air quality: dampness and mould. Available via DIALOG. www.euro.who.int/document/e92645.pdf. Cited 14 Jan 2013

World Health Organization, WHO (2010) Indoor Air Quality guidelines: selected pollutants. Available via: http://www.who.int/indoorair/en/. Cited 30 Jan 2013

World Health Organization, WHO (2011) Indoor air pollution and health. Fact sheet N°292. Available via: http://www.who.int/mediacentre/factsheets/fs292/en/index.html. Cited 8 Nov 2012

Wu LY, Wang R (2005) Carbon monoxide: endogenous production, physiological functions, and pharmacological applications. Pharmacol Rev 57:585–663

Yu C, Crump D (2002) VOC Emissions from building products: sources, testing and emission data digest 464 part 1. BRE Environment Division, UK

Zang JJ, Smith KR (2003) Indoor air pollution: a global health concern. Brit Med Bull 68:209–225

Zhang Y, Mo J, Li Y (2011) Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. Atmos Environ 45:4329–4343

Zhang X, Sahlberg B, Wieslander G et al (2012) Dampness and moulds in workplace buildings: associations with incidence and remission of sick building syndrome (SBS) and biomarkers of inflammation in a 10 year follow-up study. Sci Total Environ 430:75–81

# Toxicity Issues: Radon

**Fernando Pacheco Torgal**

**Abstract** This chapter reviews literature on radon as a source of indoor air contamination. It shows that post-construction remediation like soil depressurization systems (SDS) seems to be more cost-effective than the use of protection measures installed during construction like radon-barrier membranes which have a significant failure rate. Since radon concentration is very dependent on the air change rate (ACH), it is important to maintain adequate air ventilation. However, in some situations, the cost of additional heating to eliminate the heat losses would exceed the total costs of remediation by soil ventilation as much as eightfold. This chapter also shows that there are optimum temperature and relative humidity which minimize radon levels.

## 1 Introduction

Radon ($^{222}$Rn) is a colorless, odorless radioactive gas that comes from the ground in granitic-related areas but its source can also be from granite floor materials or even from construction materials, thus polluting indoor air. Radon was identified as a human lung carcinogen in 1986 by the WHO (Clement 2010).

According to this organization, *radon gas is by far the most important source of ionizing radiation among those that are of natural origin*. This gas constitutes the second cause of death after lung cancer (WHO 2009).

Evidence between indoor radon exposure and lung cancer was reported two decades ago by Field et al. (2003). *Most radon gas inhaled is immediately exhaled, however, if decay occurs in the lungs, the resulting solid radioactive particles can settle onto bronchial epithelial cells causing DNA damage* (Chauhan et al. 2012).

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Recent investigations carried out in Portugal show that of the 8,514 lung cancer deaths observed, 18–28 % could be associated with indoor radon exposure (Veloso et al. 2012).

Children are considered a risk group in terms of radon since association between residential radon and acute leukemia risk was reported (Brauner et al. 2010).

Synergic effects between smoking and radon, in lung cancer, have also been reported (Barros-Dias et al. 2012). Other authors confirm the radon-smoking synergism (Bochicchio et al. 2012).

A possible correlation between radon and skin cancer was suggested by other authors (Wheeler et al. 2012). However, Sethi et al. (2012) state that the possibility of radon having a causative effect on other cancers has been explored but not yet proven.

Brauner et al. (2012) analyzed the interaction between radon decay products and particular matter such as NOx from traffic-related air pollution, but the results were not conclusive.

In the past, it was commonly accepted that only radon concentrations above 400 Bq/m$^3$ could be a source of concern; however, recent investigations show that this threshold is far from being safe. Dinua et al. (2009) studied 90 households in Spain with a maximum radon concentration of 366 Bq/m$^3$, stating that an excessive number of cancer-related deaths occurred in that area.

Krewski et al. (2006) show health-related risks even for radon concentrations below 200 Bq/m$^3$. This is the radon concentration at which action is currently advocated for in many countries. Recent epidemiological findings from residential studies, however, demonstrate that lung cancer risk can arise from exposure to indoor radon at levels of the order of 100 Bq/m$^3$ (COM 2011).

According to WHO (2009), the lung cancer risk increases linearly with long-term radon exposure, with no evidence for a threshold. Extensive large-scale surveys of indoor radon in Norway show that 9 % of the present housing stock (approximately 175,000 dwellings) has an annual average radon concentration exceeding the Norwegian action level of 200 Bq/m$^3$. Also, it states that 30,000 Norwegians live in dwellings where the average radon concentration is higher than 1,000 Bq/m$^3$ (Jelle 2012).

A recent survey analyzed 506 schools located in southeast Italy, concluding that about 7 % of schools showed radon concentration values above 500 Bq/m$^3$ (Trevisi et al. 2012a).

Nevertheless, some surveys show that the majority of the public seems to consider the health risks involved from exposure to radon as being negligible. Bradley et al. (1997) found that only 10 % of those with a raised level of radon took any steps to remediate this problem. Similar figures were given by Arthur (2003) and by Chow et al. (2007).

Ryan and Kelleher (1999) discovered that even when householders knew of the existence of raised radon levels in their dwellings, they rarely remediated. There is also the general problem that the majority of the public seems to consider the health risks resulting from radon as being negligible (Phillips et al. 2000).

Despite numerous awareness campaigns, limited numbers of householders have tested their homes and only a minority of the affected householders has remediated the problem. Moreover, a recent survey shows a wide range of the public perception on radon risk not significantly influenced by public health campaigns (Denman et al. 2005).

Antignani et al. (2012) mentioned that in a very recent wide radon survey that took place in Italy, 40 % of the contacted participants refused to participate or did not even respond to the contact emails. Those authors compared the consent rate with the one obtained by other authors using the same email approach noticing that UK, Ireland, and Australia showed even lower consent rates.

The building sector is the largest energy user and $CO_2$ emitter in the European Union (EU) and is responsible for about 40 % of the EU's total final energy consumption and $CO_2$ emissions. The European Energy Performance of Buildings Directive 2002/91/EC (EPBD) has been recast in the form of the 2010/31/EU of the European Parliament. (European Union 2003, 2010).

One of the new aspects of the 2010/31/EU is the introduction of the concept of near-zero-energy building. The article nine of the European Directive establishes that, by December 31, 2020, all new constructions have to be near-zero-energy buildings. However, new buildings have limited impacts on overall energy reduction as they represent just a tiny fraction of the existent building stock. Existing buildings constitute, therefore, the greatest opportunity for energy efficiency improvements (Xing et al. 2011). Besides, new homes use four to eight times more resources than an equivalent refurbishment (Power 2008), which constitutes an extra argument in favor of building refurbishment. The energy efficiency building refurbishment context constitutes, consequently, a great opportunity to emphasize and try to solve the radon problem.

## 2 Regulation on Indoor Radon

Reference level represents the maximum accepted average annual radon concentration in a residential dwelling. When radon measurements indicate that this level has been exceeded, it is strongly recommended that action is taken to reduce the radon concentration (Synnott and Fenton 2005).

The concept of reference level differs from that of action level. The latter was used in most countries prior to the most recent recommendations of the International Commission on Radiological Protection (ICRP) (2008).

In the UK, the National Radiological Protection Board identified, in 1990, an action level of 200 $Bq/m^3$. Additionally, when more than 1 % of domestic properties in an area of the UK are above the action level, the area is designated as a "radon-affected area" in which regulatory and promotional measures are adopted (NRPB 2008).

A WHO survey of 36 countries found that almost all of them have set reference levels for existing housing of between 200 and 400 $Bq/m^3$. Some countries have

**Table 1** Summary of indoor radon concentration thresholds (Bq/m$^3$) (Bochicchio 2011)

| Organization | Previous/current | | Recent/forthcoming | |
|---|---|---|---|---|
| | Dwellings | Workplaces | Dwellings | Workplaces |
| ICRP | ≤600 | ≤1,500 | ≤300 | |
| WHO | 250 | | 100 | |
| EU | 400 | ≤1,000 | ≤300 | ≤1,000 |

**Table 2** Status of radon situation in several European countries

| Country | Action level for remediation (Bq/m$^3$) | Target level for prevention (Bq/m$^3$) | Status of remediation | | |
|---|---|---|---|---|---|
| | | | Estimated number of dwellings | Exceeding the action level | Already remediated |
| Austria | 400 | 200 | 3,700,000 | 89,000 (2.4 %) | 25 (0 %) |
| Belgium | 400 | 200 | 5,043,000 | 20,000 (0.4 %) | 1,000 (5 %) |
| Czech Republic | 400 | 200 | 3,900,000 | 76,000 (1.9 %) | 4,000 (5.3 %) |
| Finland | 400 | 200 | 2,450,000 | 59,000 (2.4 %) | 4,500 (7.6 %) |
| France | 400 | – | 32,756,000 | 968,500 (3 %) | – |
| Germany | 100 | 100 | 39,900,000 | 1,930,000 (4.8 %) | 1,000 (0.1 %) |
| Greece | 400 | 200 | 5,627,000 | – | – |
| Ireland | 200 | 200 | 1,934,000 | 91,000 (4.7 %) | – |
| Italy | 200 | 200 | 22,000,000 | 902 000(4.1 %) | 500 (0.1 %) |
| Norway | 100 | 100 | 2,274,000 | 427 00(18.8 %) | – |
| Portugal | 400 | 400 | – | 2.6 % | – |
| Spain | – | – | – | – | – |
| Switzerland | 400 | 400 | 4,000,000 | 75,000 (1.9 %) | 500 (0.7 %) |
| UK | 200 | 200 | 23,000,000 | 100,000 (0.4 %) | 15,000 (15 %) |

set different reference levels for new and existing buildings, with lower values for new houses (WHO 2009).

WHO proposes a reference level of 100 Bq/m$^3$ to minimize health hazards due to indoor radon exposure. However, if this level cannot be reached under the prevailing country-specific conditions, the chosen reference level should not exceed 300 Bq/m$^3$.

Table 1 shows how different international organizations recommend very different indoor radon concentration thresholds. However, one thing they have in common, recent and forthcoming thresholds are much lower than the previous ones.

Table 2 presents the different action levels and target levels of the currently used situation in several European countries as well as the status of the radon situation in those countries (Holmegren and Arvela 2012).

The data show that only Germany and Norway have conservative action and target levels (100 Bq/m$^3$) which are in line with the threshold recommended by the WHO. In the remaining countries, two different situations can be identified, the case of Italy, Ireland, and UK that have an action and target levels (200 Bq/m$^3$) below the ICRP threshold and the countries that still have the threshold of 200 Bq/m$^3$ as action level or both, like it happens in Switzerland and Portugal.

# 3 Protection Measures

In the UK, new properties must be fitted with a sump if more than 10 % of the existing properties in an area show readings above the action level. A fan can then be added if subsequent tests reveal that one is needed to further reduce radon levels. Regulations now require that a radon-proof membrane designed to prevent radon entering a property should be installed in new houses built in areas of the UK where 3 % or more of existing properties are above the action level (BRE 1999).

Since 1995, Czech Republic buildings located in radon prone areas must have water proofing membranes placed over the entire surface of the floors and basement walls in contact with the soil. Recent recommendations emphasize that all new homes in England and Wales, regardless of location, be built with radon-proof membranes (Environmental Radon Newsletter 2008).

Some authors (Jiranek and Hulka 2001; Rovenska and Jiranek 2012) mention that the correct selection of both the type and minimal thickness of radon-proof membranes is difficult just because they are influenced by the building and soil characteristics.

The WHO Handbook (2009) summarizes the protection measures as follows:

(a) Active soil depressurization
(b) Passive soil depressurization
(c) Sealing of surfaces
(d) Barriers and membranes
(e) Ventilation of unoccupied spaces
(f) Ventilation of occupied spaces.

Analyses of different measures show that active sub-slab depressurization systems usually are the most effective preventive measure as a stand-alone solution, assuming an airtight construction (Jelle 2012).

Several studies (Synnott et al. 2004; Denman et al. 2005a) have already demonstrated that radon-proof membranes have a significant failure rate. This leads to new homes in which radon levels are above the action level. Therefore, it is important to ensure satisfactory airtightness in the radon barrier toward the building ground, e.g., by avoiding perforations and ensuring sufficient airtightness in joints and feedthroughs.

Different authors address several design details concerning protection measures to reduce indoor radon concentration. Figure 1 shows details for the protection of a suspended concrete floor and also of a ground bearing concrete floor slab.

Arvela (2001) gives details on the use of bitumen felt and elastic sealants to achieve air tightness (Fig. 2a) and also the installation of a perforated pipe to reduce radon pressure (Fig. 2b).

Those authors compared the effectiveness of different protection measures in order to reduce indoor radon concentration (Table 3). They stated that sub-slab piping with an operating fan provides an efficient preventive measure. They also

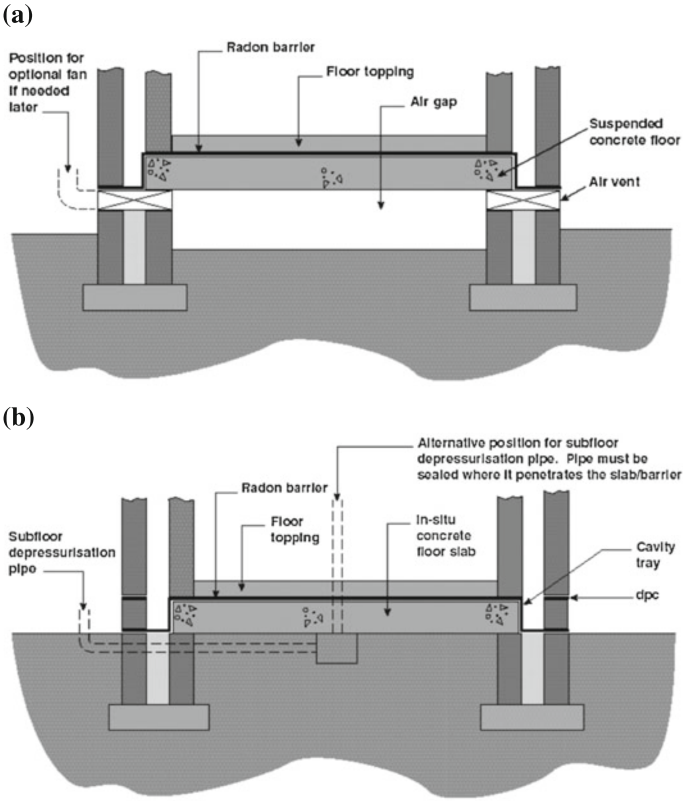


**Fig. 1** Radon protection: **a** to a suspended concrete floor and **b** to a ground bearing concrete floor slab (Scivyer 2001)

mentioned that in 80 % of houses with a sub-slab piping connected to an operating fan, radon concentration was below the action level of 200 Bq/m$^3$. In houses with piping but no fan, however, the corresponding fraction was only 45 %. The corresponding median values of radon concentration in these houses were 55 and 220 Bq/m$^3$, respectively.

They also mentioned that sub-slab piping without a fan had no remarkable effect on radon concentration. Other authors (Arvela et al. 2005) report the development of a new construction for an airtight joint between the foundation wall and the floor slab. In the new sealing practice, bitumen felt will be installed underneath the floor slab in direct contact with the concrete slab (Fig. 3).

Those authors also mention that a group of houses with this new measure located in areas with radon concentration exceeding 200 B/qm$^3$ show low indoor radon concentrations (20–60 Bq/m$^3$).

Groves-Kirkby et al. (2006) mentioned that post-construction remediation using conventional fan-assisted sump technology proved to be extremely effective in

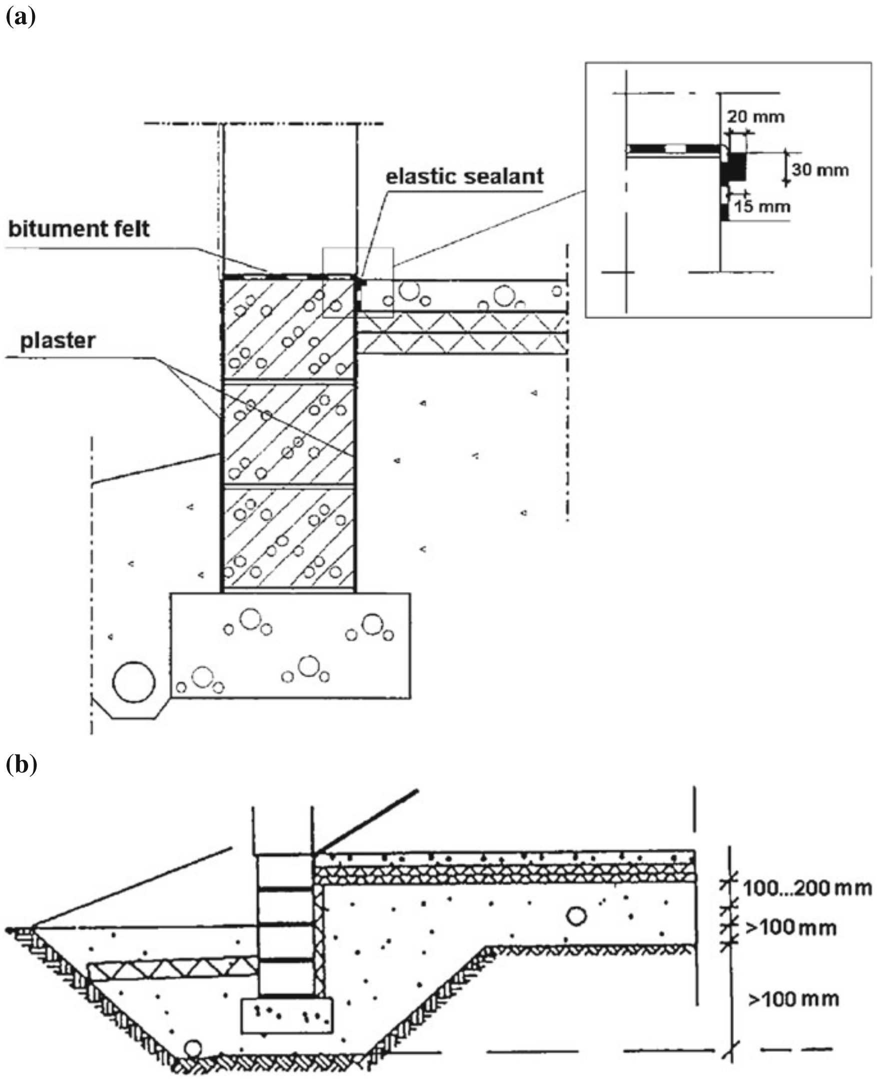


**Fig. 2** Radon protection measures. **a** Sealing of the joint between foundation wall and floor slab, when the foundation wall is made of permeable material. **b** Installation of a suction pipe in the gravel layer (Arvela 2001)

reducing radon concentrations, while the use of radon-barrier membranes installed during construction does not consistently provide adequate radon protection, specifically failing to reduce the internal radon to concentrations below the action level of 200 Bq/m$^3$. The use of soil depressurization systems (SDS) is very effective in reducing radon concentrations although the passive SDS (Fig. 4) is much more cost-effective than mechanical SDS (Abdelouhab et al. 2010).

**Table 3** Median indoor radon concentration and percentage of houses with indoor radon concentration exceeding 200 and 400 Bq/m$^3$, for different preventive measures (Arvela 2001)

| Preventive measure | Number | Median (Bq/m$^3$) | Percentage exceeding (200 Bq/m$^3$) | Percentage exceeding (400 Bq/m$^3$) |
|---|---|---|---|---|
| Sealing of leakages in substructure, slab-on-grade | 31 | 138 | 32 | 10 |
| Slab-on-grade, sealing work, sub-slab piping, no fan | 58 | 155 | 34 | 10 |
| Slab-on-grade, sub-slab piping, no fan | 141 | 220 | 55 | 26 |
| Slab-on-grade, sub-slab piping, fan operating | 21 | 55 | 19 | 10 |
| Crawl space | 20 | 70 | 10 | 5 |
| Edge-thickened slab | 4 | 66 | 0 | 0 |

**Fig. 3** Bitumen felt installed to the joint of foundation wall and floor slab before casting of the floor (Arvela et al. 2005)

Radon averages decrease as the distance from soil increases (Trevisi et al. 2012a), meaning that a simple protection measure could encompass a reduction in the time spent by occupants in the areas closer to the ground. For houses with two or more floors, the rooms must not be located near the ground. Since radon concentration is very dependent on the air change rate (ACH) (Fig. 5), it is important to maintain adequate air ventilation. Of course this means an increase in heating costs. The option for an increase in the ventilation rate must be assessed by a cost-effectiveness analysis. This will be addressed in Sect. 4.

It is also important to maintain a range of temperature and relative humidity that minimized radon levels. A recent investigation (Akbari et al. 2013) showed that for a detached one-floor house, the minimum radon levels were obtained at temperatures between 20 and 22 °C (Fig. 6) and a relative humidity of 50–60 % (Fig. 7).

According to those authors in high indoor temperatures, diffusion mechanism increases and boosts the effect of convection mechanism in radon transport

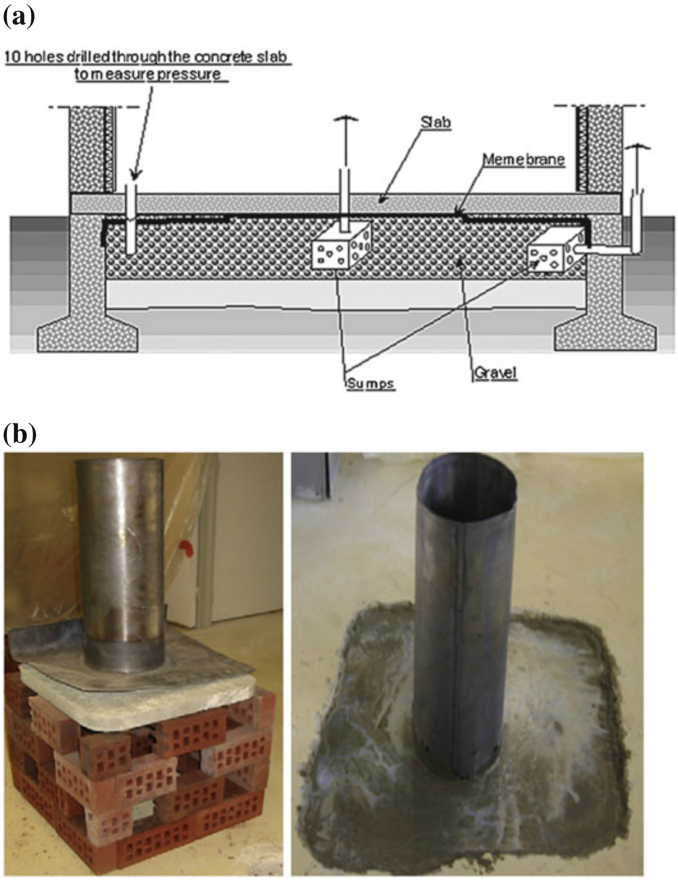
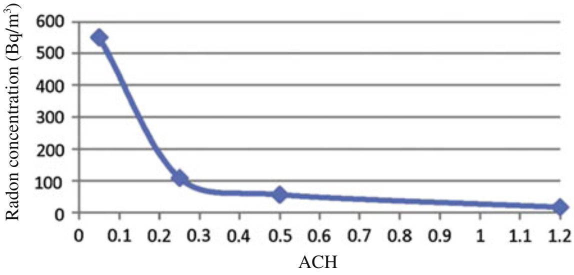


**Fig. 4** Soil depressurization system (*SDS*): **a** schematics and **b** photos (Abdelouhab et al. 2010)

**Fig. 5** Radon concentration versus air change rate (Akbari et al. 2013)



decreasing indoor radon content. Concerning the relative humidity, since radon diffusion coefficient in water ($1.2 \times 10^{-9}$ m$^2$ s) is much smaller than that in air ($1.2 \times 10^{-5}$ m$^2$ s) when relative humidity increases until 65 %, this means that

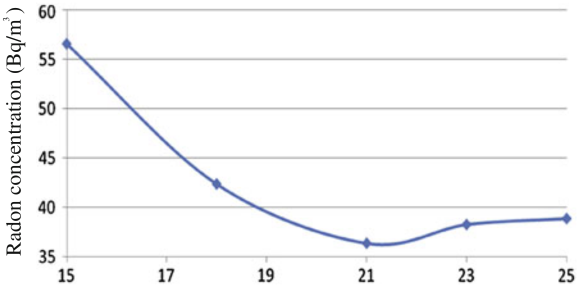


**Fig. 6** Radon concentration versus temperature (Akbari et al. 2013)

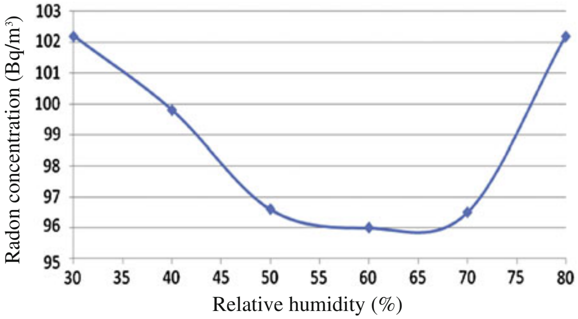


**Fig. 7** Radon concentration versus relative humidity (Akbari et al. 2013)

the water content is higher and the radon concentration decreases. However, for a relative humidity above 65 %, this means that air density also increases, and radon in the room cannot rise upward (Akbari et al. 2013).

## 4 Cost-effectiveness Analysis

Coskeran et al. (2002) used the Garber–Phelps criterion to determine the percentage of householders that must remediate, in a particular area, in order for the radon remediation program to be cost-effective. This criterion states that health programs should be considered cost-effective, for policy purposes, if the cost per life-year gained is less than the double of the average income (Garber and Phelps 1997). These authors state that radon remediation programs will only produce large health gains and be justified on cost grounds, if a higher percentage of householders takes action. They also state that the percentage of properties above the action level is a significant determinant of whether or not a program will produce cost-effective health outcomes in an area. Other authors (Coskeran et al. 2006) show that, for areas with a low percentage of homes with radon concentration above the action level, the more cost-effective course of actions is as follows:

**Table 4** Regulatory regimes (Coskeran et al. 2009)

| Regime | Key elements |
|---|---|
| Option A | • Install membrane as under the current regulations<br>• Test for radon after property built and buyer in possession<br>• Remediate property, if needed, by installing sump and fan<br>• Test to ensure property is below the action level |
| Option B | • Install membrane as under the current regulations<br>• Install sump at the time of construction<br>• Test for radon after property built and buyer in possession<br>• Fit fan to sump if test reading above the action level<br>• Test further to ensure reading below the action level |
| Option C | • Install sump only at the time of construction<br>• Test for radon after property built and buyer in possession<br>• Fit fan to sump if test reading above the action level<br>• Test further to ensure reading below the action level |
| Option D | • No action during construction<br>• Test for radon after property built and buyer in possession<br>• Remediate property, if needed, by installing sump and fan<br>• Test further to ensure reading below the action level |
| Option E | • Install membranes during construction of properties<br>• Install sump when more than 10 % of properties above the action level<br>• No testing of property after construction |

1. construct new homes without protection against radon;
2. upon completion, test all new properties for radon using NRPB protocols;
3. remediate properties above the action level by installing a sump and fan; and
4. retest these properties to verify that they are below the action level and require no additional remediation.

In another study, the same authors (Coskeran et al. 2009) analyzed the cost-effectiveness of several regulatory regimes (Table 4) when compared to the UK current regimes (BRE 1999) already described in the beginning of Sect. 4.

The study showed that all alternative regimes performed acceptably against standard criteria for assessing cost-effectiveness, contrary to the current regime, in which cost-effectiveness remained in doubt.

Denman et al. (2005b) used the European Community Radon Software (ECRS) that permits calculation of individual, rather than population-average risk, to analyze the health benefits accruing from a domestic radon remediation program. The results showed that health benefits accruing from remediation were three times lower than expected, thus confirming that UK current regulations are not very effective in targeting the groups mostly at risk. These groups include smokers and families with larger numbers of children.

Another similar study (Denman et al. 2008) concerning the health benefits analyzed before and after successful remediation using the sump and pump method showed that they range from 7 to 11 % less than that expected. These authors mention that radon emanation from building materials sets a baseline level below which radon levels cannot be reduced by sub-slab depressurization; for the area analyzed, this threshold falls in the range 50–70 Bq/m$^3$.

Jiranek and Rovenska (2010) analyzed the cost-effectiveness of 32 houses and found no significant difference between the types of soil depressurization systems studied and the remaining dose level. These authors mention that "in comparison with enhanced natural ventilation of houses, the cost of additional heating to eliminate the heat losses would exceed the total costs of remediation by soil ventilation eightfold," thus concluding that the application of any type of sub-slab depressurization system is a cost-effective solution.

# 5 Radon from Building Materials

## 5.1 *Masonry and Decorative Materials*

Until very recently, it was generally accepted that only 5 % of the indoor radon concentration was due to building materials (Lao 1990). This is why, for a long time, the scientific community has not dedicated a lot of research efforts on this issue. Radioactivity in building materials has been included in the Construction Products Directive (Pacheco Torgal and Jalali 2011; Pacheco Torgal et al. 2012), but this has still not led to any corresponding standards being adopted by the European Committee for Standardisation.

Recently, a final proposal Directive COM 593 (2011) that lays down basic safety standards for protection against the dangers arising from exposure to ionizing radiation has been disclosed. This proposal mentions a 2-year deadline in order for the member states to make the transposition of the new directive into national law.

Pavlidou et al. (2006) state that the majority of granitic rocks have low radon exhalation rates.

Fokianos et al. (2007) mention that houses with granitic floor tiles have a higher indoor radon concentration when compared to houses without this kind of floor; however, they also mention that the radon concentration is not much higher than anthropogenic radon emissions.

Chen et al. (2010) analyzed 33 different types of granites and mentioned that only two of them had exhalation rates above 200 (Bq/m$^2$d). These findings were confirmed by others (Pavlidou et al. 2006). These authors studied the combined influence of indoor air ventilation rate and granite exhalation rates serving as floor materials, concluding that the highest granite exhalation rate serving as floor material in a place with a low ventilation rate (ACH = 0.3) contributes only with 18 (Bq/m$^3$) to the total concentration (Table 5).

However, to ACH levels near-zero, high exhalation rate granite can effectively be responsible for toxic radioactive concentrations. According to these authors, the radon concentration due to radon exhalation rate is given by

**Table 5** Radom concentration (Bq/m$^3$) due to radon exhalation from floor material according to the ventilation rate (Chen et al. 2010)

| Radon exhalation rate (Bq/m$^2$d) | Air changes per hour (ACH) | | | | |
|---|---|---|---|---|---|
| | 3 | 1 | 0.3 | 0.15 | 0 |
| 5 | 0.03 | 0.09 | 0.3 | 0.6 | 5 |
| 10 | 0.06 | 0.2 | 0.6 | 1.2 | 25 |
| 50 | 0.3 | 0.9 | 3.0 | 5.9 | 123 |
| 100 | 0.6 | 1.8 | 6.0 | 12 | 246 |
| 300 | 1.8 | 5.5 | 18 | 35 | 737 |

$$C = \frac{E \cdot A}{(\lambda_0 + \lambda_v)V}$$

where $E$ is the radon exhalation rate (Bq/m$^2$/d) of the material installed, $A$ the area (m$^2$) of the material exhaling radon, $V$ the air volume (m$^3$) of the room, i.e., the room volume minus the volume occupied by room contents, $\lambda_0$ the radon decay constant (0.181/d), and $\lambda_v$ the air removal rate due to ventilation.

Anjos et al. (2011) analyzed the radon exhalation rate of several Brazilian granites, concluding that 91 % can be used inside homes without any concern in respect to health issues. They based their conclusions on the fact that 91 % of the granites were responsible for an indoor concentration below 300 Bq/m$^3$ for low ventilation conditions and 100 Bq/m$^3$ for good ventilation conditions. These conclusions seem to forget that recent epidemiological findings demonstrate a lung cancer risk from exposure to indoor radon at levels of the order of 100 Bq/m$^3$.

The radon exhalation rate is influenced, not only by the content of radionuclides, but also by the physical properties of the granites (Tuccimei et al. 2006; Shweikani and Raja 2009; Ujic et al. 2010).

Marochi et al. (2011) mentioned that the radon exhalation rate is influenced by the granite porosity and that higher porosity is associated with a higher exhalation rate. Hassan et al. (2011) reported that specimens in a dry condition show an exhalation rate 2–5 times lower when compared to specimens with just 1 % of absorbed water.

Allen et al. (2010) studied the exhalation rate of granite countertops reporting a higher dispersion. These authors mention that the use of small granite specimens does not allow for extrapolations concerning the exhalation rate of the countertops.

Other studies (Sahoo et al. 2011) criticize previous estimations on radon exhalation rate made on construction material specimens, because they under evaluate, by as much as seven times, the exhalation rate of the material when used in a wall. Results are influenced by the size of the specimens and also by the wall thickness.

These authors present a model to help predict the wall exhalation rate. According to Sahoo et al., the solution of 1D radon diffusion equation is commonly used to determine radon flux from building surfaces (such as walls and ceiling). However, one limitation in the 1D solution is the requirement of several input parameters such as radium content, density, and emanation factor and diffusion length of radon in building materials which are not easy to measure.

The new model is based on the analytical solution to 3D radon diffusion equation applicable to a building material system and can be applied to any arbitrary wall thickness irrespective of sample size and any value of radon diffusion length in the building material.

In order to maintain a high quality level of radon measurements, periodical calibration is deemed necessary (Gennaro 2007).

Collignan et al. (2012) reported that the use of a AlphaGuard monitor was first calibrated by the Institut de Radioprotection et de Sûreté Nucléaire IRSN.

For the determination of radon gas concentration, other authors and Abdallah et al. (2012) used a monitor consisting of an aluminum sphere which incorporates a surface barrier detector isolated in a PVC mounting. The monitor calibration has been carried out by introducing a known amount of radon into the sphere. From several calibrations, the average value of the detection efficiency was 720 Bq, which was fairly independent of the flow rate. At 1-h counting time interval, the sensitivity for radon was 1.1 mBq/L.

Sorimachi et al. (2012) made intercomparisons of two types of passive $^{222}$Rn–$^{220}$Rn detectors (commercially available as Raduet and Radopot detectors), developed by the National Institute of Radiological Sciences, Japan (NIRS), using the Physikalisch Technische Bundesanstalt (PTB), Germany, $^{222}$Rn chamber. The experimental uncertainties at the relative standard deviation ranged from 2 to 8 % for the Raduet detectors and 5–13 % for Radopot detectors in $^{222}$Rn concentration at each activity level.

This shows how much the radon still needs further investigations in order to have a clear picture of the real contribution of masonry and decorative materials to indoor radon concentration.

## 5.2 Other Construction Materials

It is believed that, in general, construction materials do not show alarming radioactivity levels (Papaefthmiou and Gouseti 2008; Damla et al. 2011). The same, however, cannot be said about some industrial by-products used for concrete production such as some kind of blast furnace slags and some fly ashes (Table 6).

Since mineral coal contains radionuclides, this means that the fly ashes produced in thermal power plants must be analyzed regarding this parameter (Mahur et al. 2008).

Some studies (Kovler et al. 2005a, b) show that concrete with 60 % cement replacement by fly ash has a radon concentration which is two times higher when compared to control concrete. However, there is not a direct correlation between the concentration and exhalation rates because this parameter is also influenced by the concrete internal structure and thus meaning that it is possible to have a

**Table 6** Typical and maximum activity concentrations in common building materials and industrial by-products used for building materials in Europe (Kovler et al. 2002; Kovler 2009)

| Material | Typical activity concentration (Bq/kg) | | | Maximum activity concentration (Bq/kg) | | |
|---|---|---|---|---|---|---|
| | $^{226}$Ra | $^{232}$Th | $^{40}$K | $^{226}$Ra | $^{232}$Th | $^{40}$K |
| *Construction materials* | | | | | | |
| Concrete | 40 | 30 | 400 | 240 | 190 | 1,600 |
| Lightweight concrete | 60 | 40 | 430 | 2,600 | 190 | 1,600 |
| Ceramic bricks | 50 | 50 | 670 | 200 | 200 | 2,000 |
| Concrete blocks | 10 | 10 | 330 | 25 | 30 | 700 |
| Natural stone | 60 | 60 | 640 | 500 | 310 | 4,000 |
| Natural gypsum | 10 | 10 | 80 | 70 | 100 | 200 |
| *Industrial by-products* | | | | | | |
| Phosphogypsum | 390 | 20 | 60 | 1,100 | 160 | 300 |
| Blast furnace slag | 270 | 70 | 240 | 2,100 | 340 | 1,000 |
| Coal fly ash | 180 | 100 | 650 | 1,100 | 300 | 1,500 |

concrete with a lower concentration but with a more porous structure and therefore with a higher exhalation rate (Keller et al. 2001).

Taylor-Lange et al. (2012) show that concrete floors made with 25 wt% fly ash resulted in 90 % of the simulated homes having double the dose compared to the control concrete (2.3 Bq/m$^3$). This is not only a problem for new buildings but also in the refurbishment context that often includes the replacement of wood floors by concrete-based slabs. Recent studies (Trevisi et al. 2012b) based on 2,727 concrete specimens from 23 European countries show very different radon concentrations and some as high as 1,450 Bq/kg for the radionuclide $^{40}$K in Portugal, thus meaning that some countries should have a special attention to this subject.

## 6 Conclusions

Radon constitutes the second cause of lung cancer in the general population, the first being smoking. In the past, it was accepted that only radon concentrations above 400 Bq/m$^3$ could constitute a health risk; however, recent epidemiological findings demonstrate lung cancer risk from exposure to indoor radon at levels in the order of 100 Bq/m$^3$. It is estimated that millions of residents in Europe live in homes which have radon concentrations above 200 Bq/m$^3$; however, the majority of the public seems to consider the health risks involved from exposure to radon as being negligible. Still recent regulation continues to allow high indoor radon concentrations. The recent agenda on building energy efficiency refurbishment can provide the right context in order to raise the radon problem once again. Using post-construction, remediation like SDS seems to be more cost-effective than the use of protection measures installed during construction like radon-barrier membranes which have a significant failure rate. Since radon concentration is very dependent on the (ACH), it is important to maintain adequate air ventilation. It is also important to maintain a range of temperature and relative humidity that minimized radon levels. Several investigations have attempt to estimate the contribution of building materials to the indoor radon concentration; however, while some used very small specimens, the others used specimens with different water content, which prevents comparisons between the different studies. Some authors criticize previous estimations on radon exhalation rate made on construction material specimens, because they under evaluate, by as much as seven times, the exhalation rate of the material when used in a wall. Further investigations are still needed in order to have a clear picture of the real contribution of masonry and decorative materials to indoor radon concentration. Nevertheless, it would be advisable that building refurbishment toward nearly zero energy would encompass the removal of high exhalation rate granite when used as decorative materials.

## References

Abdallah AM, Mohery M, Yaghmour SJ, Alddin SH (2012) Radon exhalation and natural radiation exposure in low ventilated rooms. Radiat Phys Chem (in press). doi:10.1016/j.radphyschem.2012.07.004

Allen J, Minegishi T, Myatt T, Stewart J, McCarthy J, MacIntosh D (2010) Assessing exposure to granite countertops part 2: Radon. J Eposure Sci Environ Epidemiol 20:263–272. doi:10.1038/jes.2009.43

Antignani S, Carelli V, Cordedda C, Zonno F, Ampollini M, Carpentieri C, Venoso G, Bochicchio F (2012) An affordable proxy of representative national survey on radon concentration in dwellings: design, organisation and preliminary evaluation of representativeness. Radiat Meas 1–5. doi:10.1016/j.radmeas.2012.06.015

Akbari K, Mahmoudi J, Ghanbari M (2013) Influence of indoor air conditions on radon concentration in a detached house. J Environ Radioact 116:166–173. doi:10.1016/j.jenvrad.2012.08.013

Arvela H (2001) Experiences in radon-safe building in Finland. Sci Total Environ 272:169–174. doi:10.1016/S0048-9697(01)00688-X

Arvela H, Bergman J, Yrjölä R, Kurnitski J, Matilainen M, Järvinen P (2005) Developments in radon-safe building in Finland. Radioact Environ 7:618–623. doi:10.1016/S1569-4860(04)07075-5

Abdelouhab M, Collignan B, Allard F (2010) Experimental study on passive soil depressurisation system to prevent soil gaseous pollutants into building. Build Environ 45:2400–2406. doi:10.1016/j.buildenv.2010.05.001

Anjos R, Ayub J, Cid A, Cardoso R, Lacerda T (2011) External gamma-ray dose rate and radon concentration in indoor environments covered with Brazilian granites. J Environ Radioact 102:1055–1061. doi:10.1016/j.jenvrad.2011.06.001

Arthur AT (2003) Lung cancer risk from exposure to radon in the home: are policies in the United Kingdom appropriate to the risk? Healthy house: promoting good health. Univ Warwick, Coventry

Barros-Dios J, Ruano-Ravina A, Pérez-Ríos M, Castro-Bernárdez M, Abal-Arca J, Tojo-Castro M (2012) Residential radon exposure, histologic types, and lung cancer risk. A case–control study in Galicia, Spain. Cancer Epidemiol Biomarker Prev 21:951–958

Bochicchio F, Antignani S, Venoso G, Forastiere F (2012) Quantitative evaluation of the lung cancer deaths attributable to residential radon: a simple method and results for all the 21 Italian Regions. Radiat Meas 1–6. doi:10.1016/j.radmeas.2012.09.011

Bochicchio F (2011) The newest international trend about regulation of indoor radon. Radiat Prot Dosim 146:2–5. doi:10.1093/rpd/ncr093

Bradley EJ, Lomas PR, Green BMR, Smithard J (1997) Radon in dwellings in England: 1997 review. National Radiological Protection Board report (NRPB) R293, Chilton, Oxon

Bräuner E, Andersen C, Andersen H, Gravesen P, Lind M, Ulbak K, Hertel O et al (2010) Is there any interaction between domestic radon exposure and air pollution from traffic in relation to childhood leukemia risk? Cancer Causes Control 21:1961–1964. doi:10.1007/s10552-010-9608-4

Bräuner E, Andersen C, Sorensen M, Andersen Z, Gravesen P, Lind M, Ulbak K, Hertel O et al (2012) Residential radon and lung cancer incidence in a Danish cohort. Environ Res 118:130–136. doi:10.1016/j.envres.2012.05.012

Coskeran T, Denman A, Phillips P, Gillmore G (2002) A critical comparison of the cost-effectiveness of domestic radon remediation programmes in three counties of England. J Environ Radioact 62:129–144

Chauhan V, Howland M, Mendenhall A, O'Hara S, Stocki T, McNamee J, Wilkins R (2012) Effects of alpha particle radiation on gene expression in human pulmonary epithelial cells. Int J Hyg Environ Health 215:522–535. doi:10.1016/j.ijheh.2012.04.004

Chen J, Rahman N, Atiya I (2010) Radon exhalation from building materials for decorative use. J Environ Radioact 101:317–322. doi:10.1016/j.jenvrad.2010.01.005

Chow Y, Green B, Zhang W, Meara J (2007) Radon health equity audit—is the radon programme fair? Health prot 2007, University of Warwick

Coskeran T, Denman A, Phillips P, Tornberg R (2006) A cost-effectiveness analysis of radon protection methods in domestic properties: a comparative case study in Brixworth, Northamptonshire, UK. J Environ Radioact 91:73–89. doi:10.1016/j.jenvrad.2006.08.005

Coskeran T, Denman A, Phillips P, Tornberg R (2009) A critical evaluation of the cost-effectiveness of radon protection methods in new homes in a radon Affected Area of England. Environ Int 35:943–951. doi:10.1016/j.envint.2009.04.004

Collignan B, Lorkowski C, Améon R (2012) Development of a methodology to characterize radon entry in dwellings. Build Environ 57:176–183. doi:10.1016/j.buildenv.2012.05.002

COM (2011) 593, Proposal for a council directive laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation

Clement C (2010) Assessment of the detriment from exposure to radon and its progeny. Ann ICRP 40:41–47

Damla N, Cevik U, Kobya A, Celik A, Celik N, Yıldırım I (2011) Assessment of natural radioactivity and mass attenuation coefficients of brick and roofing tile used in Turkey. Radiat Meas 46:701–708. doi:10.1016/j.radmeas.2011.06.004

Denman A, Groves-Kirkby C, Coskeran T, Parkinson S, Phillips P, Torneberg R (2005) Evaluating the health benefits and cost-effectiveness of the radon remediation programme in domestic properties in Northamptonshire, UK. Health Policy 73:139–150. doi:10.1016/j.healthpol.2004.11.005

Denman A, Phillips P, Groves-Kirkby C, Crockett R (2005a) Do radon-proof membranes reduce radon levels adequately in new houses? In: Proceedings of the seventh SRP international symposium; Cardiff, pp 12–17

Denman A, Phillips P, Torneberg R, Groves-Kirkby C (2005b) Analysis of the individual health benefits accruing from a domestic radon remediation programme. J Environ Radioact 79:7–23. doi:10.1016/j.jenvrad.2004.05.011

Denman A, Briggs D, Allison C, Groves-Kirkby C, Phillips P, Crockett R (2008) A detailed evaluation of the individual health benefits arising in a domestic property following radon remediation e a case-study in Northamptonshire, UK. J Environ Radioact 99:1175–1184. doi:10.1016/j.jenvrad.2008.01.018

Dinua A, Cosma C, Sainz C, Poncelab L, Vasiliniuc S (2009) Lung cancer attributable to indoor radon exposures in two radon—Prone Areas, Ştei (Romania) and Torrelodones (Spain). In: Proceedings of the 1131 physics conference, TIM-08, AIP conference, Timisoara, Romania, pp 175–180

Environmental Radon Newsletter (2008) Health Protection Agency Board gives advice on radon measures for new homes. Autumn 56, Chilton, Oxon, UK

European Union (2003) Directive 2002/91/EC of the European Parliament and of the Council of December 16th, 2002 on the energy performance of buildings. Official J Eur Commun, 4 Jan 2003

European Union (2010) Directive 2010/31/EU of the European Parliament and of the Council of May 19th, 2010 on the energy performance of buildings (recast). Official J Eur Union, 18 June 2010

Field R, Duport P, Hendee W (2003) Exposure to residential radon causes lung cancer. Med Phys 30:485–488. doi:10.1118/1.1562943

Fokianos K, Sarrou I, Pashalidis I (2007) Increased radiation exposure by granite used as natural tiling rock in Cypriot houses. Radiat Meas 42:446–448. doi:10.1016/j.radmeas.2007.02.001

Garber A, Phelps C (1997) Economic foundations of cost-effectiveness analysis. J Health Econ 16:1–31. doi:10.1016/S0167-6296(96)00506-1

Gennaro V (2007) Development of calibration techniques for active and passive radon detectors. PhD in fundamental and applied physics, University of Naples

Groves-Kirkby C, Denman A, Phillips P, Crockett R, Woolridge A, Tornberg R (2006) Radon mitigation in domestic properties and its health implications—a comparison between during-construction and post-construction radon reduction. Environ Int 32:435–443. doi:10.1016/j.envint.2005.10.004

Hassan N, Ishikawa T, Hosoda M, Iwaoka K, Sorimachi A, Sahoo S, Janik M, Kranrod C, Yonehara H, Fukushi M, Tokonami S (2011) The effect of water content on the radon emanation coefficient for some building materials used in Japan. Radiat Meas 46:232–237. doi:10.1016/j.radmeas.2010.11.006

Holmgren O, Arvela H (2012) Assessment of current techniques used for reduction of indoor radon concentration in existing and new houses in European countries. STUK, A251, Radiation and Nuclear Safety Authority-STUK, Helsinki

International Commission on Radiological Protection (2008) Recommendations of the ICRP. ICRP Publication 103

Jelle B (2012) Development of a model for radon concentration in indoor air. Sci Total Environ 416:343–350. doi:10.1016/j.scitotenv.2011.11.052

Jiranek M, Hulka J (2001) Applicability of various insulating materials for radon barriers. Sci Total Environ 272:79–84. doi:10.1016/S0048-9697(01)00668-4

Jiranek M, Rovenska K (2010) Limited applicability of cost–effectiveness and cost–benefit analyses for the optimization of radon remedial measures. J Hazard Mater 182(2010):439–446. doi:10.1016/j.jhazmat.2010.06.051

Krewski D, Lubin J, Zielinski J, Alavanja M, Catalan V, Field R, Klotz J, Létourneau E, Lynch C, Lyon J, Sandler D, Schoenberg J, Steck D, Stolwijk J, Weinberg C, Wilcox H (2006) A combined analysis of North American case-control studies of residential radon and lung cancer. J Toxicol Environ Health A 69:533–597. doi:10.1080/15287390500260945

Kovler K, Haquin G, Manasherov V, Neman E, Lavi N (2002) Natural radionuclides in building materials available in Israel. Build Environ 37:531–537. doi:10.1016/S0360-1323(01)00048-8

Kovler K (2009) Radiological constraints of using building materials and industrial by-products in construction. Constr Build Mater 23:246–253. doi:10.1016/j.conbuildmat.2007.12.010

Kovler K, Perevalov A, Steiner V, Metzger L (2005a) Radon exhalation of cementitious materials made with coal fly ash: Part 1—scientific background and testing of the cement and fly ash emanation. J Environ Radioact 82:321–334. doi:10.1016/j.jenvrad.2005.02.004

Kovler K, Perevalov A, Steiner V, Metzger L (2005b) Radon exhalation of cementitious materials made with coal fly ash: Part 2—testing hardened cement fly ash pastes. J Environ Radioact 82:335–350. doi:10.1016/j.jenvrad.2005.02.003

Keller G, Hoffmann B, Feigenspan T (2001) Radon permeability and radon exhalation of building materials. Sci Total Environ 272:85–89. doi:10.1016/S0048-9697(01)00669-6

Lao K (1990) Controlling indoor radon: measurement, mitigation, and prevention. Van Nostrand Reinhold, New York

Marocchi M, Righi S, Bargossi G, Gasparotto G (2011) Natural radionuclides content and radiological hazard of commercial ornamental stones: An integrated radiometric and mineralogical-petrographic study. Radiat Meas 46:538–545. doi:10.1016/j.radmeas.2011.03.017

Mahur A, Kumar R, Mishra M, Sengupta D, Prasad R (2008) An investigation of radon exhalation rate and estimation of radiation doses in coal and fly ash samples. Appl Radiat Isot 66:401–406. doi:10.1016/j.apradiso.2007.10.006

NRPB (2008) National Radiological Protection Board (NRPB). Statement on human exposure to radon in homes. Doc NRPB 1990, 1, 17–32

NRPB; 1997 BRE (Building Research Establishment) (1999) Radon: guidance on protective measures for new dwellings 1999 edition. BRE report BR211. BRE, Garston, Herts, UK

Pacheco Torgal F, Jalali S (2011) Toxicity of building materials. A key issue in sustainable construction. Int J Sustain Eng 4:281–287. doi:10.1080/19397038.2011.569583. Taylor & Francis

Pacheco Torgal F, Jalali S, Fucic A (2012) Toxicity of Building Materials. Woodhead Publishing Limited, Cambridge, p 480

Pavlidou S, Koroneos A, Papastefanou C, Christofides G, Stoulos S, Vavelides M (2006) Natural radioactivity of granites as building materials. J Environ Radioact 89:48–60. doi:10.1016/j.jenvrad.2006.03.005

Papaefthmiou H, Gouseti O (2008) Natural radioactivity and associated radiation hazards in building materials used in Peloponnese, Greece. Radiat Meas 43:1453–1457. doi:10.1016/j.radmeas.2008.03.032

Phillips P, Fraser J, Denman A (2000) Effectiveness of secondary radon protection in Northamptonshire houses. Environ Manag Health 11(4):337–352. doi:10.1108/09566160010372752

Power A (2008) Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? Energy Policy 36:4487–4501. doi:10.1016/j.enpol.2008.09.022

Ryan D, Kelleher C (1999) A survey of householders' mitigation strategy. Eur J Pub Health 9:62–64. doi:10.1093/eurpub/9.1.62

Rovenska M, Jiranek M (2012) Radon diffusion coefficient measurement in waterproofings—A review of methods and an analysis of differences in results. Appl Radiat Isot 70:802–807. doi:10.1016/j.apradiso.2012.01.002

Sethi T, El-Ghamry M, Kloecker G (2012) Radon and lung cancer. Clin Adv Hematol Oncol 10:157–164

Shweikani R, Raja G (2009) Radon exhalation from some finishing materials frequently used in Syria. Radiat Meas 44:1019–1023. doi:/10.1016/j.radmeas.2009.10.034

Synnott H, Fenton D (2005) An evaluation of radon reference levels and radon measurement techniques and protocols in European countries. European Radon Research and Industry Collaborative Concerted Action (ERRICCA2), European Commission Contract (FIRI-CT-2001-20142)

Synnott H, Pollard D, Colgan P, Fenton D (2004) A survey of the impact of amending building regulations on radon concentrations in Irish homes. In: Proceeding of the 11th Congress of the International Radiation Association (IRPA11) Madrid

Scivyer C (2001) Radon protection for new buildings: a practical solution from the UK. Sci Total Environ 272:91–96. doi:org/10.1016/S0048-9697(01)00670-2

Sahoo B, Sapra B, Gaware J, Kanse S, Mayya Y (2011) A model to predict radon exhalation from walls to indoor air based on the exhalation from building material samples. Sci Total Environ 409:2635–2641. doi:10.1016/j.scitotenv.2011.03.031

Sorimachi A, Ishikawa T, Tokonami S (2012) Performance test for radon measuring instruments using radon chamber at PTB. Appl Radiat Isot 10:994–998. doi:10.1016/j.apradiso.2012.02.100

Taylor-Lange S, Stewart J, Juenger M, Siegel J (2012) The contribution of fly ash toward indoor radon pollution from concrete. Build Environ 56:276–282. doi:10.1016/j.buildenv.2012.03.009

Trevisi R, Leonardi F, Simeoni C, Tonnarini S, Veschetti M (2012a) Indoor radon levels in schools of South-East Italy. J Environ Radioact 112:160–164. doi:10.1016/j.jenvrad.2012.05.030

Trevisi R, Risica S, D'Alessandro M, Paradiso D, Nuccetelli C (2012b) Natural radioactivity in building materials in the European Union: a database and an estimate of radiological significance. J Environ Radioact 105:11–20. doi:10.1016/j.jenvrad.2011.10.001

Tuccimei P, Moroni M, Norcia D (2006) Simultaneous determination of $^{222}$Rn and $^{220}$Rn exhalation rates from building materials used in Central Italy with accumulation chambers and a continuous solid state alpha detector: Influence of particle size, humidity and precursors concentration. Appl Radiat Isot 64:254–263. doi:10.1016/j.apradiso.2005.07.016

Ujic P, Celikovic I, Kandic A, Vukanac I, Durasevic M, Dragosavac D, Zunic Z (2010) Internal exposure from building materials exhaling $222^{\mathrm{Rn}}$ and $220^{\mathrm{Rn}}$ as compared to external exposure due to their natural radioactivity content. Appl Radiat Isot 68:201–206. doi:10.1016/j.apradiso.2009.10.003

Veloso B, Nogueira J, Cardoso M (2012) Lung cancer and indoor radon exposure in the north of Portugal—An ecological study. Cancer Epidemiol 36:e26–e32. doi:10.1016/j.canep.2011.10.005

Wheeler B, Allen J, Depledge M, Curnow A (2012) Radon and skin cancer in southwest England: an ecologic study. Epidemiol 23:44–52. doi:10.1097/EDE.0b013e31823b6139

WHO (2009) WHO Handbook on indoor radon: a public health perspective. World Health Organization, Geneva 27, Switzerland

Xing Y, Hewitt N, Griffiths P (2011) Zero carbon buildings refurbishment—A hierarchical pathway. Renew Sustain Energy Rev 15:3229–3236. doi:doi.org/10.1016/j.rser.2011.04.020

# Ventilation: Thermal Efficiency and Health Aspects

**J. Laverge**

**Abstract** This chapter will focus on the performance of ventilation, both in reducing adverse effects of indoor air on building occupants and in reducing the energy required for this. The first section of the chapter elaborates on the adverse effects stemming from airborne pollution: why do we need fresh air? The next section than explores the specific merits and limitations of ventilation as a strategy to renew air, while the last section focuses on the different ventilation concepts and their performance. The main focus in that section is on technologies that allow to reduce ventilation heat loss without increasing the exposure of occupants to airborne pollutants, more specifically air-to-air heat exchangers, exhaust air heat pumps (EAHP) and demand-controlled ventilation.

## 1 Airborne Pollutants

The very first question in constructing a framework to assess the performance of ventilation self-evidently asks for the goal of ventilation. What do we hope to achieve by ventilating? And why? Since ventilation is nothing else than replacing the air in a room with new air from outside the room, its effect can be no other than making the indoor air more like the outdoor air. The fact that this is desirable implies that indoor air and outdoor air are different and that there are either positive effects associated with exposure to outdoor air or adverse effects associated with exposure to indoor air. In other words, indoor air is polluted.

There are a large number of pollutants typically found in indoor air, and new pollutants are introduced at an astounding rate (Weschler 2009). The properties of these pollutants depend on their physical nature, in which the two main categories

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are gases (Wu et al. 2011) and particulates (Wheeler et al. 2011). The distribution of both is governed by the general airflow field in interaction with local sources and sinks. In addition to that, gravity will cause particulates to settle. This effect is proportional to the size of the particulate (Cuccia et al. 2013), with the smallest particulates acting more or less as gases.

Gases can be both inorganic (Pacheco Torgal 2012) and organic (Hun et al. 2010) in nature, while particulates usually have complex chemical compositions and often contain biological agents such as bacteria and viruses (Chang and Chou 2011). In both categories, the abundant presence of other pollutants and boundary conditions such as temperature and humidity levels can affect the stability of the pollutants (Weschler and Nazaroff 2008) and trigger secondary pollutant formation in the air itself (Corsi et al. 2007; Huang et al. 2011).

## *1.1 Effects*

The mostly adverse effects of airborne pollutants have been the topic of numerous studies over the last decades. They can be divided into three main categories: effects on health, effects on productivity and effects on comfort. With respect to health effects, there is a large grey zone as to what effects should be included or not. In the overview of the reported effects below, all effects that relate to short-term direct effects, such as headache, dry or burning sensation, usually grouped under the term ‘sick building syndrome’, are listed as comfort effects.

### 1.1.1 Health Effects

WHO has prioritized a number of inadequate housing conditions based on their associated burden of disease, expressed in disability-adjusted life years (DALYs) (Braubach and Jacobs 2011), including airborne agents such as dampness, radon, second-hand smoke, carbon monoxide and formaldehyde. Ventilation rates are negatively correlated with the prevalence of inflammation, respiratory infections, asthma symptoms, short-term sick leave and allergic manifestations (Sundell et al. 2011; Wargocki et al. 2002b). In these studies, ventilation rate is used as a proxy for overall pollutant concentration. For a discussion on epidemiological research focused on the health effects of exposure to specific pollutants, “A Multiple-Case Study of Passive House Retrofits of School Buildings in Austria”.

### 1.1.2 Productivity Effects

A series of independent studies has shown a positive relation between student’s academic performance, across different lesson subjects, and the ventilation rate in the class room, both on intervention studies (Bakó-Biró et al. 2012; Wargocki and

Wyon 2007) as in epidemiological studies (Haverinen-Shaughnessy et al. 2011; Lee et al. 2012b). Particle filtration in the classroom did not have a similar effect (Wargocki et al. 2008).

Similar effects were observed for office workers (Seppänen et al. 2006), both for simple, repetitive tasks (Wargocki et al. 2002a) and for more complex strategic decision making (Satish et al. 2012). Although the effect is rather small, a few % of productivity gain, the economic value of that increase in productivity is much higher than the cost of increased ventilation (Fisk et al. 2012; Wargocki and Djukanovic 2005)

### 1.1.3 Comfort Effects

Ventilation flow rates, as a proxy for pollutant concentrations, have been shown to improve the perceived quality of the indoor air (Fanger 1988; Frontczak et al. 2012) as well a number of acute physiological complaints such a dry eyes, blinking rate, dry throat, head ache usually grouped under the term 'sick building syndrome' (Seppanen and Fisk 2004). The correlation fades at flow rates higher than 25 l/s/person.

Some of these symptoms were attributed to specific pollutant types, such as human metabolites (Claeson et al. 2009) or volatile organic compound (VOC) emissions from common building materials (Johnsen et al. 1991; Gminski et al. 2011).

Occupants have reported discomfort at excessive humidity levels, especially in hot conditions (Toftum et al. 1998a; Toftum et al. 1998b), and there are some early indications that high pollution loads have an impact on the quality of sleep and dreaming (Schredl et al. 2009; Laverge et al. 2012).

Other parameters, such as temperature, acoustics and air speed, definitely influence occupant comfort, but are not directly related to the reduction in pollutant levels, which is considered the primary goal of ventilation in this chapter, and are therefore not discussed further.

## *1.2 Sources*

Within the indoor built environment, the main sources of the pollutants associated with adverse effects can be grouped in three categories: the building itself, and more specifically the building materials used in it, the activities of the building occupants inside the building in general or in specific locations of the building and pollutants coming from the outside environment penetrating into the indoor environment. In the following paragraphs, these categories are each discussed more in detail.

### 1.2.1 Materials

Part of the discomfort caused by VOCs in offices can be traced back to emissions from building materials (Fanger et al. 1988) and typical plastic finishes of appliances (Kowalska and Gierczak 2012). Even materials concealed behind finishing materials can emit pollutants to the space (Hayashi and Osawa 2008). Wood-based panels have become notorious for emitting formaldehyde (Gminski et al. 2011; Yu and Kim 2012). In addition to the release of their primary chemical compounds to the space, ozone deposition on building materials can trigger an important release of secondary pollutants (Lamble et al. 2011; Toftum et al. 2008). Desorption of previously sorbed chemicals similar causes space surfaces to act as secondary sources (Ongwandee and Sawanyapanich 2012; Weschler and Nazaroff 2008). Stony materials and rock bed terrain are known sources of radon and are extensively discussed in toxicity issues: radon“ State-of-the-art on Retrofit Strategies Selection Using Multi-Objective Optimization and Genetic Algorithms”.

In particular important for the residential context, mattresses have been shown to be important sources of VOCs (Hillier et al. 2009; Hoffmann and Schupp 2009) or SVOCs (Kemmlein et al. 2003) and act incubators for house dust mites (Wu et al. 2012; Ucci et al. 2011).

Typical for material emissions is that they show large initial source strengths, decreasing over time (Marion et al. 2011; Han et al. 2012). The emissions from building materials are not only dependent on the (chemical) composition of the materials, but are also affected by the boundary conditions in the space, increasing with temperature and especially relative humidity (Fang et al. 1999; Lee and Kim 2012; Wolkoff 1998, Xu and Zhang).

Hygroscopic materials, especially cellulose-based ones, are prone to the development of fungi in long-lasting high humidity conditions (Haverinen-Shaughnessy 2012; Vereecken and Roels 2012).

### 1.2.2 Activities

One of the most significant sources of a broad range of pollutants indoors is fire in all its forms, be it tobacco smoking (Petrick et al. 2011; Butz et al. 2011), the use of cooking (Buonanno et al. 2009; Kabir and Kim 2011; Wan et al. 2011) or heating (Schmidl et al. 2011; Kinsey et al. 2012) appliances or the burning of candles and incense (Stabile et al. 2012; Derudi et al. 2012), all of them are significant sources of particles, VOCs, nitrogen oxides and carbon monoxide. In developing countries, these activities are the primary sources of indoor pollution and especially women are exposed to them (Carter et al. 2012; Baumgartner et al. 2011). Although emissions from combustion engines are usually considered outdoor sources, the tendency to have attached garages introduces typical gasoline-related pollutants such as MTBE indoors (Hun et al. 2011; Nirvan et al. 2012).

In addition to the kitchen, the bathroom is a room where a lot of pollutant producing activities are concentrated, ranging from bathroom use (odours) and showering (moisture) to the intensive use of cosmetics and cleaning products (VOCs) (Kwon et al. 2008; Steinemann et al. 2011; Moran et al. 2012). Likewise, as with material emissions, emissions from household products may trigger secondary chemical reactions (Coleman et al. 2008; Updyke et al. 2012).

Building activities (Kumar et al. 2012) and painting (Celebi and Vardar 2008) are often large temporary sources. In office environments, large amounts of particles are released by laser printers (Salthammer et al. 2012; Jayaratne et al. 2012; Byeon and Kim 2012). The operation of building services, such as HVAC unit, can resuspend previously deposited particles (Wang et al. 2012). Ill-conceived or ill-maintained building services can also become sources of biological contaminants such as odours, VOCs, mould spores (Clausen 2004; Schleibinger and Rüden 1999) and Legionella bacteria (Cooper et al. 2004; Stout and Muder 2004).

The occupants themselves are sources of carbon dioxide, moisture, bio-effluents, bacteria, viruses, etc. (Gao and Niu 2006; Hathway et al. 2011; Olmedo et al. 2012; Zhang et al. 2011b). Due to the movement of the occupants, these pollutants are usually dispersed throughout the entire building (Choi and Edwards 2012; Spitzer et al. 2010; Wang and Chow 2011) and often continuously resuspended (Stranger et al. 2008). Particularly high exposures can be found in episodes of (unintended) inter-occupant contact, such as cough or sneeze (Redrow et al. 2011). Self-evidently, overcrowding increases the intensity of these sources (Firdaus and Ahmad 2012).

### 1.2.3 Outdoor Environment

Although the basic idea of ventilation is that the outdoor air is less polluted than the indoor air, some pollutants are mainly produced in the outdoor environment, e.g. traffic-related emissions and emissions from industrial processes. Other, even typically indoor, pollutants may not have sources in a specific building, but are found in the ambient air (Longinelli et al. 2011). These pollutants are therefore brought into the indoor space through air exchange with the outdoor environment (Sangiorgi et al. 2013; Hodas et al. 2012). Typical determinants of outdoor pollution levels are of course the proximity (Amato et al. 2011) and timing of the outdoor sources (Menut et al. 2012; Haas et al. 2013), such as locations near busy traffic on rush hours (Lim et al. 2011; Lobscheid et al. 2012) or dense cities (Lu et al. 2011), but modifying factors such as meteorology (Liu et al. 2012) and the proximity of other buildings can have a significant impact on indoor concentrations (Mavroidis et al. 2012).

## 2 Exposure Risk Management Strategies

A number of approaches can be adopted to avoid the adverse effects caused by exposure indoors. Such risk management strategies include reducing the strength of known sources, local exhaust around known sources, eliminating airborne pollutants by filtration or catalytic activity, dilution of pollutant concentrations by bulk ventilation or alerting occupants in case of alarming concentrations.

## 2.1 Source Control

The most effective way to reduce exposure is preventing the release of the pollutants in the indoor environment. This approach can be applied effectively for a wide range of sources. Through the careful selection of components, emissions from common building materials can be reduced by a factor 10 (Lee et al. 2012c; Kurnitski and Seppanen 2008). Regular duct cleaning prevents resuspension of accumulated dust by HVAC operation (Zuraimi 2010; Zuraimi et al. 2012). Resuspension can also be avoided by careful surface design (China and James 2012). The selection of well-designed cooking appliances and their adequate use can reduce particle and carbon monoxide exposure by more than half (Singh et al. 2012; L'Orange et al. 2012). Maintaining elevated water temperatures and avoiding stagnation throughout the distribution system stops Legionella development and kills viable Legionella bacteria present in the system (Geary 2000; Turner 2004). Self-evidently, banning polluting activities such as indoor smoking, candle burning eliminate the associated primary sources (Gleich et al. 2011; Madureira et al. 2012). The entry of outdoor pollutants and radon can be mitigated by improved air tightness (Santos et al. 2011) and pressure management (Chen et al. 2011; Hyttinen et al. 2011).

## 2.2 Local Exhaust

If a polluting activity is the purpose of the space, effective source control through banning the activity is not an option. Local concentrated exhaust, however, can in such a case prevent the spread of the produced pollutants to other parts of the space or building (Inthavong et al. 2009; Kim et al. 2012). In residential settings, the application of this principle to kitchens and bathrooms is widespread and very effective (Tung et al. 2009; Tung et al. 2010).

## 2.3 Air Cleaning

In case, the sources are of a more diffuse nature or cannot be localized easily and in case of outdoor sources, cleaning the air of the pollutants present in it can be considered. This can achieved by actively filtering the air (Bekö et al. 2008; Zhang et al., Zuraimi et al. 2011; Sidheswaran et al. 2012), either locally or on building scale, although the technology available for this is usually only able to target a specific type of pollutants.

Organic pollutants can be targeted by passive degradation at catalytically active surfaces. Concerning with this technology include long-term effectiveness, the accessibility of the bulk air to these surfaces in natural convection regimes and formation of hazardous secondary products. Most products also require incident UV radiation to activate the catalytic effect (Cros et al. 2012; Kolarik and Toftum 2012; Darling et al. 2012; Destaillats et al. 2012).

### *2.4 Dilution*

A further strategy to reduce indoor pollutant levels is diluting the indoor air with fresh air until acceptable concentrations are reached (Deng and Kim 2007, Offermann). If the fresh air is targeted to the occupant, this is basically the inverse of local exhaust. This approach can even be adopted in outdoor environments (Mirzaei and Haghighat 2010). A precondition for this strategy is of course the availability of fresh air with lower pollution levels than those present in the indoor air.

### *2.5 Alarms*

Certain acute airborne health threats, such as carbon monoxide poisoning, require to alert and evacuate the occupants immediately. In such a case, the sensor has to target the right pollutants (Abbassi et al. 2012; Wong et al. 2006) and be well positioned to detect the threat as soon as possible (Mui et al. 2006). In addition to that, signal processing and integrated modelling can be used to locate the pollution source, allowing for instance to select an appropriate evacuation scenario (Bastani et al. 2012; Chen and Wen 2012).

## 3 Ventilation: The Backup Plan

The order of the mitigation strategies listed above reflects their effectiveness in reducing the risk of incurring adverse effects from exposure to airborne pollution indoors. The risk chain extends from the actual intake of a pollutant by the occupant to the concentration of the pollutant in the indoor air and eventually to the sources of these pollutants. The earlier in this chain the risk is eliminated, the better. Therefore, source control, or in case of unavoidable sources, local exhaust should always be the priority. Some sources, especially those related to the biological nature of the occupants, cannot be reduced with source control and are moving through the building. In that case, only strategies that reduce the concentrations of the pollutants in the indoor air, namely ventilation and air cleaning, can and should be adopted. Even if such concerns are not applicable, the emissions of a large array of sources, such as materials and household products, can be significantly reduced, but not eliminated. Adequate ventilation and/or air cleaning are therefore indispensable in any risk management scheme (Bluyssen 2009). Although alarms are the final fail safe, adequate ventilation and/or air cleaning will also provide sufficient redundancy in case unexpected sources occur. The rest of the chapter will only focus on ventilation.

Due to the broad range of pollutants and sources that can manifest themselves in indoor environments, proposing universal or general sizing rules for ventilation is an ambitious goal. This is clearly reflected by the number of different performance criteria proposed in ventilation standards (CEN 1998, 2007, 2009) and the large spread in observed ventilation rates applied in Europe (Dimitroulopoulou 2012). In general, minimal ventilation rates of about 0.5 ACH are recommended for houses, about 1 ACH for occupied area of an office space and about 0.1 ACH for low-polluted unoccupied spaces.

Provided clean air is available, the risk of adverse airborne exposure effects is best mitigated by large volumes of fresh air. In most climates, however, maintaining thermal comfort indoor within acceptable limits associates the indoor environment with an energy cost, introducing a trade-off in ventilation sizing (Tian et al. 2011; Zhang et al. 2011a). For any level of risk, a corresponding investment of energy has to be accepted (Laverge and Janssens 2010). In the total risk-energy trade-off, a number of modifying factors are present, concentrated in three media: the ventilation system, the indoor space and the occupant, summarized in the scheme shown in Fig. 1.

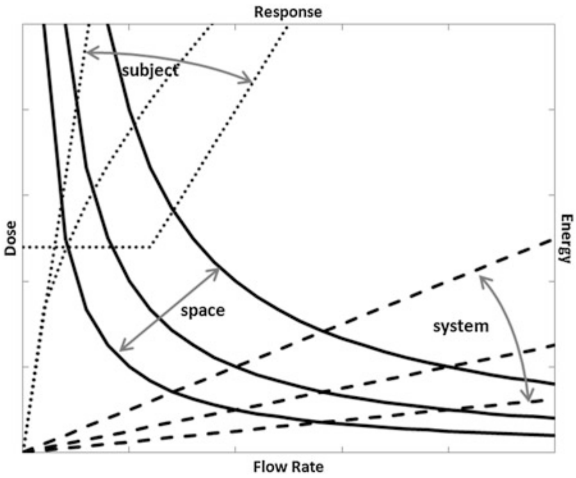


**Fig. 1** The energy–response relation is influenced by system, space and subject parameters and possesses and inherent trade-off

## 3.1 Subject

Examples of adverse effects associated with the intake of airborne pollutants were discussed in "A Multiple-Case Study of Passive House Retrofits of School Buildings in Austria". For any of these pollutants, there is a probabilistic dose–response function that determines wetter a certain dose will be likely to trigger the effect or not (Calthrop and Maddison 1996; Mendelsohn and Orcutt 1979; Page and Fellner 1978; Van Bree et al. 1995). The form of these functions is dependent on the specific pollutant. It can be either linear or nonlinear, include a 'no effect' threshold or not (Lewtas et al. 1997; Roberts and Martin 2007) and be modified by specific sensitivity of the subject such as age, allergy, pregnancy.

## 3.2 Space

A series of processes in the ventilated space create the conditions that allow getting from a flow rate, delivered by the ventilation system, to the dose inhaled by an occupant (Meng et al. 2012; Hsu et al. 2012). First of all, the layout and size of the air supplies and exhausts (Hviid and Svendsen 2013; Aziz et al. 2012), the production of buoyancy forces in the space and other momentum sources create a specific and usually unsteady flow field in the space (Gong et al. 2010; Peng and Davidson 1997). Specific approaches include displacement ventilation, creating more or less stable zone fresh air in the occupied zone of the space (Zhong et al. 2012), and personal ventilation, which directs the fresh air directly at the occupant's breathing zone (Makhoul et al. 2013; Pan et al. 2012). The geometrical distribution and type of sources in the space, as was elaborated on above, will interact with the flow field, and this results in a spatially distributed concentration and associated ventilation efficiency for each of the pollutants (Jones et al. 2007; Sandberg and Sjoberg 1983; Villafruela et al. 2013). The presence, behaviour and whereabouts of occupants in the space (Guerra Santin 2011; Yun et al. 2011; Lee et al. 2012a) will both influence the flow field, due to their movements and the thermal plume generated by their metabolic heat output (Thomas et al. 2011; Zukowska et al. 2012), and determine their exposure to the pollutants. Flow conditions in the microenvironment of the breathing zone, again influenced by movement and thermal plume, and personal factors such as breathing rate will then determine the intake and dose (Rim and Novoselac 2009; Schuda et al. 2009; Djupesland and Borresen 2000). The complete set of modifying factors influencing the relation between source strength, rather than the ventilation rate, and dose, including ventilation, is integrated in the 'intake fraction' concept (Bennett et al. 2002; Laverge et al. 2013a).

### 3.3 System

A last set of modifying factors is imbedded in the ventilation system. Its characteristics will determine the energy required to deliver a predefined ventilation flow rate. This energy contains both the energy required to condition the air to acceptable temperatures and that to move the air (Orme 1998; Santos and Leal 2012). Other associated costs are investment costs and maintenance (Blom et al. 2010).

The layout of the supply and exhaust vents not only influences the flow field in the ventilated space, but can also have a significant impact on the duct configuration and thus on the total pressure drop in the system. The latter is exponentially related to fan energy required to provide the desired flow rate in fan driven systems and determines the achievable flow rates in systems relying on natural driving forces such as wind and buoyancy. The performance of systems relying on natural driving forces is less robust due to the variability of these forces (van Moeseke et al. 2005; Ji et al. 2011; Gładyszewska-Fiedoruk and Gajewski 2012).

Figure 2 shows the optimal ventilation heat loss/exposure to carbon dioxide trade-off in a detached dwelling in Belgium (Laverge et al. 2013b; Laverge and Janssens 2010) for both purposely designed natural ventilation systems (*A*) and mechanical ventilation (*D*). For each system type, the pareto optimal sizing options were selected from 8,000 individually simulated sizing options. Although the optimal mean exposure is virtually the same for both systems, the peak exposure, defined here as the 95 % percentile of the distribution of the exposure, is much higher for the natural ventilation system. Adding components such as pressure-regulated trickle ventilators (CEN 2004; Karava et al. 2003), (solar) chimneys (Khanal and Lei 2011; Prajongsan and Sharples 2012) and wind cowls (van Hooff et al. 2011; Montazeri, Pfeiffer et al. 2008) helps achieve more stable airflow rates.

Fan-supported ventilation provides more robust indoor air quality, but requires fan energy (Nilsson 1995; Liu and Liu 2012). This introduces the conversion between heat loss and electrical power consumption as an additional dimension in

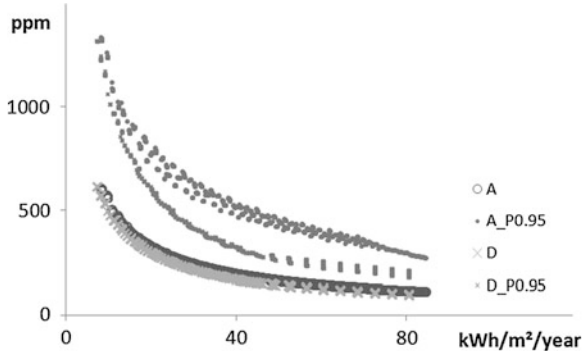


**Fig. 2** Pareto optimal mean exposure (ppm) versus ventilation heat loss (kWh/m$^2$/year) in a Belgian detached house for natural (*A*) and mechanical (*D*) ventilation, with associated peak exposures ($P_{0.95}$)

the trade-off. The choice of a conversion framework, e.g. energy, primary energy (IEA 2008a, b), carbon dioxide emission (IEA 2010; Soimakallio and Saikku 2012) or exergy, has a significant effect on the performance of the fan-supported systems (Laverge and Janssens 2012). The implementation of filter technology is virtually exclusively reserved for fan-supported systems, but again requires additional fan energy (Montgomery et al. 2012; Stephens et al. 2010). Fan-supported systems also require adequate commissioning, cleaning and maintenance, as well as a minimum of occupant education to function properly. A large number of installed systems fail in one of these aspects (Balvers et al. 2012; Dorer and Breer 1998).

In this chapter, the potential of air movement to create thermal comfort conditions is not discussed. The supply air is assumed to be at the minimal temperature required to eliminate the heating demand. During the heating season, when the outdoor air temperature is below this threshold, the supply air has to be heated to achieve this. Mutatis mutandis, the same can be said for the cooling season. Modifying factors determining the amount of energy required to do so obviously include climate conditions and the thermal performance of the building (Laverge and Janssens 2012) as well as the extent to which the energy contained in the exhaust air can be reused to heat the supply air. Most heat recovery systems require additional energy input to function. Their performance is discussed in the following section dealing with specific types of ventilation.

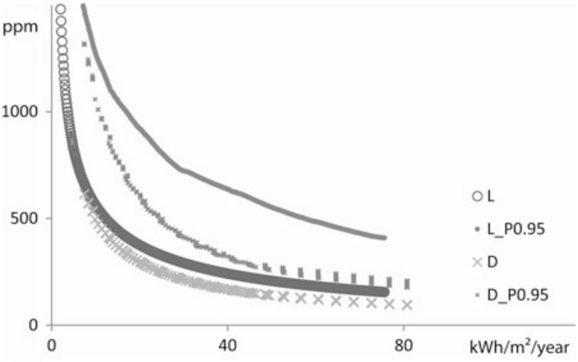
## 4 Ventilation: Strategies and Technology

Ventilation, as a means of risk management, can be achieved by simple low-tech solutions relying on leakage and window opening by occupants, or by fully mechanical ventilation systems that use fans to move the air where it is needed, or by any conceivable compromise between these extremes. In this section, the merits of a few of these options are discussed.

### *4.1 Leakage*

Traditionally, occupants have relied on infiltration of outdoor air through the building envelope to maintain acceptable contaminant concentrations indoor (Younes et al. 2012). Assuming a required air change rate of 0.5 ACH and an average available driving force due to wind and buoyancy of 1.5 Pa, a leakage rate of 10 ACH during a pressurization test at 50 Pa (CEN 2001) is required to accommodate this. In the USA, estimates show that about 50 % of the dwelling achieve a median air change rate of 0.5 ACH due to infiltration (Persily et al.), although mean values in traditional construction in Europe are smaller, at about 0.1–0.2 ACH (Pietrzyk and Hagentoft 2008; Jokisalo et al. 2009; Kalamees 2007).

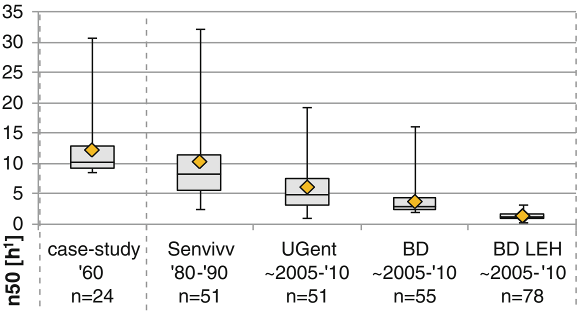
**Fig. 3** Pareto optimal mean exposure (ppm) versus ventilation heat loss (kWh/m$^2$/year) in a Belgian detached house for mechanical ventilation (*D*) and ventilation by leakage



Since the available driving forces are variable and leakage is usually concentrated around details in the building envelope (Van Den Bossche et al. 2012; Relander et al. 2012), the distribution of the fresh air in the dwelling is not necessary correlated with the needs. This reduces the overall efficiency of air leakage as a ventilation strategy, especially when compared to mechanical ventilation. This is shown in Fig. 3, where the optimal ventilation heat loss/mean exposure to carbon dioxide trade-off in a detached dwelling in Belgium is shown for a mechanical ventilation system and for ventilation through leakage. The performance of the former is systematically better. Although the difference is smaller, the same is found when the optimal performance of ventilation by leakage is compared to that of natural ventilation.

Due to the intensification of energy performance requirements for new buildings, the building industry is moving into more tight construction, favouring more efficient types of ventilation (Chen et al. 2012). This is typically achieved by reducing the number of joints in the construction (Pan); 10 ACH at 50 Pa is a typical value for older construction (Sinnott and Dyer 2012; Bossaer et al. 1998) and mild climates (Sfakianaki et al. 2008; Montoya et al. 2011), but high-performance buildings are up to 10 times more airtight. This is clearly visible in time evolution of air tightness in Belgium shown in Fig. 4 in "Toxicity issues: Radon".

**Fig. 4** Evolution of leakage rates ($n_{50}$) for single family houses in Belgium. Boxplots for social housing from the 1960s ('case-study'), standard construction from the early 1990s and after 2000 ('Senvivv' and 'UGent'), frontrunners ('BD') and low-energy houses ('BD LEH')



Draft problems, common in leaky construction, are an additional driver for more airtight construction (Bjarløv and Vladykova 2011). Therefore, leakage rates are often reduced considerably in refurbishments of older buildings, along with the installation of more efficient ventilation systems (Nabinger and Persily 2011; van der Wal et al. 1991).

## 4.2 Airing

Another traditional ventilation strategy is the opening of windows. Although this usually generates large flow rates of 4–20 ACH (Caciolo et al. 2012; Cheung and Liu (2011)), especially if cross-ventilation is possible (Bu and Kato, Bangalee et al. 2012) and is, therefore, very effective to evacuate acute high pollution loads, people tend to close the windows when they are present due to draft, especially when the outdoor temperature is low.

In a sense, windows are opened to prevent overheating rather than to reduce indoor air pollution (Dubrul 1988; Andersen et al. 2011; Fabi et al. 2012). Windows are also frequently closed, despite high indoor pollutant concentrations, because of acoustical discomfort (Barclay et al. 2012). The combination of these factors leads to the conclusion that the possibility of airing by opening windows is a necessary feature to restore the indoor air quality to acceptable levels within a short time span in case of acute high pollution loads, but is less appropriate as a ventilation strategy during occupancy.

## 4.3 System Sizing

From the discussion of leakage and airing as ventilation strategies, it is clear that both of these strategies fail to achieve good ventilation efficiency. In both cases, there is a mismatch between air supply and source strength or occupancy. These drawbacks are mitigated by the conception of dedicated continuous flow ventilation systems. As shown in Fig. 3, in optimal conditions, they achieve much better indoor air quality for a given ventilation heat loss than ventilation through leakage. There is, however, no consensus about the design and sizing of such systems. This is reflected in the large differences found in the requirements put forward in ventilation standards (Brelih and Seppänen 2011; Yoshino et al. 2004; Dimitroulopoulou 2012), resulting in a large spread in performance (Koffi 2009; Laverge et al. 2013b). Suboptimal sizing self-evidently reduces system performance (Djunaedy et al. (2011).

Roughly, balanced mechanical ventilation dominates the market in cold climates (Kurnitski and Seppanen 2008), simple exhaust is most prevalent in moderate climate regions (Durier 2008), and natural ventilation is the dominant strategy in mild climates.

## 4.4 Ventilation Heat Recovery

Fan-supported systems, on the one hand, allow for the implementation a range of heat recovery technologies, while on the other hand they require fan energy to operate. The trade-off between both, taking into account some conversion between heat loss and electrical power, frames the effectiveness of the heat recovery technology in question. The amount of heat loss that can be recovered is, next to the performance of the specific technology, determined by the climate and building energy performance (Zhou et al. 2007; Juodis 2006; El Fouih et al. 2012). Although some progress is made on the development of heat recovery systems for systems relying on natural driving forces, their performance and practical feasibility are still under debate (Hviid and Svendsen).

The two most widespread heat recovery technologies available are air-to-air heat exchangers (Roulet et al. 2001; Fernandez-Seara et al. 2011; Lazzarin and Gasparella 1998) and exhaust air heat pumps (EAHP) (Fehrm et al. 2002; Fracastoro and Serraino 2010; Sakellari and Lundqvist 2005; Wallman et al. 1987). The thermal effectiveness of commercially available air-to-air heat exchangers reaches up to 80 % (CEN 1997; WTCB 2012). Some of these systems include enthalpy exchange (Nasif et al. 2010; Hemingson et al. 2011). Due to the small diameters within these heat exchangers, filtering is usually necessary to prevent excessive fouling and the associated loss in performance (Markowski et al. 2013).

The assessment of heat recovery ventilation can be made only taking into account the intended ventilation (Laverge and Janssens 2012). The total heat recovered annually by a heat recovery unit (HRU) can be calculated from the heat content of the ventilation air, using the heating degree day data (ISO 2007; Day 2006).

$$Q_{\mathrm{HR}} = \int_a \rho \cdot c \cdot \varepsilon \cdot g(t) \cdot \Delta T(t)\,\mathrm{d}t \tag{1}$$

With:

| | |
|---|---|
| $Q_{\mathrm{HR}}$ | Total annual heat recovered (J) |
| $\rho$ | Density (kg/m$^3$) |
| $c$ | Specific heat capacity (j/kgK) |
| $\varepsilon$ | Effectiveness of HRU (-) |
| $\dot{g}$ | Flow rate (m$^3$/s) |
| $t$ | Time (s) |
| $\Delta T$ | Indoor/outdoor temperature difference (K) |

Assuming density, specific heat capacity and effectiveness to be constant over the whole heating season and assuming 1,224 J/m$^3$K to be the volumetric heat capacity of air, normalized per m$^3$/h, this can be transformed to:

$$q_{\mathrm{HR}} = 24 \cdot 1224 \cdot \varepsilon \cdot \ \mathrm{HDD} \ = \varepsilon \cdot 29376 \cdot \ \mathrm{HDD} \ = \varepsilon \cdot q_V \tag{2}$$

With:

| | |
|---|---|
| $q_{\mathrm{HR}}$ | Total annual heat recovered per m$^3$/h (Jh/m$^3$) |
| $q_V$ | Total ventilation heat loss (Jh/m$^3$) |
| $\varepsilon$ | Effectiveness of HRU (-) |
| HDD | Number of heating degree days (HDD) (Kday) |

HDD data for the whole EU are freely available from Eurostat (2010). In accordance with the Eurostat definition of HDD (Eurostat), which assumes a heating threshold of 15 °C and an indoor temperature of 18 °C, the number of HDD for any given day is defined as 18 °C minus the daily mean temperature, whenever that daily mean temperature is below 15 °C. The daily mean temperature is defined as the mathematical average of the minimum and maximum temperature of that day. Based on this definition, the number of HDD for the EU averaged over a 10-year period from 2000 to 2009 is 3,000.

The ventilation systems can be assumed to run at a constant rate, all year long. This is a valid assumption since, although occupants tend to open windows during summer (see above), thus increasing the total airflow rate, the system is rarely shut down. The ability to shut the system down is even forbidden in some ventilation standards (BIN 1991). The (increase in) electric load for fan operation in the heat recovery ventilation system is highly dependent on fan and ducting characteristics. In addition, fan power will typically increase with higher HRU effectiveness. Nevertheless, the use of specific fan power (SFP) allows for a straightforward approach to it. The European standard EN 13779 (CEN 2007) specifies SFP 3–4, 750–2,000 J/m$^3$ per fan, as default values for heat recovery systems.

The balance between the total heat recovered and the fan power difference is, beside by system characteristics, strongly affected by climate and by the conversion factor used to compare electricity consumption to fossil fuel consumption. Primary energy is a widely accepted framework for this conversion. To calculate the primary energy factors, the 2008 country energy balances reported by the international energy agency (IEA 2008a, b) were used. The primary energy factor was calculated by dividing the sum of the primary energy input of electricity plants and CHP plants by the net produced electricity. Since we assume the ventilation systems considered to permanently run at a fixed rate all year long, average factors were preferred to peak load factors. Due to the constraints of the first law of thermodynamics, this factor cannot be inferior to 1. The availability of the data limits the resolution of the calculated factors to country scale. Since, in spite of efforts of the EU to integrate its electricity market, electricity production is still mostly organized on a national scale, this is also the most logical scale within the primary energy framework.

Based on the calculated total heat recovered annually by the heat recovery unit, associated fan power difference and conversion factors, the equivalent HRU can be calculated by:

$$\varepsilon_{\mathrm{eq}} = \left(\varepsilon \cdot f_g \cdot q_V - \Delta\mathrm{SFP} \cdot f_e \cdot 24 \cdot 365\right) / \left(f_g \cdot q_V\right) \tag{3}$$

With:

| | |
|---|---|
| $\varepsilon$ | Effectiveness of HRU (-) |
| $q_V$ | Total ventilation heat loss (Jh/m$^3$) |
| HDD | Number of HDD (Kday) |
| $\Delta$SFP | Increase in SFP (J/m$^3$) |
| $f_g$ | Conversion factor condensing gas boiler (-) |
| $f_e$ | Primary energy factor electricity (-) |

Evidently, heat recovery operation will only be net positive for the total performance of the ventilation system under the framework considered if the real effectiveness is higher than the minimal effectiveness thus calculated.

To assess the performance of EAHP-based domestic hot water production as a ventilation heat recovery measure, compared to air-to-air heat exchanger technology, a similar definition of equivalent heat recovery effectiveness $\varepsilon_{\mathrm{eq}}$ is proposed. $\varepsilon_{\mathrm{eq}}$ is defined as the ratio of the energy savings achieved by the EAHP system in comparison with a reference system, converted to heat, and the ventilation heat losses:

$$\varepsilon_{\mathrm{eq}} = \left(f_g \cdot Q_{\mathrm{DHW}} - - f_e \cdot \ \mathrm{SPF} \ \cdot Q_{\mathrm{DHW}}\right) / \left(f_g \cdot Q_{\mathrm{vent}}\right) \tag{4}$$

With:

| | |
|---|---|
| $Q_{\mathrm{DHW}}$ | Annual energy for domestic hot water (J) |
| $Q_{\mathrm{vent}}$ | Annual ventilation heat loss (J) |
| SPF | Seasonal performance factor EAHP (Kday) |
| $f_g$ | Conversion factor condensing gas boiler (-) |
| $f_e$ | Primary energy factor electricity (-) |

The equivalent effectiveness of both air-to-air heat recovery units and EAHPs for domestic hot water production, taking into account an increase in fan energy of 1,500 j/m$^3$ and a thermal effectiveness of 80 % for the HRU, an air change rate of 0.5 ACH, seasonal performance factor of 2.96 and 85 % efficiency for a condensing gas boiler, is shown in Figs. 5 and 6 respectively .

Air-to-air heat recovery is highly efficient with equivalent effectiveness of 50 % and more in the northern part of Europe. EAHPs for domestic hot water production are less effective in this region. In contrast to HRUs, their performance is higher in the Mediterranean Basin, although it is still very low (equivalent effectiveness <0.4).

The performance of HRU is highly dependent on the efficiency of the fan. The equivalent effectiveness calculated above takes into account fans with performance levels at the top of the recommended default values by the European standard (750 J/m$^3$ per fan). Measurements show that the performance in practice can range over a broad spectrum. Lowering fan performance with one class (1,250 J/m$^3$ per fan), to the mid-range of the CEN default values, reduces their profitability in the major part of Europe, leaving only Scandinavia as an interesting region for their application (see Fig. 7).

When, on the other hand, a difference in fan power of only 500 J/m$^3$ is considered (Fig. 8.), which would correspond to the addition of a low pressure drop HRU in an

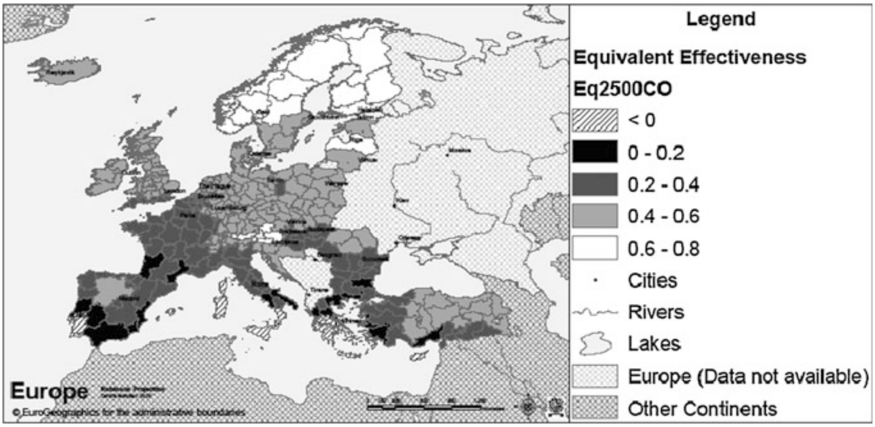


**Fig. 5** Equivalent effectiveness of HRU in Europe with ΔSFP 1,500 J/m$^3$, $\varepsilon = 0.8$ and $\eta = 0.85$

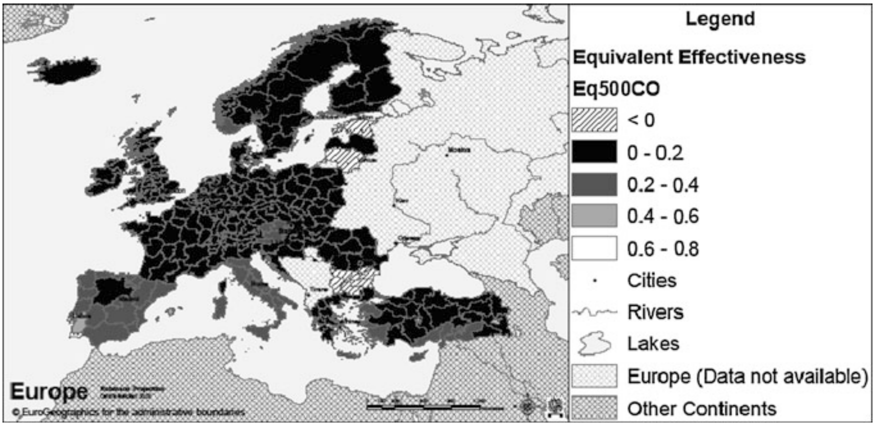


**Fig. 6** Equivalent effectiveness of EAHP in Europe with 0.5 ACH, SPF = 2.96 and $\eta = 0.85$

fully mechanical ventilation system, the application of air-to-air heat exchanger technology is vastly beneficial anywhere in Europe. Mind that this scenario is only valid when mechanical ventilation is necessary anyway and with high-end HRUs that combine a high thermal effectiveness ($\varepsilon = 0.8$) and low pressure drop.

### *4.5 Demand-Controlled and Hybrid Ventilation*

By modulating the ventilation flow rate to the pollution load, thus providing ventilation if and when needed, the ventilation heat loss can also be considerably reduced (Mansson 1993). In order to do this efficiently, sensors are usually used to

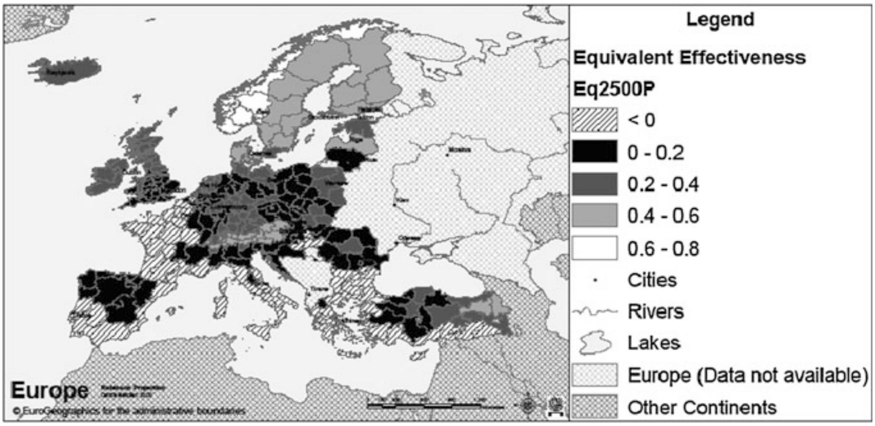


**Fig. 7** Equivalent effectiveness of HRU in Europe with ΔSFP 2,500 J/m$^3$, $\varepsilon = 0.8$ and $\eta = 0.85$

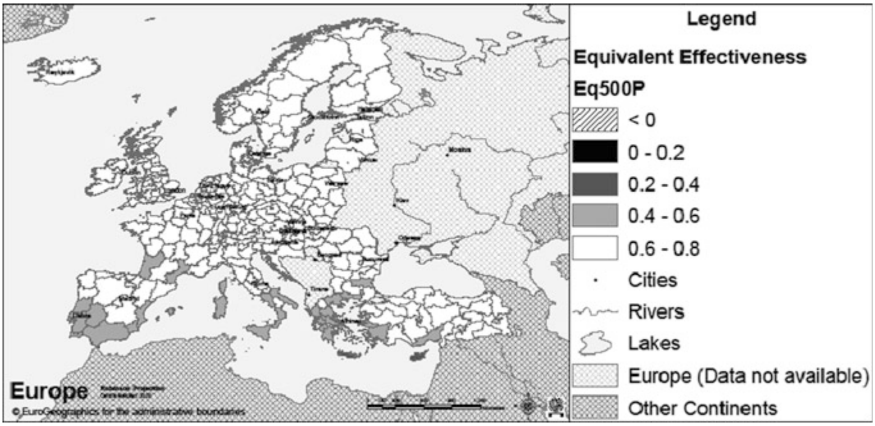


**Fig. 8** Equivalent effectiveness of HRU in Europe with ΔSFP 500 J/m$^3$, $\varepsilon = 0.8$ and $\eta = 0.85$

assess the pollutant load (Fisk and De Almeida 1998), either directly (Lin et al. 2011) or through the bias of a proxy, such as occupancy (Johansson et al., Mysen et al. 2005) or a tracer gas (Lawrence and Braun 2007; Nabil 2012). As shown in Fig. 9, demand-controlled ventilation, when optimally sized and controlled, achieves up to 50 % of ventilation heat loss savings for equal mean exposure. Additionally, the associated peak exposures are also reduced, demonstrating that demand control systems also provide more robust indoor air quality.

Most research is focussed on the technical issues of the control strategy (Dounis et al. (2011); Parameshwaran et al. 2010; Wang and Xu 2004), though the application of the technology has been studied in residences (Laverge et al. 2011, Nielsen and Drivsholm 2010; Sherman and Walker 2011), offices (Mysen et al.

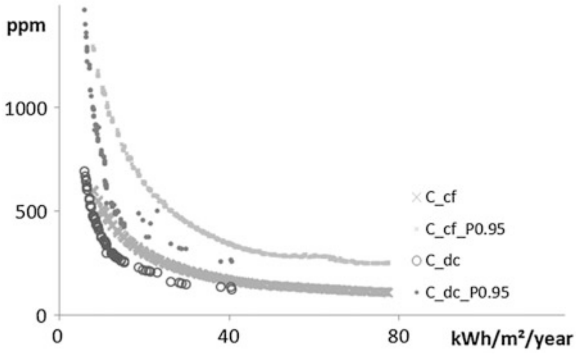


**Fig. 9** Pareto optimal mean exposure (ppm) versus ventilation heat loss (kWh/m$^2$/year) in a Belgian detached house for continuous flow (*C_cf*) and demand-controlled (*C_dc*) exhaust ventilation, with associated peak exposures ($P_{0.95}$)

2003, Shan et al. 2012) and schools (Wachenfeldt et al. 2007). In each of these settings, a considerable ventilation heat loss reduction potential (20–50 %) was reported.

Hybrid ventilation adopts the same strategy to reduce fan energy: fans are only operated if available natural driving forces are insufficient to provide the required ventilation flow rate (Delsante and Aggerholm 2002; Dorer et al. 2005). The latter can of course be demand modulated, combining hybrid fan technology with traditional demand control (Op't Veld 2008).

## 5 Conclusions

In this chapter, we have first discussed the possible effects of exposure to airborne pollutants. Health effects from specific pollutants with common indoor sources include increased prevalence of cancer, cardiovascular disease and asthma as well as a long list of acute symptoms. Subsequently, ventilation was discussed as one of the possible risk management strategies to minimize these effects. The performance of ventilation system approaches was presented as a trade-off between ventilation heat loss and effect minimization. The energy-saving potential of heat recovery by air-to-air heat exchangers as well as demand control in Western Europe was shown to be around 50 %.

## References

Abbassi R, Dadashzadeh M, Khan F et al (2012) Risk-based prioritisation of indoor air pollution monitoring using computational fluid dynamics. Indoor Built Environ 21:663–673

Amato F, Pandolfi M, Moreno T et al (2011) Sources and variability of inhalable road dust particles in three European cities. Atmos Environ 45:6777–6787

Andersen RK, Olesen BW, Toftum J (2011) Modeling window opening behaviour in Danish dwellings. Indoor Air Austin

Aziz MA, Gad IAM, Mohammed ESFA et al (2012) Experimental and numerical study of influence of air ceiling diffusers on room air flow characteristics. Energy Build 55:738–746

Bakó-Biró Z, Clements-Croome DJ, Kochhar N et al (2012) Ventilation rates in schools and pupils' performance. Build Environ 48:215–223

Balvers J, Bogers R, Jongeneel R et al (2012) Mechanical ventilation in recently built Dutch homes: technical shortcomings, possibilities for improvement, perceived indoor environment and health effects. Architectural Sci Rev 55:4–14

Bangalee MZI, Lin SY, Miau JJ (2012) Wind driven natural ventilation through multiple windows of a building: a computational approach. Energy Build 45:317–325

Barclay M, Kang J, Sharples S (2012) Combining noise mapping and ventilation performance for non-domestic buildings in an urban area. Build Environ 52:68–76

Bastani A, Haghighat F, Kozinski JA (2012) Contaminant source identification within a building: toward design of immune buildings. Build Environ 51:320–329

Baumgartner J, Schauer JJ, Ezzati M et al (2011) Patterns and predictors of personal exposure to indoor air pollution from biomass combustion among women and children in rural china. Indoor Air 21:479–488

Bekö G, Clausen G, Weschler CJ (2008) Is the use of particle air filtration justified? Costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity. Build Environ 43:1647–1657

Bennett DH, Mckone TE, Evans JS et al (2002) Peer reviewed: defining intake fraction. Environ Sci Technol 36:206A–211A

Bin (1991) Ventilatievoorzieningen in woongebouwen. Brussels

Bjarløv SP, Vladykova P (2011) The potential and need for energy saving in standard family detached and semi-detached wooden houses in Arctic Greenland. Build Environ 46:1525–1536

Blom I, Itard L, Meijer A (2010) Lca-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings. Build Environ 45:2362–2372

Bluyssen PM (2009) Towards an integrative approach of improving indoor air quality. Build Environ 44:1980–1989

Bossaer A, Demeester J, Wouters P et al (1998) Airtightness performances in new Belgian dwellings. In: Proceedings of 19th AIVC conference, ventilation technologies in urban areas, Oslo, pp 77–84

Braubach M, Jacobs DE (2011) Environmental burden of disease associated with inadequate housing. Methods for quantifying health impacts of selected housing risks in the WHO European region. Summary report, WHO

Brelih N, Seppänen O (2011) Ventilation rates and IAQ in European standards and national regulations. In: Proceedings of AIVC conference, Brussels

Bu Z, Kato S Wind-induced ventilation performances and airflow characteristics in an areaway-attached basement with a single-sided opening. Build Environ 46:911–921

Buonanno G, Morawska L, Stabile L (2009) Particle emission factors during cooking activities. Atmos Environ 43:3235–3242

Butz AM, Breysse P, Rand C et al (2011) Household smoking behavior: effects on indoor air quality and health of urban children with asthma. Matern Child Health J 15:460–468

Byeon JH, Kim J-W (2012) Particle emission from laser printers with different printing speeds. Atmos Environ 54:272–276

Caciolo M, Stabat P, Marchio D (2012) Numerical simulation of single-sided ventilation using RANS and LES and comparison with full-scale experiments. Build Environ 50:202–213

Calthrop E, Maddison D (1996) The dose—response function approach to modelling the health effects of air pollution. Energy Policy 24:599–607

Carter E, Earnest CM, Gall ET et al (2012) Progress and priorities in reducing indoor air pollution in developing countries. Indoor Air 22:1–2

Celebi UB, Vardar N (2008) Investigation of voc emissions from indoor and outdoor painting processes in shipyards. Atmos Environ 42:5685–5695

Cen (1997) Heat exchangers—test procedures for establishing performance of air to air and flue gases heat recovery devices, CEN

Cen (1998) Ventilation for buildings—design criteria for the indoor environment, Brussels

Cen (2001) Thermal performance of buildings—determination of air permeability of buildings—fan pressurization method (ISO 9972:1996, modified), CEN

Cen (2004) Ventilation for buildings—performance testing of components/products for residential ventilation—part. 1: externally and internally mounted air transfer devices, Brussels

Cen (2007) Ventilation for non-residential buildings—performance requirements for ventilation and room-conditioning systems, Brussels

Cen (2009) Ventilation in buildings—determining performance criteria for design of residential ventilation systems, Brussels

Chang CW, Chou FC (2011) Methodologies for quantifying culturable, viable, and total Legionella pneumophila in indoor air. Indoor Air 21:291–299

Chen C, Zhao B, Yang X (2011) Preventing the entry of outdoor particles with the indoor positive pressure control method: analysis of influencing factors and cost. Build Environ 46:1167–1173

Chen S, Levine MD, Li H et al (2012) Measured air tightness performance of residential buildings in north china and its influence on district space heating energy use. Energy Build 51:157–164

Chen YL, Wen J (2012) The selection of the most appropriate airflow model for designing indoor air sensor systems. Build Environ 50:34–43

Cheung JOP, Liu C-H (2011) CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings. Energy Build 43:1149–1158

China S, James DE (2012) Influence of pavement macrotexture on PM10 emissions from paved roads: a controlled study. Atmos Environ 63:313–326

Choi JI, Edwards JR (2012) Large-eddy simulation of human-induced contaminant transport in room compartments. Indoor Air 22:77–87

Claeson AS, Nordin S, Sunesson AL (2009) Effects on perceived air quality and symptoms of exposure to microbially produced metabolites and compounds emitted from damp building materials. Indoor Air 19:102–112

Clausen G (2004) Ventilation filters and indoor air quality: a review of research from the international centre for indoor environment and energy. Indoor Air 14:202–207

Coleman BK, Lunden MM, Destaillats H et al (2008) Secondary organic aerosol from ozone-initiated reactions with terpene-rich household products. Atmos Environ 42:8234–8245

Cooper AJ, Barnes HR, Myers ER (2004) Assessing risk of Legionella. Ashrae J 46:22–27

Corsi RL, Siegel J, Karamalegos A et al (2007) Personal reactive clouds: introducing the concept of near-head chemistry. Atmos Environ 41:3161–3165

Cros CJ, Morrison GC, Siegel JA et al (2012) Long-term performance of passive materials for removal of ozone from indoor air. Indoor Air 22:43–53

Cuccia E, Massabò D, Ariola V et al (2013) Size-resolved comprehensive characterization of airborne particulate matter. Atmos Environ 67:14–26

Darling EK, Cros CJ, Wargocki P et al (2012) Impacts of a clay plaster on indoor air quality assessed using chemical and sensory measurements. Build Environ 57:370–376

Day T (2006) Degree days: theory and application. CIBSE, London

Delsante A, Aggerholm S (2002) The use of simulation tools to evaluate hybrid ventilation control strategies. Annex 35 technical report, IEA/ECBCS

Deng B, Kim CN (2007) CFD simulation of VOCs concentrations in a resident building with new carpet under different ventilation strategies. Build Environ 42:297–303

Derudi M, Gelosa S, Sliepcevich A et al (2012) Emissions of air pollutants from scented candles burning in a test chamber. Atmos Environ 55:257–262

Destaillats H, Sleiman M, Sullivan DP et al (2012) Key parameters influencing the performance of photocatalytic oxidation (PCO) air purification under realistic indoor conditions. Appl Catal B 128:159–170

Dimitroulopoulou C (2012) Ventilation in European dwellings: a review. Build Environ 47:109–125

Djunaedy E, Van Den Wymelenberg K, Acker B et al (2011) Oversizing of HVAC system: signatures and penalties. Energy Build 43:468–475

Djupesland PG, Borresen BA (2000) Computational simulation of accumulation of expired air in the infant cot. Acta Otolaryngol 120:183–185

Dorer V, Breer D (1998) Residential mechanical ventilation systems: performance criteria and evaluations. Energy Build 27:247–255

Dorer V, Pfeiffer A, Weber A (2005) Parameters for the design of demand controlled hybrid ventilation systems for residential buildings. AIVC Technical Notes, AIVC, Brussels

Dounis AI, Tiropanis P, Argiriou A et al (2011) Intelligent control system for reconciliation of the energy savings with comfort in buildings using soft computing techniques. Energy Build 43:66–74

Dubrul C (1988) Inhabitant behaviour with respect to ventilation—a summary report of IEA annex viii, Oscar Fabe

Durier F (2008) Trends in the French building ventilation market and drivers for changes. In: AIVC (ed) Ventilation information papers

Fouih YE, Stabat P, Rivière P et al (2012) Adequacy of air-to-air heat recovery ventilation system applied in low energy buildings. Energy Build 54:29–39

Eurostat (2011) Eurostat metadata—heating degree days (Online). Eurostat, Luxemburg, Available: http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/EN/nrg_esdgr_esms.htm. (Accessed on 2011)

Eurostat (2010) Heating degree-days—annual data. Accessed on 18 Feb 2010 ed

Fabi V, Andersen RV, Corgnati S et al (2012) Occupants' window opening behaviour: a literature review of factors influencing occupant behaviour and models. Build Environ 58:188–198

Fang L, Clausen G, Fanger PO (1999) Impact of temperature and humidity on chemical and sensory emissions from building materials. Indoor Air 9:193–201

Fanger PO (1988) Introduction of the olf and decipol unit to quantify air-pollution perceived by humans indoors and outdoors. Energy Build 12:1–6

Fanger PO, Lauridsen J, Bluyssen P et al (1988) Air pollution sources in offices and assembly halls, quantified by the olf unit. Energy Build 12:7–19

Fehrm M, Reiners W, Ungemach M (2002) Exhaust air heat recovery in buildings. Int J Refrigeration-Revue Int Du Froid 25:439–449

Fernandez-Seara J, Diz R, Uhia FJ et al (2011) Experimental analysis of an air-to-air heat recovery unit for balanced ventilation systems in residential buildings. Energy Convers Manage 52:635–640

Firdaus G, Ahmad A (2012) Relationship between housing and health: a cross-sectional study of an urban centre of India. Indoor Built Environ

Fisk WJ, Black D, Brunner G (2012) Changing ventilation rates in U.S. Offices: implications for health, work performance, energy, and associated economics. Build Environ 47:368–372

Fisk WJ, De Almeida AT (1998) Sensor-based demand-controlled ventilation: a review. Energy Build 29:35–45

Fracastoro GV, Serraino M (2010) Energy analyses of buildings equipped with exhaust air heat pumps (EAHP). Energy Build 42:1283–1289

Frontczak M, Andersen RV, Wargocki P (2012) Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. Build Environ 50:56–64

Gao N, Niu J (2006) Transient CFD simulation of the respiration process and inter-person exposure assessment. Build Environ 41:1214–1222

Geary DF (2000) New guidelines on Legionella. Ashrae J 42:44–49

Yun GY, Kong HJ, Kim JT (2011) A field survey of occupancy and air-conditioner use patterns in open plan offices. Indoor Built Environ 20:137–147

Gładyszewska-Fiedoruk K, Gajewski A (2012) Effect of wind on stack ventilation performance. Energy Build 51:242–247

Gleich F, Mons U, Poetschke-Langer M (2011) Air contamination due to smoking in German restaurants, bars, and other venues-before and after the implementation of a partial smoking ban. Nicotine Tob Res 13:1155–1160

Gminski R, Marutzky R, Kevekordes S et al (2011) Chemosensory irritations and pulmonary effects of acute exposure to emissions from oriented strand board. Hum Exp Toxicol 30:1204–1221

Gong GC, Han B, Luo HF et al (2010) Research on the air stability of limited space. Int J Green Energy 7:43–64

Guerra Santin O (2011) Behavioural patterns and user profiles related to energy consumption for heating. Energy Build 43:2662–2672

Haas D, Galler H, Luxner J et al (2013) The concentrations of culturable microorganisms in relation to particulate matter in urban air. Atmos Environ 65:215–222

Han K, Zhang JS, Wargocki P et al (2012) Model-based approach to account for the variation of primary voc emissions over time in the identification of indoor voc sources. Build Environ 57:403–416

Hathway EA, Noakes CJ, Sleigh PA et al (2011) CFD simulation of airborne pathogen transport due to human activities. Build Environ 46:2500–2511

Haverinen-Shaughnessy U (2012) Prevalence of dampness and mold in European housing stock. J Expos Sci Environ Epidemiol 22:461–467

Haverinen-Shaughnessy U, Moschandreas DJ, Shaughnessy RJ (2011) Association between substandard classroom ventilation rates and students' academic achievement. Indoor Air 21:121–131

Hayashi M, Osawa H (2008) The influence of the concealed pollution sources upon the indoor air quality in houses. Build Environ 43:329–336

Hemingson HB, Simonson CJ, Besant RW (2011) Steady-state performance of a run-around membrane energy exchanger (RAMEE) for a range of outdoor air conditions. Int J Heat Mass Transf 54:1814–1824

Hillier K, King DA, Henneuse C (2009) Study of odours coming out of polyurethane flexible foam mattresses. Cell Polym 28:113–144

Hodas N, Meng Q, Lunden MM et al (2012) Variability in the fraction of ambient fine particulate matter found indoors and observed heterogeneity in health effect estimates. J Expos Sci Environ Epidemiol 22:448–454

Hoffmann H-D, Schupp T (2009) Evaluation of consumer risk resulting from exposure against diphenylmethane-4, 4′-diisocyanate (MDI) from polyurethane foam. Excli J 8:58–65

Hsu S-I, Ito K, Kendall M et al (2012) Factors affecting personal exposure to thoracic and fine particles and their components. J Expos Sci Environ Epidemiol 22:439–447

Huang Y, Ho KF, Ho SSH et al (2011) Physical parameters effect on ozone-initiated formation of indoor secondary organic aerosols with emissions from cleaning products. J Hazard Mater 192:1787–1794

Hun DE, Corsi RL, Morandi MT et al (2010) Formaldehyde in residences: long-term indoor concentrations and influencing factors. Indoor Air 20:196–203

Hun DE, Corsi RL, Morandi MT et al (2011) Automobile proximity and indoor residential concentrations of BTEX and MTBE. Build Environ 46:45–53

Hviid CA, Svendsen S Analytical and experimental analysis of a low-pressure heat exchanger suitable for passive ventilation. doi: 10.1016/j.enbuild.2010.08.003

Hviid CA, Svendsen S (2013) Experimental study of perforated suspended ceilings as diffuse ventilation air inlets. Energy Build 56:160–168

Hyttinen M, Rautio A, Pasanen P et al (2011) Airborne infection isolation rooms—a review of experimental studies. Indoor Built Environ 20:584–594

IEA (2008a) Energy balances of non-OECD countries

IEA (2008b) Energy balances of OECD countries

IEA (2010) $Co_2$ emissions from fuel combustion, 2010 edn. IEA, Paris

Inthavong K, Tian ZF, Tu JY (2009) Effect of ventilation design on removal of particles in woodturning workstations. Build Environ 44:125–136

ISO (2007) Hygrothermal performance of buildings—calculation and presentation of climatic data—part 6: accumulated temperature differences (degree-days), Geneva

Jayaratne ER, Ling X, He C et al (2012) Monitoring charged particle and ion emissions from a laser printer. J Electrostat 70:333–338

Ji L, Tan H, Kato S et al (2011) Wind tunnel investigation on influence of fluctuating wind direction on cross natural ventilation. Build Environ 46:2490–2499

Johansson D, Bagge H, Lindstrii L Measurements of occupancy levels in multi-family dwellings–application to demand controlled ventilation. Energy Build In Press, Corrected Proof

Johnsen CR, Heinig JH, Schmidt K et al (1991) A study of human reactions to emissions from building materials in climate chambers. Part i: clinical data, performance and comfort. Indoor Air 1:377–388

Jokisalo J, Kurnitski J, Korpi M et al (2009) Building leakage, infiltration, and energy performance analyses for Finnish detached houses. Build Environ 44:377–387

Jones J, Stick S, Dingle P et al (2007) Spatial variability of particulates in homes: implications for infant exposure. Sci Total Environ 376:317–323

Juodis E (2006) Extracted ventilation air heat recovery efficiency as a function of a building's thermal properties. Energy Build 38:568–573

Kabir E, Kim K-H (2011) An investigation on hazardous and odorous pollutant emission during cooking activities. J Hazard Mater 188:443–454

Kalamees T (2007) Air tightness and air leakages of new lightweight single-family detached houses in Estonia. Build Environ 42:2369–2377

Karava P, Stathopoulos T, Athienitis AK (2003) Investigation of the performance of trickle ventilators. Build Environ 38:981–993

Kemmlein S, Hahn O, Jann O (2003) Emissions of organophosphate and brominated flame retardants from selected consumer products and building materials. Atmos Environ 37:5485–5493

Khanal R, Lei C (2011) Solar chimney–a passive strategy for natural ventilation. Energy Build 43:1811–1819

Kim T, Park B-Y, Cheong CH (2012) Ventilation systems to prevent food odour spread in high-rise residential buildings. Indoor Built Environ 21:304–316

Kinsey JS, Touati A, Yelverton TLB et al (2012) Emissions characterization of residential wood-fired hydronic heater technologies. Atmos Environ 63:239–249

Koffi J (2009) Analyse multicritère des stratégies de ventilation en maisons individuelles. PhD, Université de La Rochelle

Kolarik J, Toftum J (2012) The impact of a photocatalytic paint on indoor air pollutants: sensory assessments. Build Environ 57:396–402

Kowalska J, Gierczak T (2012) Qualitative and quantitative analyses of the halogenated volatile organic compounds emitted from the office equipment items. Indoor Built Environ

Kumar P, Mulheron M, Fisher B et al (2012) New directions: Airborne ultrafine particle dust from building activities—a source in need of quantification. Atmos Environ 56:262–264

Kurnitski J, Seppanen OA (2008) Trends and drivers in the Finnish ventilation and AC market. In: AIVC (ed.) Ventilation information papers, AIVC, Brussels

Kwon K-D, Jo W-K, Lim H-J et al (2008) Volatile pollutants emitted from selected liquid household products. Environ Sci Pollut Res 15:521–526

L'orange C, Volckens J, Defoort M (2012) Influence of stove type and cooking pot temperature on particulate matter emissions from biomass cook stoves. Energy Sustain Dev 16:448–455

Lamble SP, Corsi RL, Morrison GC (2011) Ozone deposition velocities, reaction probabilities and product yields for green building materials. Atmos Environ 45:6965–6972

Laverge J, Janssens A (2010) Residential ventilation system optimization using Monte-Carlo and genetic algorithm techniques. In: Proceedings of IAQ 2010, Kuala Lumpur, ASHRAE, 10

Laverge J, Janssens A (2012) Heat recovery ventilation operation traded off against natural and simple exhaust ventilation in Europe by primary energy factor, carbon dioxide emission, household consumer price and exergy. Energy Build 50:315–323

Laverge J, Novoselac A, Corsi R et al. (2012) Experimental assessment of ventilation in the bedroom: physiological response to ventilation and impact of position on rebreathing. In: Proceedings of 5th international building physics conference, 5th IBPC organizing committee, pp 973–980

Laverge J, Novoselac A, Corsi R et al (2013a) Experimental assessment of exposure to gaseous pollutants from mattresses and pillows while asleep. Build Environ 59:203–210

Laverge J, Pattyn X, Janssens A (2013b) Performance assessment of residential mechanical exhaust ventilation systems dimensioned in accordance with Belgian, British, Dutch, French and ASHRAE standards. Build Environ 59:177–186

Laverge J, Van Den Bossche N, Heijmans N et al (2011) Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. Build Environ 46:1497–1503

Lawrence TM, Braun JE (2007) A methodology for estimating occupant $CO_2$ source generation rates from measurements in small commercial buildings. Build Environ 42:623–639

Lazzarin RM, Gasparella A (1998) Technical and economical analysis of heat recovery in building ventilation systems. Appl Therm Eng 18:47–67

Lee H-Y, Yang IT, Lin Y-C (2012a) Laying out the occupant flows in public buildings for operating efficiency. Build Environ 51:231–242

Lee MC, Mui KW, Wong LT et al (2012b) Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. Build Environ 49:238–244

Lee S, Kwon G, Joo J et al (2012c) A finish material management system for indoor air quality of apartment buildings (FinIAQ). Energy Build 46:68–79

Lee Y-K, Kim H-J (2012) The effect of temperature on VOCs and carbonyl compounds emission from wooden flooring by thermal extractor test method. Build Environ 53:95–99

Lewtas J, Walsh D, Williams R et al (1997) Air pollution exposure–DNA adduct dosimetry in humans and rodents: evidence for non-linearity at high doses. Mutat Res Fundam Mol Mech Mutagen 378:51–63

Lim JM, Jeong JH, Lee JH et al (2011) The analysis of pm2.5 and associated elements and their indoor/outdoor pollution status in an urban area. Indoor Air 21:145–155

Lin Z, Lee CK, Fong KF et al (2011) Comparison of annual energy performances with different ventilation methods for temperature and humidity control. Energy Build 43:3599–3608

Liu G, Liu M (2012) Development of simplified in situ fan curve measurement method using the manufacturers fan curve. Build Environ 48:77–83

Liu W-T, Hsieh H-C, Chen S-P et al (2012) Diagnosis of air quality through observation and modeling of volatile organic compounds (VOCs) as pollution tracers. Atmos Environ 55:56–63

Lobscheid AB, Nazaroff WW, Spears M et al (2012) Intake fractions of primary conserved air pollutants emitted from on-road vehicles in the United States. Atmos Environ 63:298–305

Longinelli A, Langone L, Ori C et al (2011) Atmospheric $CO_2$ concentrations and [delta] 13c over western and eastern Mediterranean basins during summer 2007. Atmos Environ 45:5514–5522

Lu W-Z, He H-D, Leung AYT (2011) Assessing air quality in Hong Kong: a proposed, revised air pollution index (API). Build Environ 46:2562–2569

Madureira J, Mendes A, Santos H et al (2012) Evaluation of the indoor air quality in restaurants before and after a smoking ban in Portugal. Indoor Built Environ 21:323–331

Makhoul A, Ghali K, Ghaddar N (2013) Desk fans for the control of the convection flow around occupants using ceiling mounted personalized ventilation. Build Environ 59:336–348

Mansson L (1993) Demand controlled ventilating systems: case studies. In: IEA (ed)

Marion M, Tiffonnet AL, Santa-Cruz A et al (2011) Study of the resistances to transfer of gaseous pollutant between material and indoor air. Build Environ 46:356–362

Markowski M, Trafczynski M, Urbaniec K (2013) Identification of the influence of fouling on the heat recovery in a network of shell and tube heat exchangers. Appl Energy 102:755–764

Mavroidis I, Andronopoulos S, Bartzis JG (2012) Computational simulation of the residence of air pollutants in the wake of a 3-dimensional cubical building. The effect of atmospheric stability. Atmos Environ 63:189–202

Mendelsohn R, Orcutt G (1979) An empirical analysis of air pollution dose-response curves. J Environ Econ Manage 6:85–106

Meng QY, Svendsgaard D, Kotchmar DJ et al (2012) Associations between personal exposures and ambient concentrations of nitrogen dioxide: a quantitative research synthesis. Atmos Environ 57:322–329

Menut L, Goussebaile A, Bessagnet B et al (2012) Impact of realistic hourly emissions profiles on air pollutants concentrations modelled with CHIMERE. Atmos Environ 49:233–244

Mirzaei PA, Haghighat F (2010) A novel approach to enhance outdoor air quality: Pedestrian ventilation system. Build Environ 45:1582–1593

Montazeri H Experimental and numerical study on natural ventilation performance of various multi-opening wind catchers. Build Environ 46:370–378

Montgomery JF, Green SI, Rogak SN et al (2012) Predicting the energy use and operation cost of HVAC air filters. Energy Build 47:643–650

Montoya MI, Pastor E, Planas E (2011) Air infiltration in Catalan dwellings and sealed rooms: an experimental study. Build Environ 46:2003–2011

Moran RE, Bennett DH, Tancredi DJ et al (2012) Frequency and longitudinal trends of household care product use. Atmos Environ 55:417–424

Mui KW, Wong LT, Ho WL (2006) Evaluation on sampling point densities for assessing indoor air quality. Build Environ 41:1515–1521

Mysen M, Berntsen S, Nafstad P et al (2005) Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools. Energy Build 37:1234–1240

Mysen M, Rydock JP, Tjelflaat PO (2003) Demand controlled ventilation for office cubicles–can it be profitable? Energy Build 35:657–662

Nabil N (2012) A robust $CO_2$-based demand-controlled ventilation control strategy for multi-zone HVAC systems. Energy Build 45:72–81

Nabinger S, Persily A (2011) Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home. Energy Build 43:3059–3067

Nasif M, Al-Waked R, Morrison G et al (2010) Membrane heat exchanger in HVAC energy recovery systems, systems energy analysis. Energy Build 42:1833–1840

Nielsen TR, Drivsholm C (2010) Energy efficient demand controlled ventilation in single family houses. Energy Build 42:1995–1998

Nilsson LJ (1995) Air-handling energy efficiency and design practices. Energy and Buildings 22:1–13

Nirvan G, Haghighat F, Wang L et al (2012) Contaminant transport through the garage—house interface leakage. Build Environ 56:176–183

Offermann FJ IAQ in airtight homes. Ashrae J 52:58–60

Olmedo I, Nielsen PV, Ruiz De Adana M et al (2012) Distribution of exhaled contaminants and personal exposure in a room using three different air distribution strategies. Indoor Air 22:64–76

Ongwandee M, Sawanyapanich P (2012) Influence of relative humidity and gaseous ammonia on the nicotine sorption to indoor materials. Indoor Air 22:54–63

Op't Veld P (2008) Introduction to EC RESHYVENT–EU cluster project on demand controlled hybrid ventilation for residential buildings. Build Environ 43:1342–1349

Orme M (1998) Energy impact of ventilation. AIVC Technical Notes, AIVC, Brussels

Pacheco Torgal F (2012) Indoor radon: an overview on a perennial problem. Build Environ 58:270–277

Page WP, Fellner W (1978) Exploratory techniques for the determination of potential dose-response relationships between human health and air pollution. J Environ Econ Manage 5:376–389

Pan D, Chan M, Xia L et al (2012) Performance evaluation of a novel bed-based task/ambient conditioning (TAC) system. Energy Build 44:54–62

Pan W Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. Build Environ 45:2387–2399

Parameshwaran R, Karunakaran R, Kumar CVR et al (2010) Energy conservative building air conditioning system controlled and optimized using fuzzy-genetic algorithm. Energy Build 42:745–762

Peng SH, Davidson L (1997) Towards the determination of regional purging flow rate. Build Environ 32:513–525

Persily A, Musser A, Emmerich SJ Modeled infiltration rate distributions for U.S. Housing. Indoor Air 20:473–485

Petrick LM, Sleiman M, Dubowski Y et al (2011) Tobacco smoke aging in the presence of ozone: a room-sized chamber study. Atmos Environ 45:4959–4965

Pfeiffer A, Dorer V, Weber A (2008) Modelling of cowl performance in building simulation tools using experimental data and computational fluid dynamics. Build Environ 43:1361–1372

Pietrzyk K, Hagentoft C-E (2008) Probabilistic analysis of air infiltration in low-rise buildings. Build Environ 43:537–549

Prajongsan P, Sharples S (2012) Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. Build Environ 50:104–113

Redrow J, Mao S, Celik I et al (2011) Modeling the evaporation and dispersion of airborne sputum droplets expelled from a human cough. Build Environ 46:2042–2051

Relander T-O, Holøs S, Thue JV (2012) Airtightness estimation—a state of the art review and an en route upper limit evaluation principle to increase the chances that wood-frame houses with a vapour- and wind-barrier comply with the airtightness requirements. Energy Build 54:444–452

Rim D, Novoselac A (2009) Transport of particulate and gaseous pollutants in the vicinity of a human body. Build Environ 44:1840–1849

Roberts S, Martin MA (2007) A distributed lag approach to fitting non-linear dose–response models in particulate matter air pollution time series investigations. Environ Res 104:193–200

Roulet CA, Heidt FD, Foradini F et al (2001) Real heat recovery with air handling units. Energy Build 33:495–502

Sakellari D, Lundqvist P (2005) Modelling and simulation results for a domestic exhaust-air heat pump heating system. In J Refrigeration-Revue Int Du Froid 28:1048–1056

Salthammer T, Schripp T, Uhde E et al (2012) Aerosols generated by hardcopy devices and other electrical appliances. Environ Pollut 169:167–174

Sandberg M, Sjoberg M (1983) The use of moments for assessing air-quality in ventilated rooms. Build Environ 18:181–197

Sangiorgi G, Ferrero L, Ferrini BS et al (2013) Indoor airborne particle sources and semi-volatile partitioning effect of outdoor fine pm in offices. Atmos Environ 65:205–214

Santos HRR, Leal VMS (2012) Energy vs. ventilation rate in buildings: a comprehensive scenario-based assessment in the European context. Energy Build 54:111–121

Santos JM, Mavroidis I, Reis NC Jr et al (2011) Experimental investigation of outdoor and indoor mean concentrations and concentration fluctuations of pollutants. Atmos Environ 45:6534–6545

Satish U, Mendell M, Shekhar K et al (2012) Is $CO_2$ an indoor pollutant? Direct effects of low-to-moderate $CO_2$ concentrations on human decision-making performance. Environ Health Perspect 120

Schleibinger H, Rüden H (1999) Air filters from HVAC systems as possible source of volatile organic compounds (VOC)—laboratory and field assays. Atmos Environ 33:4571–4577

Schmidl C, Luisser M, Padouvas E et al (2011) Particulate and gaseous emissions from manually and automatically fired small scale combustion systems. Atmos Environ 45:7443–7454

Schredl M, Atanasova D, Hormann K et al (2009) Information processing during sleep: the effect of olfactory stimuli on dream content and dream emotions. J Sleep Res 18:285–290

Schuda L, Moya J, Mccurdy T et al (2009) Metabolically derived human ventilation rates: a revised approach based upon oxygen consumption rates. In: EPA (ed.)

Seppänen O, Fisk WJ, Lei QH (2006) Ventilation and performance in office work. Indoor Air 16:28–36

Seppanen OA, Fisk WJ (2004) Summary of human responses to ventilation. Indoor Air 14:102–118

Sfakianaki A, Pavlou K, Santamouris M et al (2008) Air tightness measurements of residential houses in Athens, Greece. Build Environ 43:398–405

Shan K, Sun Y, Wang S et al (2012) Development and in situ validation of a multi-zone demand-controlled ventilation strategy using a limited number of sensors. Build Environ 57:28–37

Sherman MH, Walker IS (2011) Meeting residential ventilation standards through dynamic control of ventilation systems. Energy Build 43:1904–1912

Sidheswaran MA, Destaillats H, Sullivan DP et al (2012) Energy efficient indoor voc air cleaning with activated carbon fiber (ACF) filters. Build Environ 47:357–367

Singh A, Tuladhar B, Bajracharya K et al (2012) Assessment of effectiveness of improved cook stoves in reducing indoor air pollution and improving health in Nepal. Energy Sustain Dev 16:406–414

Sinnott D, Dyer M (2012) Air-tightness field data for dwellings in Ireland. Build Environ 51:269–275

Soimakallio S, Saikku L (2012) $CO_2$ emissions attributed to annual average electricity consumption in OECD (the organisation for economic co-operation and development) countries. Energy 38:13–20

Spitzer IM, Marr DR, Glauser MN (2010) Impact of manikin motion on particle transport in the breathing zone. J Aerosol Sci 41:373–383

Stabile L, Fuoco FC, Buonanno G (2012) Characteristics of particles and black carbon emitted by combustion of incenses, candles and anti-mosquito products. Build Environ 56:184–191

Steinemann AC, Macgregor IC, Gordon SM et al (2011) Fragranced consumer products: chemicals emitted, ingredients unlisted. Environ Impact Assess Rev 31:328–333

Stephens B, Novoselac A, Siegel JA (2010) The effects of filtration on pressure drop and energy consumption in residential HVAC systems (RP-1299). HVAC R Research 16:273–294

Stout JE, Muder RR (2004) Legionella in residential water systems. Ashrae J 46:52–54

Stranger M, Potgieter-Vermaak SS, Van Grieken R (2008) Characterization of indoor air quality in primary schools in Antwerp, Belgium. Indoor Air 18:454–463

Sundell J, Levin H, Nazaroff WW et al (2011) Ventilation rates and health: multidisciplinary review of the scientific literature. Indoor Air 21:191–204

Thomas LP, Marino BM, Tovar R et al (2011) Flow generated by a thermal plume in a cooled-ceiling system. Energy Build 43:2727–2736

Tian L, Lin Z, Wang Q (2011) Experimental investigation of thermal and ventilation performances of stratum ventilation. Build Environ 46:1309–1320

Toftum J, Feund S, Salthammer T et al (2008) Secondary organic aerosols from ozone-initiated reactions with emissions from wood-based materials and a "green" paint. Atmos Environ 42:7632–7640

Toftum J, Jorgensen AS, Fanger PO (1998a) Upper limits for indoor air humidity to avoid uncomfortably humid skin. Energy Build 28:1–13

Toftum J, Jorgensen AS, Fanger PO (1998b) Upper limits of air humidity for preventing warm respiratory discomfort. Energy Build 28:15–23

Tung Y-C, Hu S-C, Tsai T-Y (2009) Influence of bathroom ventilation rates and toilet location on odor removal. Build Environ 44:1810–1817

Tung Y-C, Shih Y-C, Hu S-C et al (2010) Experimental performance investigation of ventilation schemes in a private bathroom. Build Environ 45:243–251

Turner F (2004) Reducing risks from Legionella. Ashrae J 46:5

Ucci M, Biddulph P, Oreszczyn T et al (2011) Application of a transient hygrothermal population model for house dust mites in beds: Assessment of control strategies in uk buildings. J Build Perform Simul 4:285–300

Updyke KM, Nguyen TB, Nizkorodov SA (2012) Formation of brown carbon via reactions of ammonia with secondary organic aerosols from biogenic and anthropogenic precursors. Atmos Environ 63:22–31

Van Bree L, Marra M, Van Scheindelen HJ et al (1995) Dose-effect models for ozone. Toxicol Lett 82–83:317–321

Van Den Bossche N, Huyghe W, Moens J et al (2012) Airtightness of the window–wall interface in cavity brick walls. Energy Build 45:32–42

Van Der Wal JF, Moons AMM, Cornelissen HJM (1991) Indoor air quality in renovated Dutch homes. Indoor Air 1:621–633

Van Hooff T, Blocken B, Aanen L et al (2011) A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations. Build Environ 46:1797–1807

Van Moeseke G, Gratia E, Reiter S et al (2005) Wind pressure distribution influence on natural ventilation for different incidences and environment densities. Energy Build 37:878–889

Vereecken E, Roels S (2012) Review of mould prediction models and their influence on mould risk evaluation. Build Environ 51:296–310

Villafruela JM, Castro F, San José JF et al (2013) Comparison of air change efficiency, contaminant removal effectiveness and infection risk as IAQ indices in isolation rooms. Energy Build 57:210–219

Wachenfeldt BJ, Mysen M, Schild PG (2007) Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation. Energy Build 39:1073–1079

Wallman PH, Pedersen BS, Mowris RJ et al (1987) Assessment of residential exhaust-air heat-pump applications in the United-States. Energy 12:469–484

Wan M-P, Wu C-L, To G-NS et al (2011) Ultrafine particles, and pm(2.5) generated from cooking in homes. Atmos Environ 45:6141–6148

Wang J, Chow T–T (2011) Numerical investigation of influence of human walking on dispersion and deposition of expiratory droplets in airborne infection isolation room. Build Environ 46:1993–2002

Wang S, Zhao B, Zhou B et al (2012) An experimental study on short-time particle resuspension from inner surfaces of straight ventilation ducts. Build Environ 53:119–127

Wang SW, Xu XH (2004) Optimal and robust control of outdoor ventilation airflow rate for improving energy efficiency and IAQ. Build Environ 39:763–773

Wargocki P, Djukanovic R (2005) Simulations of the potential revenue from investment in improved indoor air quality in an office building. ASHRAE Trans 2(111):699–711

Wargocki P, Lagercrantz L, Witterseh T et al (2002a) Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office. Indoor Air 12:74–80

Wargocki P, Sundell J, Bischof W et al (2002b) Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN). Indoor Air 12:113–128

Wargocki P, Wyon DP (2007) The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (rp-1257). HVAC R Research 13:193–220

Wargocki P, Wyon DP, Lynge-Jensen K et al (2008) The effects of electrostatic particle filtration and supply-air filter condition in classrooms on the performance of schoolwork by children (rp-1257). HVAC R Research 14:327–344

Weschler CJ (2009) Changes in indoor pollutants since the 1950s. Atmos Environ 43:153–169

Weschler CJ, Nazaroff WW (2008) Semivolatile organic compounds in indoor environments. Atmos Environ 42:9018–9040

Wheeler AJ, Dobbin NA, Lyrette N et al (2011) Residential indoor and outdoor coarse particles and associated endotoxin exposures. Atmos Environ 45:7064–7071

Wolkoff P (1998) Impact of air velocity, temperature, humidity, and air on long-term voc emissions from building products. Atmos Environ 32:2659–2668

Wong LT, Mui KW, Hui PS (2006) A statistical model for characterizing common air pollutants in air-conditioned offices. Atmos Environ 40:4246–4257

WTCB. 2012. EPBD [Online]. Available: http://www.epbd.be/media/pdf/donnees_produits_peb/product_data/4-4_ventil_NL.pdf. (Accessed)

Wu FF-S, Wu M-W, Pierse N et al (2012) Daily vacuuming of mattresses significantly reduces house dust mite allergens, bacterial endotoxin, and fungal beta-glucan. J Asthma 49:139–143

Wu X, Apte MG, Maddalena R et al (2011) Volatile organic compounds in small- and medium-sized commercial buildings in California. Environ Sci Technol 45:9075–9083

Xu J, Zhang JS An experimental study of relative humidity effect on VOCs' effective diffusion coefficient and partition coefficient in a porous medium. Build Environ 46:1785–1796

Yoshino H, Murakami S, Akabayashi S-I et al (2004) Survey on minimum ventilation rate of residential buildings in fifteen countries. AIVC, Prague

Younes C, Shdid CA, Bitsuamlak G (2012) Air infiltration through building envelopes: a review. J Build Phys 35:267–302

Yu CWF, Kim JT (2012) Long-term impact of formaldehyde and voc emissions from wood-based products on indoor environments; and issues with recycled products. Indoor Built Environ 21:137–149

Zhang J, Bai Z, Chang VWC et al (2011a) Balancing BEC and IAQ in civil buildings during rapid urbanization in China: regulation, interplay and collaboration. Energy Policy 39:5778–5790

Zhang T, Yin S, Wang S (2011b) Quantify impacted scope of human expired air under different head postures and varying exhalation rates. Build Environ 46:1928–1936

Zhang Y, Mo J, Li Y et al Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. Atmos Environ In Press, Accepted Manuscript

Zhong K, Yang X, Feng W et al (2012) Pollutant dilution in displacement natural ventilation rooms with inner sources. Build Environ 56:108–117

Zhou YP, Wu JY, Wang RZ (2007) Performance of energy recovery ventilator with various weathers and temperature set-points. Energy Build 39:1202–1210

Zukowska D, Melikov A, Popiolek Z (2012) Impact of personal factors and furniture arrangement on the thermal plume above a sitting occupant. Build Environ 49:104–116

Zuraimi MS (2010) Is ventilation duct cleaning useful? A review of the scientific evidence. Indoor Air 20:445–457

Zuraimi MS, Magee R, Nilsson G (2012) Development and application of a protocol to evaluate impact of duct cleaning on IAQ of office buildings. Build Environ 56:86–94

Zuraimi MS, Nilsson GJ, Magee RJ (2011) Removing indoor particles using portable air cleaners: implications for residential infection transmission. Build Environ 46:2512–2519

# Insulation Materials Made with Vegetable Fibres

**Xiaoshu Lü, Tao Lu, Olli Lipponen and Martti Viljanen**

**Abstract** Vegetable fibres are finding increasing applications in building industry due to their economic, energy and environmental sustainability. In view of utilization of insulation materials made from vegetable fibres for near zero energy buildings, this chapter presents a summary of physical, mechanical and chemical characteristics of vegetable fibres incorporating building insulating properties with recommendations and suggestions. Subsequently, relevant issues of the raw materials and the manufacturing processes that lead to certain common characteristics are highlighted. The greatest challenge in working with vegetable fibres is their large variations in thermal properties and characteristics dependent on their complex architectures of geometrical structures. Mathematical models are of great importance in understanding and predicting the thermal performances of the fibres and their global responses in the building system. Coupled heat and mass transfer through a fibrous insulation in buildings is therefore studied. The most important vegetable fibrous composites, properties of the composites and their applications in buildings are briefly reviewed also. The chapter provides a guide to the fundamentals and latest developments in building insulation technology for vegetable fibrous materials.

## 1 Introduction

The EU Directive has set ambitious binding targets for 20 % share of energy from renewable sources by 2020 (EC 2005). Among renewable energy sources, the biggest contribution (63 %) comes from biomass. As biomass is all vegetable-based materials generically, vegetable-based natural materials are gaining

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increasing popularity as potentially renewable structural materials in building industry. These materials are low cost, environmentally sustainable, recyclable, nontoxic and healthy constructions of green buildings. Examining their thermal performances, physical, mechanical and chemical properties is key to understanding their overall insulating behaviour and global responses to internal and external stimuli, such as temperature, moisture and other inputs from building's heating, ventilating and air conditioning (HVAC) system and climate. Most importantly and challengingly, the mandatory EU standard requires nearly zero energy buildings (NZEB), or zero energy buildings (ZEB), for all new buildings by 2020 and for public buildings by 2018 (Parliament 2010). Energy-efficient insulating systems are no doubt one of the keys to achieving these future energy goals. There is need for a new design paradigm of energy-efficient and sustainable insulation materials, which lies at least partially within the study of vegetable-based natural fibres as they are playing an increasingly key role in green buildings and are definitely the step in the direction towards sustainable future of building materials (Infolink 2011).

Natural fibres have been used historically to produce insulation in pipes and building materials. The use of natural fibres, for example hemp fibres, goes back the ancient Egyptians, Greeks, Romans and China. Hemp was cultivated in China in 2800 BC and was used to make papers, ropes and other fabric products. Some developments have taken place in natural fibre history since then; however, growth has been slow until the Second World War owing to economic demands of the post-war building boom (Lotz 2006). Today, fibrous materials are still the most widely used insulating materials in buildings. However, natural fibres have been limited by the inherent qualities available in the natural world. Since the 1960s, the insulation industry has moved to synthetic fibres causing natural fibre industry to lose much of its market. But in recent years, the fibre markets are once again shifting towards the natural fibres because of the increase in oil prices and environmental concerns. Natural plants, for example, are discarded after harvest which have no economic values but may have negative health effects on people and environment. Re-utilizing these natural materials as renewable resources would bring economic, environmental and societal benefits as they can be produced indefinitely. However, natural materials need to process to achieve particular properties depending on the applications and it may be expensive to manufacture. The current challenges and trends have led to innovative processing technologies which should reduce costs of production, processing, distribution and marketing in the near future.

Natural vegetable fibres, produced from plants, have a large-scale production worldwide which has made an important contribution to the global economy. They are often easily extracted from the stems, the leaves, the inner barks or seed pods in various plants. Insulation can be made out of them, such as wood, cotton, hemp and flax.

Natural vegetable fibres as grown in fields and trees change their state, structure, and, consequently, have large variations in thermal, physical, mechanical and chemical properties dependent on their complex architectures of geometrical structures. Due to the evolution and adaptation to changeable conditions in nature, their structures are hierarchically organized and optimized with multifunctions which make them outperform man-made synthetic insulation in strength, durability, and thermal and moisture performances. Most natural fibres are hygroscopic in nature and they absorb and release moisture depending on environments which can reduce the condensation and mould risks through careful design process. They also have the unique ability to absorb volatile organic compound gases and lock them up permanently which reduces health risks. These unique features as "breathable" materials are especially important in achieving NZEB/ZEB goal as the use of thick and very airtight insulation, or even super insulation, is an essential solution in zero energy buildings. Very thick insulation tends to increase the moisture levels of the constructions and the risks of condensation, mould, mildew and structural damages if it is not designed or installed properly. Therefore, these good features, such as breathable and moisture-absorbable, plus low processing costs make vegetable fibres by far the most common materials used in insulation market (Crosson 2012).

However, the strong ability to absorb water means that vegetable fibres are prone to becoming saturated or swelling to mould growth and the structures may gradually deteriorates. Their hydrogen bonds account for fibres' strong ability to absorb water. Due to hydrogen bonding of water molecules to the hydroxyl groups within the fibre cell wall and fibre–matrix interface (Rowell 1997), natural fibres can contain high moistures which support mould growth. Some moulds are known human pathogens and found in natural vegetable fibres and fibre-processing plants (Forgacs et al. 1972). Generally, borates are added to the vegetable fibres acting as a fungicide, insecticide and fire retardant in the insulation manufacturing process. Note that processing of natural fibres must be also designed to be green and chemical free simultaneously to ensure a sustainable manufacturing process for green insulating products, which entails challenges. Therefore, an understanding of the performance of vegetable-based fibres from growing the plants to the manufacture of insulating products by researchers is of growing importance. Such knowledge is critical to the design and control of energy-efficient and sustainable buildings because insulation in buildings is not independent unit, but part of the building system.

This chapter presents an update of literature reviews on vegetable-based fibres, composites and their physical, mechanical and chemical characteristics incorporating building thermal insulating properties with recommendations and suggestions. Subsequently, relevant issues of the raw materials and the manufacturing processes that lead to certain common characteristics are highlighted. The greatest challenge in working with vegetable fibres is their large variations in thermal properties and characteristics dependent on their complex architectures of geometrical structures. Mathematical models critical to understanding and predicting the thermal performances of the fibres and their global responses in the building system as insulation systems are an important part of building systems. Therefore, heat and mass transfer through fibrous insulations in buildings is briefly presented since the basic theories and models associated with fibrous insulations do not differ from those with porous media. The fibrous insulation materials, their composites, properties of the composites, their applications and available studies on most relevant to vegetable-based fibres are reviewed with an overview of the opportunities and challenges associated with their utilization. Finally, some open problems that may in turn play important role in years to come are discussed and several research perspectives are proposed. The chapter provides a guide to the fundamentals and latest developments in building insulation technology for vegetable fibrous materials.

## 2 Overview of Nearly Zero Energy Building and Insulation

### *2.1 Nearly Zero Energy Building*

Directive 2010/31/EU (2010) defines "Nearly Zero Energy Building" (NZEB) as a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Since the Directive did not provide a definite energy requirement of NZEB technically, researches on applications of the definition from different Member States are still on-going. But NZEB commonly refers to the operational energy of the building, ignoring the energy inputs from the construction and delivery of the building and its components. Good thermal insulation, high levels of air tightness and ventilation with very efficient heat recovery are essential for minimizing energy usage. The use of thick and very airtight insulation, or even super insulation, is no doubt one of the essential solutions. Figures 1 and 2 show the changes of insulation thickness in both walls and roofs between 1982 and 1999 in Europe (Papadopoulos 2005). Increasing trends are clearly seen over the years.

### *2.2 Building Insulation*

In buildings, thermal insulation is installed in various types of building construction such as walls, roof, floor, pipes and ducts to protect the building and to provide thermal comfort for its occupants. Table 1 presents some of the examples (Desideri et al. 2012).

The materials of the insulation are used to reduce heat transfer and satisfy the requirements depending on the building construction design, climate, energy costs and many other factors. Combination of different insulation materials is often applied to achieve an optimum of the overall thermal performance. The design and control of building systems is a complex process which necessitates the use of

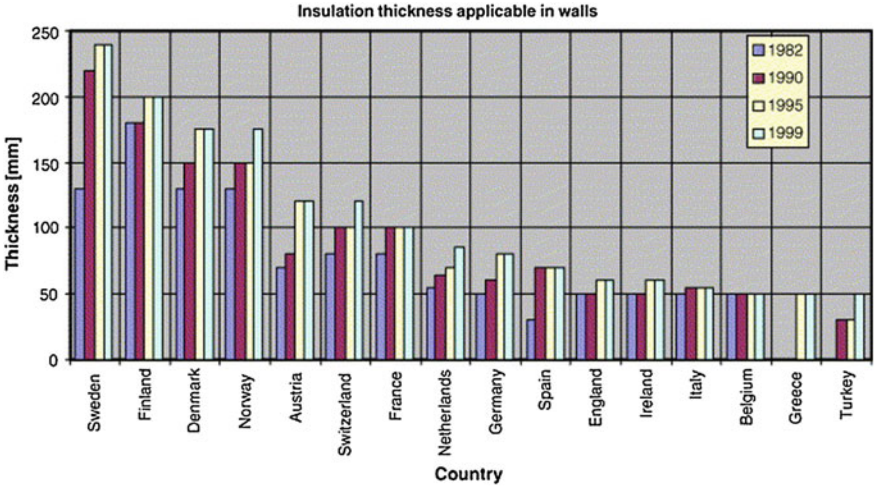


**Fig. 1** Changes of insulation thickness in walls in Europe (Papadopoulos 2005); reprinted here with kind permission of Elsevier, 2013

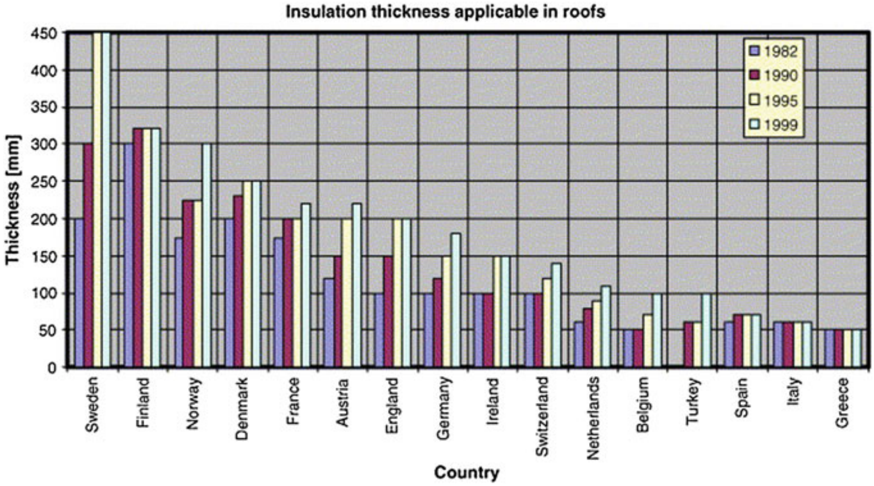


**Fig. 2** Changes of insulation thickness in roofs in Europe (Papadopoulos 2005); reprinted here with kind permission of Elsevier, 2013

mathematical models and simulations, see below sections of heat and mass transfer models.

Building insulation materials can be classified in a number of different ways according to different criteria. Here, we broadly classify them at three levels in a hierarchical tree-like structure, see Fig. 3. At the highest level, building insulations

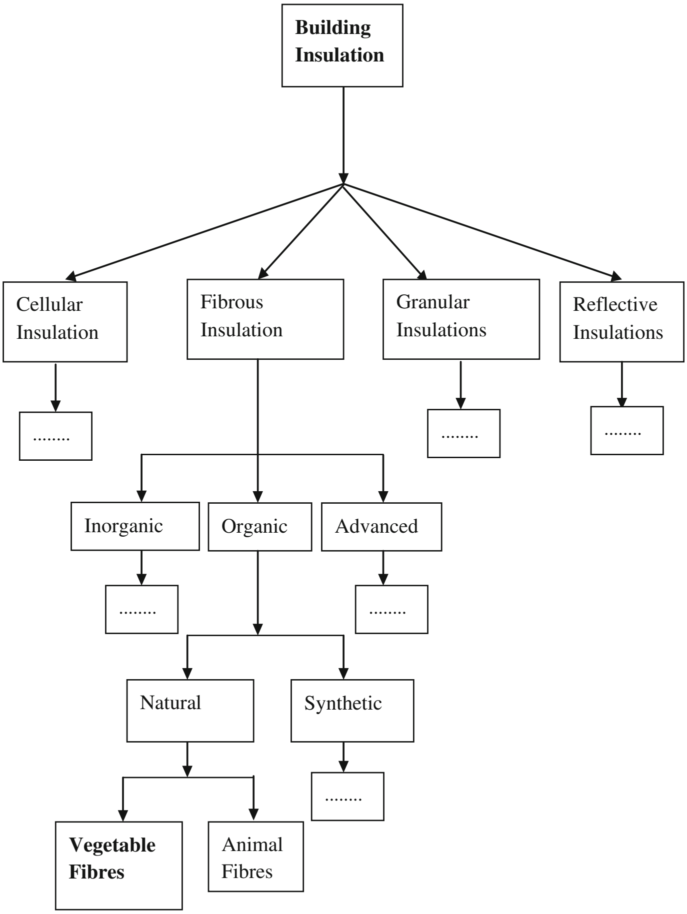


**Fig. 3** Classification of fibrous materials

are categorized into four classes (Turner and Malloy 1981): (1) cellular (2) fibrous (3) granular and (4) reflective insulations.

Cellular insulations are composed of small individual cells which are either interconnected or sealed from each other for forming a cellular structure. Examples of insulation materials are polystyrene and polyisocyanurate. Granular insulations are composed of small nodules that contain voids or hollow spaces. The materials are sometimes considered as open-cell materials as gases can be transferred between the individual spaces. Examples of insulation materials are expanded polystyrene. Reflective insulations consist of layers of reflective foil materials on surfaces as reflective surfaces to reduce the radiate heat to or from the surfaces. Examples of insulation materials are various radiant barriers. Fibrous insulations are composed of small diameter fibres that finely divide the air space.

**Table 1** Examples of installed insulations in buildings

| Building components | |
|---|---|
| Walls | 1. *Exterior*: installed in the exterior walls |
| | 2. *Interior:* installed in the interior surface of the walls |
| | 3. *Ventilated*: installed in the direct contact with the wall and separated from the lining |
| | 4. *Gap:* installed between two vertical elements |
| Roofs | 1. *Intrados*: installed directly on the pitch structures |
| | 2. *Under the outer skin (warm roof)*: installed just below tiles, pantiles or slabs |
| | 3. *Under the outer skin (vented roof)*: placed under the vent |
| Floors | 1. *Floors on the ground and vented crawl space*: installed on the extrados of the floor |
| | 2. *Insulation of floor intrados (or lower surface)*: insulation of the floor which looks out onto porticoes or open spaces |
| | 3. *Insulation of floor extrados (or upper surface)*: insulation of floor covering open spaces or basements |

The fibres, both organic and inorganic, may be bonded together. Examples of insulation materials are fibreglass and mineral wool.

Further hierarchical organization of fibrous insulations can be grouped according to the properties and origins of the fibres that they are made out of as organic, inorganic and advanced fibres. At the organic natural level, fibres can be divided broadly into two categories as natural and man-made, or synthetic, fibres, such as oil-derived fibre, while natural fibres can be further subdivided as vegetable-based and animal-based fibres.

Vegetable fibres, also called plant fibres or lingnocellulosic fibres, are those that originate from plants and have plant anatomy. They are characterized by light weight, low thermal conductivity, strong tension, superior acoustic resistance, flexibility and low processing cost. As a potential energy-efficient and sustainable source for NZEBs/ZEBs in insulation industry, vegetable fibres would open up a new potential market for building construction materials as already demonstrated in building industrial application (Bisanda 1993). From a production process point of view, it has been reported that the energy needed for production of vegetable fibres is, on average, more than half of the amount needed for synthetic fibres (Cristaldi et al. 2010). This figure highlights a high perspective for vegetable fibre markets. This chapter will focus on vegetable fibres.

## 3 Vegetable Fibres and Manufacturing Process

### *3.1 Vegetable Fibres*

All plants are made up from cells. When a cell is very long in relation to its width, it is called a fibre (Olesen and Plackett). Vegetable fibres have long cells characterized by relatively thick walls and narrow central cavities. Different plants

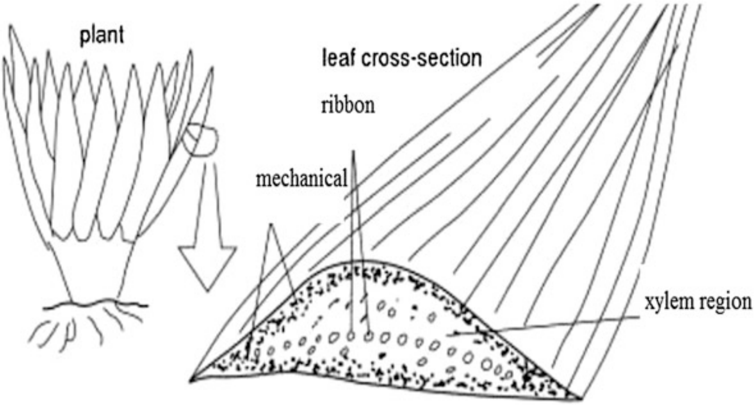


**Fig. 4** An illustration of the cross section of a sisal leaf; adapted from (Li et al. 2000a) with kind permission of Elsevier, 2013

contain several different types of fibres. Sisal, for example, contains three types of fibres: mechanical, ribbon and xylem, see Fig. 4 the cross section of a sisal leaf.

Like building insulation materials, vegetable fibres can also be categorized in many different ways. A more detailed version of their classification has been provided by Suddell which classified them as (Suddell 2008): (1) straw (e.g. corn and wheat); (2) grass (e.g. bamboo); (3) bast (e.g. flax and hemp); (4) leaf (e.g. sisal); (5) seed (e.g. cotton); (6) fruit (e.g. coconut and pineapple); and (7) wood (e.g. pinewood and sawdust, depending on their original sources).

As described in (Suddell 2008), vegetable fibres are rich in different types and functions determined by their various and complex structures. All plant and vegetable cells have cell walls which provide support and strength for them. Cell walls are important features for their cells that perform specific and essential functions. As the plant or vegetable matures, the cell walls thicken and give more strength and stiffness. There are two main classes of cells: single-celled vegetable fibres, cotton for instance, are called ultimates. They have unicellular structure. Most vegetable fibres are multicellular-structured with a bundle of single cells of varying lengths and widths. The cell walls are complex composites which have hierarchical internal structures consisting of cellulose fibrils embedded in lignin hemicellulose matrix.

The major component in the cell walls of vegetable fibres is cellulose which is a long chain of linked sugar molecules that gives fibres or their cell walls the strength. The chains are held together by amorphous hemicellulose and lignin and form microfibrils. The microfibrils are submicroscopic structures that are grouped to form the fibrils which in turn are grouped to form the fibres, see Fig. 5 of a schematic structure of a fibre adapted from (Dufresne 2008; Rong et al. 2001; Pietak et al. 2007).

From Fig. 5, we can see that fibres exhibit a multiscale structural hierarchy. This structural hierarchy can play a major part in determining the fibres'

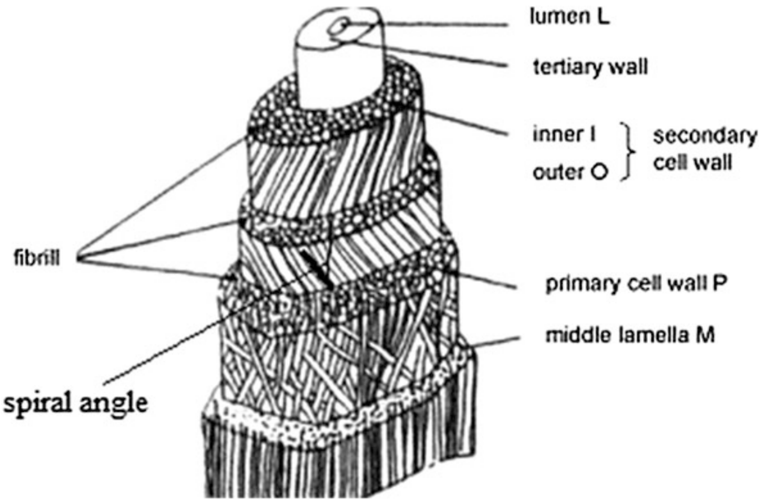


**Fig. 5** Schematic structure of a fibre; adapted from (Dufresne 2008; Rong et al. 2001; Pietak et al. 2007) with kind permission of Elsevier, 2013

properties. Understanding the effects of hierarchical structure can guide the synthesis of fibre-reinforced materials with properties which are tailored for specific applications. Figure 5 shows that each fibre is consisted of a primary wall, a secondary wall, a lumen and middle lamellae. The central region of the fibre is the hollow lumen which transports water and nutrients to the plant or vegetable. The cell wall has four layers which perform rigidity functions depending on the way the cellulose microfibrils are arranged. Each layer has characteristics variations in morphology and composition (Pietak et al. 2007). The microfibrils in most natural fibres orient themselves at an angle to the fibre axis called the microfibril angle, see the spiral angle in Fig. 5. A weak correlation between strength and cellulose content and microfibril or spiral angle is found for different vegetable fibres. Roughly speaking, fibre strength increases with increasing cellulose content and decreasing spiral angle with respect to fibre axis (Dufresne 2008). In nature, the hierarchical structure is primarily driven by chemistry of specific interchain and intrachain interactions (NMAB 1994). In the following subsection, a brief description of some of the basic and important chemical components for vegetable fibres is presented.

## *3.2 Chemical Composition*

The chemical composition of vegetable fibres varies greatly from one type of vegetables and one vegetable to another depending on age, environment, season and extraction process. The principal constituents are cellucose, hemicellucose and

**Table 2** Chemical composition of some vegetable fibres (percentage of total)

| | Cellulose | Hemicellulose | Lignin | Pentin |
|---|---|---|---|---|
| Flax | 71 | 19 | 2.2 | 2.0 |
| Hemp | 75 | 18 | 3.7 | 0.9 |
| Jute | 72 | 13 | 13 | 0.2 |
| Ramie | 76 | 15 | 0.7 | 2.1 |
| Abaca | 70 | 22 | 5.7 | 0.6 |
| Sisal | 73 | 13 | 11 | 0.9 |
| Cotton | 93 | 2.6 | 0 | 2.6 |
| Kapok | 64 | 23 | 13 | – |

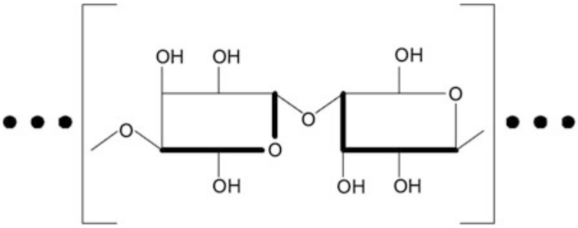
lignin (Reddy and Yang 2005). Other components, such as pectin, ash and waxes, can be found in much lower quantities generally. Table 2 illustrates an example of the chemical analysis of the major components of some vegetable fibres (Roberts 2007). As can be seen, a substantial variation is observed for the constituents which can be attributed to nature.

A more detailed description of the chemical composition of vegetable fibres can be found in (Mishra 2000; Saheb and Jog 1999; Bismarck et al. 2005). Most of them, such as, flax, hemp, jute, ramie, sisal and palm, are composed of cellulose, hemicelluloses and lignin with varied proportions, except for cotton that has principally cellulose.

Cellulose is generally the main component of the cell walls in vegetables and makes the fibres strong and flexible. Cellulose is a long-chain polymer made by the linking of smaller molecules. Its long-chain polysaccharides consist of glucose units as links. Figure 6 presents the basic chemical structure of cellulose. Each monomer bears hydroxyl groups which form hydrogen bonds. The hydrogen bonds play a major role in directing the structure and governing the physical properties of the cellulose, for example its moisture-absorbable property.

Specifically, cellulose acts as the basic building block for the fibrous materials for providing strength and stability to the walls and the fibre (Paster et al. 2003). The existence of cellulose as in plant and vegetable cell walls was first discovered by Anselm Payen in 1838. The Young's modulus of the basic cellulose crystalline nanocrystal is roughly 130 GPa, and its tensile strength is close to 1 Gpa which is potentially stronger than steel and similar to Kevlar (Gibson 2012; Dufresne 2008). Gibson reviewed the composition and microstructure of the cell wall and the

**Fig. 6** Basic chemical structure of cellulose



cellular structure in three plant materials, wood, parenchyma and arborescent palm stems, in related to the mechanical properties of the vegetable fibres (Gibson 2012). The amount of cellulose in a fibre affects the fibre's mechanical properties. Fibre's strength and stiffness has been found to correlate weakly with the cellulose content (Lee 1991).

Hemicellulose of vegetables is a sort-chain, unlike cellulose, partially soluble polysaccharides consisting of glucose units. Hemicellulose is embedded in the cell walls acting as filler between cellulose and lignin (Reddy and Yang 2005). Mechanically, hemicellulose contributes little to the stiffness and strength of fibres or individual cells (Thompson 1993).

Lignin consists of various aromatic polymers with complex structures. Nonlignocellulosic fibres, for example, potatoes, beets and cotton, are fibres that do not contain lignin. Lignin binds to cellulose fibres and hardens and strengthens the cell walls to protect the carbohydrates from chemical and physical damage (Saheb and Jog 1999). Lignin plays major roles in determining the mechanical properties of the cell wall. Generally, fibres with a lower amount of cellulose have a higher lignin content, which appear finer and more flexible (Sukumaran et al. 2001).

The most important structures of vegetable fibrous cellulose cell wall and microfibrils are shown in the diagram Fig. 7, which provide a clear illustration of how they are organized in a hierarchical structure (Energy 2010; Siqueira et al. 2010).

## 3.3 Raw Materials

The raw materials of fibrous insulations can be categorized according to the fibre classification presented in Fig. 3 based on the specific type of insulation product. Among the vegetable fibres that are regularly used as building insulators, bast fibres of flax and hemp are the most widely adopted raw materials for thermal insulations. Tow of these fibres has traditionally been used in insulation tapes

**Fig. 7** Schematic diagram of structures of vegetable fibrous cellulose cell wall and microfibrils

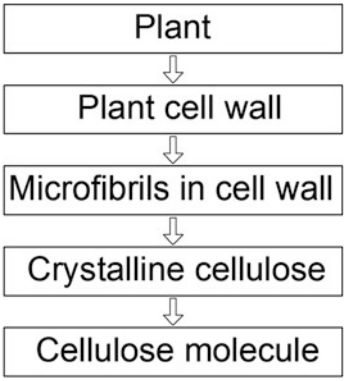


**Fig. 8** Flax and flax fibre insulation product

between timbers. During the past decades such fibres have been commonly used in commercial mats and loose-fill insulations for modern houses (Kymalainen and Sjöberg 2008). Figure 8 shows an example of the natural flax and the processed insulation product (http://www.ekologiskabyggvaruhuset.se/638/linisolering). Thermal properties of some of the common insulations are provided in Table 3 (Kymalainen and Sjöberg 2008).

Other typical vegetable fibres as raw materials for insulation materials include cork from natural cork oak, kenaf, cotton, sawdust from wood, straw, moss and wood, to cite a few examples. Many studies have been done on physical and chemical properties of vegetable fibres as raw materials used to manufacture thermal insulations. A life cycle assessment of a kenaf-fibre insulation board from kenaf production and board manufacture was conducted in (Ardente et al. 2008). Results showed a reduction in the environmental impacts, high thermophysical and noise-abatement properties of the insulations based on kenaf fibres. Lazko et al. (2011) investigated the thermal and hygroscopic performance of insulating materials based on flax short fibres in which the linseed oil was added to improve their hydrophobicity. They found that the high water affinity of the short fibres composites was significantly reduced by a linseed-oil-based hydrophobic treatment.

**Table 3** Thermal properties of some insulations with flax and hemp as raw materials, adapted from (Kymalainen and Sjöberg 2008) with kind permission of Elsevier, 2013

| Insulation Type | Raw material | Density (Kg/m$^3$) | Conductivity (W/m K) |
|---|---|---|---|
| – | Flax | – | 0.040–0.046 |
| Mat | Flax | 5–50 | 0.038–0.075 |
| – | Flax | 20–100 | 0.035–0.045 |
| – | Flax and hemp | 25–40 | 0.050 |
| Mat | Flax and hemp | 39 | 0.033 |
| Mat | Flax and hemp | 19 | 0.060 |
| Mat | Hemp, retted | 5–50 | 0.040–0.082 |
| Mat | Hemp, green | 5–50 | 0.044–0.094 |
| Loose-fill | Hemp, frost-retted | 25–100 | 0.040–0.049 |
| – | Hemp | 20–45 | 0.040–0.060 |

**Table 4** Productions of flax and hemp fibres in top EU countries in 2005/2006

| Flax(tons) | Hemp(tons) |
|---|---|
| France(178 500) | France(18 000) |
| Belgium(26 547) | Germany(3 768) |
| The Netherlands(8412) | Spain(2 047) |
| Czech Rep.(4700) | UK(1062) |
| Lithuania(4337) | – |

In summary, studies show that vegetable fibres as raw materials of building insulation materials are increasingly being used to substitute for conventional materials. Today, the annual distribution of production of vegetable fibrous raw materials is about 4 billion tons, of which roughly 60 % comes from agricultural crops and 40 % from forests (Olesen and Plackett). As an illustration, Table 4 shows top EU countries and annual productions of flax and hemp. For vegetable fibre composites, approximately $2 \times 10^{11}$ tons of lignocellulosics are produced annually in contrast to $1.5 \times 10^{8}$ tons of synthetic polymers (Reddy and Yang 2005).

This growing trend has been well described in the literature, for example (Satyanarayana et al. 2009a), demonstrating particularly strong interest in vegetable fibre-based composites in building markets since natural fibres have the additional advantage of being composted or recycled with calorific value recovered at the end of their life cycle, which is not possible with glass fibres (Hill et al. 1998). Furthermore, they have significantly less energy and cost for manufacturing and do not affect the manufacturing tools. A short review briefly illustrating their manufacturing process and the main results in composite construction will be provided in the following subsections.

### *3.4 Manufacturing Process*

Manufacturing involves processing vegetable fibres into the products to satisfy needs of insulation products. Manufacturing enterprises use various raw machines and in operations organized according to the well-prepared plan or schedule. Today, manufacturing strategies generally integrate environmental sustainability so that the entire manufacturing process, beginning with the basic raw materials and ending with the products, requires ecological. All the raw materials used in the manufacture of the insulation can be recycled in the process. At the end of life cycle of building, vegetable fibrous materials can be recycled back to the insulation material. The whole manufacturing process can be very complex and affected by many factors. Depending on the unique application and requirement, manufacturing processes can vary and big differences of qualities can be obtained at the end of the process even if for the same type of insulation product. Additionally, manufacturers may have confidential information about the processes. Nevertheless, the aim of any manufacturing is to provide customer satisfaction for the industry.

In building industry, the uses and purposes of fibrous insulation products are mainly for cavity walls, solid walls, structural insulated panels, roof insulation, and insulation materials for heating systems as well as water services. Each product has its own role in different applications depending on its general properties. All products are likely to have both advantages and disadvantages for use in certain applications. Therefore, every property required for an application influences material selection in varying degrees. When choosing a material, consideration needs to be given such as to the thickness requirement, fire resistance, acoustic performance, breathability and reliability (BNIM01 2008). Very often, a combination of different types of product would help to satisfy a wider range of requirements. Nevertheless, the very first step is to select raw materials. The selection rules are the same as those applied to the products, according to many criteria including their thermal, physical, mechanical and chemical properties, cost, and their human and environmental safety. Obviously, the basic criteria are the resources of the particular type of raw material, the cost and the manufacturing progress.

Fundamentals of fibre manufacturing process comprehensively cover the principles of transport phenomena and chemical reaction engineering (Weinberger 1996). Figure 9 summarizes the four main areas of fibre manufacture: pumping, filtration, fibre forming and fibre treatment, focusing on the fundamentals associated with the transport phenomena of fibre production based on the study of (Weinberger 1996).

For vegetable fibres, the most commonly used manufacturing process can be roughly divided into three different steps involving harvesting, fibre processing and utilization (Dam 1999), depending on many different factors, such as quality of the raw materials and quantity of the final product. Figure 10 presents the steps.

Harvest is the process of collecting mature vegetables from the fields which, basically, involves two processes associated with vegetable fibre: pulling and reaping. The raw material, flax and hemp for example, is pulled using specific machines or hands. After pulling, the plants are laid on the filed for drying before going through retting and extraction process.

The extraction and retting process has a major impact on the fibre product quality. Vegetable fibres can be extracted manually or mechanically by machines

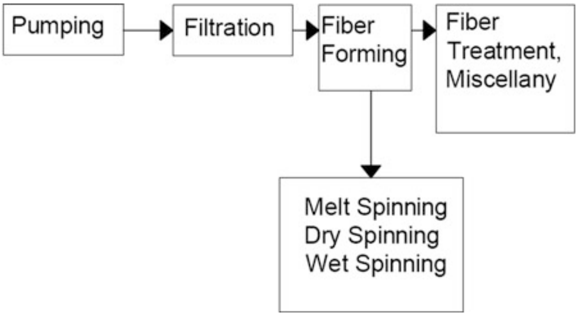


**Fig. 9** Synthetic fibre module

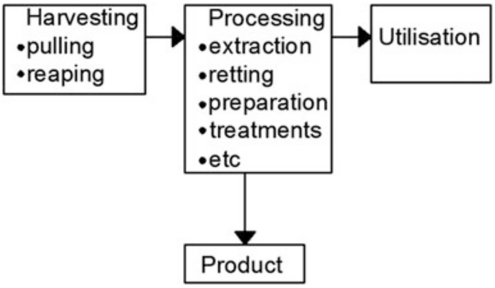


**Fig. 10** Illustrative production diagram

through traditional or advanced techniques. Figure 11 shows some of the major extraction methods which are detailed in (Satyanarayana et al. 2007).

Retting is the biological process of extracting natural fibres (Agriculture 2000). In the retting process, the pectin and lignin between the fibre bundles are dissolved so that the fibres can be extracted. The available retting process includes mechanical, chemical retting, steam/vapour/dew retting and water or microbial retting.

Traditionally, bacteria and fungi are used in the retting process to remove lignin, pectin and other substances (Sumere 1992). Dew or field retting by fungi mainly is most commonly applied process using this method. Another commonly applied process by this method is water retting which involves bacteria as the main agent. Water retting produces better quality fibres than dew retting does generally with more cost. Water retting has been largely abandoned in some countries due to its cost and pollution.

**Fig. 11** Extraction processes of some lignocelluosic fibres (Satyanarayana et al. 2007); reprinted here with kind permission of Elsevier, 2013

Good quality natural fibres can be obtained with these traditional methods. However, long duration and intensive care are normally needed and its control is difficult (Reddy and Yang 2005). Uncontrollable weather conditions of humidity, temperature and sun have large influence on the retted products. Direct correlation has been demonstrated between retting time and fibre strength. Both dew retting and water retting processes suffer large fibre product variations.

To improve the traditional methods, chemical and enzymatic methods (Henriksson et al. 1997) have been applied in order to reduce product variability. In this process, chemical agents, such as alkalis, sodium hydroxide and enzymes, are used. For enzymatic fibre extraction, agents such as pectinases, hemicellulases and cellulases are employed with a pre- or post-chemical treatment. Chemical concentration, temperature and duration of the process can effectively control the extracted fibre quality.

Mechanical retting uses decorticating machines, steam explosion, Tilby cane and other mechanical means to extract the fibres. At the end of the retting process, the fibres are washed, dried and extracted manually or mechanically for multi-functional utilization.

Each type of retting has certain advantages and disadvantages (Sharma et al. 1989). Selection of these retting processes depends on the production requirement, location, the equipment and the cost. Retting method influences fibre quality properties. Control of the factors affecting field retting is very difficult and has always been a problem.

Retting and extraction processes have a profound effect on the quality of the fibre produced. The production process is often very labour-intensive and costly. The length of the retting process is critical for the whole manufacturing process. Mishra (2000) presented time duration of the three commonly used retting processes for jute fibres. Averagely, 7–15 days are needed in dew retting, 10–30 days are required in water retting and only 6–8 hours are estimated in chemical retting. Chemical retting has apparent advantages over other processes. These figures showed large variations over duration days in water retting.

Next, the fibres enter the conveyor belt of the secondary mineral wool layer where they are thermally treated and finalized to the desired density, thickness and size. Then, they are collected in a chamber and mechanically formed, for example by compression, into the final product. More detailed description of the manufacturing process can be found in (Pasila 2004). Figures 12 and 13 illustrate simple production lines for flax and short fibre (Pasila 2004).

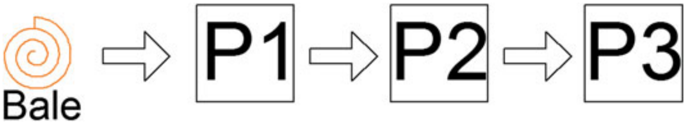


**Fig. 12** Illustrative production line for flax bales. *P1* opening the mat-form bale, *P2* decorticating, *P3* scutching the fibres

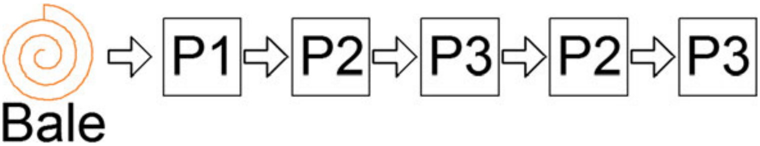


**Fig. 13** Illustrative production line for short fibre bale. *P1* opening and pretreatment, *P2* decorticating, *P3* shaking sieve

## 4 Vegetable Fibrous Materials Characteristics and Properties

"Characteristics and properties", here, refer to the insulation performances of the vegetable fibres. The characteristics and properties of vegetable fibres are strongly influenced by many factors, e.g., chemical composition, internal fibre structure, such as microfibril angle and cell dimensions, which differ from different parts of a vegetable as well as from different species of vegetables (Dufresne 2008). We should always bear in mind that the manufacturing process also affects the properties of the raw materials. As a result, the overall insulation performances of vegetable fibres are determined by the combined effects of these properties and many other unknown and uncontrollable factors. The resulting insulator can display a wide range of properties; however, some common features are highly conserved. The following subsection describes these common properties together with key criteria for assessing building insulation sustainability associated with vegetable fibres.

### *4.1 Requirements of Insulations*

The sustainability criteria by which the insulations are measured cover two main criteria: reducing both energy demand and environmental impacts. Both elements are essential to achieve the overall sustainability performances of the products. The primary energy requirements of the commonly used insulation materials are the measures of materials' technical performances based on the physical properties. Many standards are available today, such as EN and ASTM, for general guidance. Some of the key properties are presented in (ISO 6946:2007, 1996).

The primary environmental requirements of the commonly used insulation materials are the measures of materials "ecological performances" based on the properties which can in principle be assessed in a wide variety of ways, and hence are not clearly stated and even less commonly accepted (Papadopoulos 2005). Some of the key properties include the primary embodied energy, the gas emissions, the waste treatment, the re-usability or the recyclability, which are associated with a range of health effect assessment including dust and fibres emissions, biopersistence and toxicity. A number of standards have been adopted. However, there has not been any consensus about the criteria. Nevertheless, these criteria have provided a basis of study for the sustainable properties of vegetable fibrous insulations that are used and examined today. Based on these requirements, vegetable fibrous materials sustainable properties are presented below.

## 4.2 Insulating Properties

As described previously, porous fibres have the void structures which make them very good at reducing heat, sound, electrical and chemical transfer. They are at low thermal conductivity due to the trapped air or gases in the void pores and hollow lumens. Therefore, they are naturally resistant to heat losses through both conduction and convection. Their cellulose contains many polar hydroxyl groups which make fibres structurally strong and resistant to chemicals.

The thermal conductivity range of all vegetable fibres is 0.29–0.32 W/m.K (Wallenberger 2004) with large specific heat capacity of the order of 1900 J/kg. K (Mussig 2010). Therefore, they make a good thermal insulation. Furthermore, approximately constant conductivity is observed for most vegetable fibrous insulators over a large range of temperatures. This thermal property plays an important role in extreme temperatures. Thus, under extreme cold and hot conditions, they outperform many other types of insulators, for example, fibreglass and mineral fibres, with more consistent R-value (ASHRAE "Handbook of Fundamentals", BNL 50862).

The densities of vegetable fibres lie roughly in the 1.25–1.51 g/cm3 (Beckwith 2003) which are of the same order as those of plastics and only half of those of glass fibres (Natural-fibre-reinforced polyurethane microfoams, Andrzej K. Bledzki). They are light weighted, flexible and easily to shape which possess the greatest potential for lightweight construction. Lightweight construction is a trend that is present in building construction industry. Furthermore, when vegetable fibres are used as natural fibre insulations, such as hemp, woodfibre and cellulose, high densities can be achieved (Crosson 2012). These features can be combined effectively to provide good indoor temperature control through reducing temperature fluctuations in order to prevent overheating or cooling.

Overall, vegetable fibres generally give good thermal protection. However, they suffer low thermal stability in terms of the possibility at moderate temperature 230–250 °C thereby have the drawback of low thermal processing temperatures, which in turns affect the qualities of the reinforced composites due to inadequate bond strength between fibre and matrix (Cristaldi et al. 2010).

## 4.3 Combustion Properties

Most natural cellulosic fibres absorb oxygen readily and burn rapidly owing to their cellulosic structures. Cotton and flax, for example, can smoulder for weeks inside their bales without discovering it. They have poor fire resistance. Therefore, fire-resistant chemical treatment is often applied to vegetable fibres to resist heat and increase their combustion property. However, although vegetable fibres are not naturally combustion resistant, they commonly contain high amounts of silica, which could be beneficial for fire retardancy applications (Ardanuy et al. 2012).

## *4.4 Hygroscopic Properties*

Vegetable fibres are very hygroscopic generally and they can absorb or release moisture in response to their environment (Patel et al. 2012). This property is especially favoured for winter season when low indoor air humidity is presented for a long period. However, high moisture level in vegetable fibre can have negative effects and health risk.

Cellulose and hemicellulose in vegetable fibre contribute largely to the high moisture absorption, since they absorb water as hydroxyl groups held by hydrogen bonding within the fibre cell wall. This leads to a fibre swelling which can cause the changes of hygroscopic nature of the cell wall leading to dimensional instability and poor mechanical and thermal properties (Rowell 1992). As the thermal conductivity increases with increasing moisture, thermal losses become higher and insulating properties are poorer. High moisture absorption is also prone to microbiological growth (Bisanda and Ansell 1992) and increases risks to the environment or human health. Controlling the moisture content of fibrous material is essential for manufacturing processors and buildings. The vegetable fibres should always be controlled since moisture into the material during processing procedures is inevitable. Similarly, accurately identifying and control moisture levels in fibreous insulation in buildings is paramount in order to ensure healthy buildings.

Rode (1998) conducted an investigation into the hygrothermal behaviour of wall constructions and the occupied spaces when an organic insulation material, such as vegetable fibres and animal wool, was used to verify the common belief that “a vapour barrier is not needed when using organic insulation materials” and “organic insulation materials have a stabilizing effect on the indoor humidity”. The analyses revealed interesting results. Not surprisingly, it shows that unless there is no vapour retarder or other material between the insulation layers of the wall and the adjacent space, the hygroscopic capacity of the insulation material cannot act as a buffer for the indoor relative humidity level. Moisture diffusion through the wall might desiccate the room by a small amount under winter conditions in a Nordic climate if there is little or no vapour diffusion resistance between the insulation and the indoor space. Furthermore, the same conditions may cause high humidity levels in the exterior wall leading to fungal attack on wood-based materials that are in contact with the insulation.

Based on Finnish and Swedish sources, some of the commonly used vegetable fibres in Finland and Sweden are given in Table 5. (http://www.nordicnaturfibre.se/getpage.asp?do=3&lang=sv);

**Table 5** Properties of some vegetable fibres

| Material | Density (kg/m$^3$) | Thermal conductivity (W/m/K) | Heat capacity (J/kg/K) | Air coefficient flow (m$^3$/(m*s*Pa)) |
|---|---|---|---|---|
| Hemp | 30–42 | 0.038 | 2,300 | $167*10^{-6}$ |
| Linen | 35–60 | 0.038 | 1,600 | $230*10^{-6}$ |
| Straw | – | 0,05–0,07 | – | – |
| Peat/moss | 48 | 0.037 | – | – |
| Coarse sawdust | 160 | 0,058–0,071 | 1,000 | – |
| Fine sawdust | 180 | 0,058–0,071 | 1,000 | – |

http://www.ekologiskabyggvaruhuset.se/746/hampisolering-med-majsstarkelse;
http://www.ekologiskabyggvaruhuset.se/638/linisolering;
http://www.goshandel.se/Broschyrer/Alla_Egenskaper.pdf
http://www.rakennustieto.fi/lehdet/ry/index/lehti/5wvdVAMVQ.html;
http://www.rakennusperinto.fi/Hoito/Korjaus_artikkelit/fi_FI/Vanhan_talon_eristeista%20/;
http://www.konto.fi/fi/tuotteet/eristaminen)

## 4.5 Environmental Properties

Vegetable fibrous materials are eco-friendly materials that are biodegradable and recyclable and have good environmental performance. As previously described, assessing the environmental properties of the materials is difficult. Still, some quantitative approaches have been suggested and used, see Table 6 from (Papadopoulos 2005) as an example.

In conclusion, vegetable fibres have good energy and environmental performances as summarized below in (Olesen and Plackett).

- *Very good strength and tensile properties.* In relation to its weight the best bast fibres attain strength similar to that of Kevlar.
- *Very good heat, sound, electrical and chemical insulating properties.*
- *Combustibility.*
- *Biodegradability.*

**Table 6** Environmental properties/impacts of some vegetable fibres

| | Production | Use | Total |
|---|---|---|---|
| Material | | | |
| Flax | 0.25 | 0.25 | 0.5 |
| Cotton | 0.25 | 0.25 | 0.5 |
| Cellulose | 0.25 | 0 | 0.25 |
| Cork | 0.25 | 0.25 | 0.5 |

However, some disadvantages related to vegetable fibres do exist, such as dimensional stability and reactivity (Olesen and Plackett), mainly due to their strong water absorption, hygroscopic swelling, low resistance to microbiological attack. Most of the vegetable fibres suffer alkali attack which need special treatment of chemical modification. For fibre-reinforced composites, ecological treatment of fibres is essential because of their limited compatibility between the fibre and the polymeric matrix. Specifically, controlling the moisture content of fibrous material is essential, but difficult. The vegetable fibres should always be carefully controlled since moisture into their fibrous insulation material is inevitable naturally due to the rains, snow, etc. Accurately identifying and controlling moisture levels in fibreous insulation in buildings is of the most importance in order to ensure energy efficient healthy buildings. The control stresses the need for modelling and simulation of heat and mass transfer which is presented below.

## 5 Modelling Heat and Moisture Transport in Vegetable Fibrous Materials

Thermal insulation is an important element of energy conservation. To maximize energy efficiency of the insulating materials, various factors that may affect the efficiency of heat insulation should be taken into account. The knowledge of simultaneous heat and moisture transfer through the insulators is very important. Vegetable fibrous materials have a unique structure of complex geometry which belongs to a typical kind of porous media. Therefore, heat and mass transport theories in porous media provide a fundamental understanding of the thermal and moisture transport performance for the vegetable fibrous materials.

### *5.1 Basic Concepts*

A porous medium is defined as a material characterized by the presence of solid matrix and voids which is presented by its porosity. Porosity $\varepsilon$ describes the fraction of void space $V_v$ in the material of volume $V$ as:

$$\varepsilon = \frac{V_v}{V}$$

Porosity has been reported to be an important factor to the thermal insulating performance (Farnworth 1983; Fan et al. 2004; Wu et al. 2007; Cheng and Fan 2004).

The tortuosity is another important dimensionless parameter which describes the complex structure of the material and is defined as

$$\tau = \frac{L_{transverse}}{L}$$

where

| | |
|---|---|
| $L_{transverse}$ | length of the path transversed by fluid |
| $L$ | body length of the path transversed by fluid |

In describing the properties of porous materials, pore shape factors are sometimes introduced, relating the behaviour of real pore shapes to that which would be obtained for circular pores. In the case of an oval shape with longer axis $\alpha$ and shorter axis $b$, the pore shape factor is defined as

$$\delta = \frac{b}{a}$$

For a fibrous material, the fibre is often described by a convenient parameter called "fibre aspect ratio" which is defined as a ratio of fibre length to diameter as

$$s = \frac{l_f}{D_f}$$

where $l_f$; fibre length, $D_f$; fibre diameter

For example, the aspect ratio of the dispersed fibre is about 75 (Home 2012).

## 5.2 Models

It has been reported widely that moisture problem is one of the most serious factors in building and housing industry. Over the last decade, moisture failures in building systems have reached billions of Euros in damages in Europe, many of which involved the deterioration of sheathing panels. Additionally, excess moisture in envelopes can lead to the presence of moulds which results in poor indoor air. However, despite of the vast research work on heat transfer in vegetable fibrous insulation, little has been done on the coupled heat and moisture transfer until 1980s. This subsection is devoted to modelling heat and moisture transfer in fibrous insulation materials.

The engineering analysis of the heat and moisture transfer in porous media can be dated as early as 1920s in the fields of drying science. The transport behaviour of porous media is largely governed by the interactions among coexisting components. These interactions occur through interfaces. Theoretically, transport processes in a porous medium domain may be described for a continuum at the microscopic level as taking into account the multiphase nature of the material. However, this is impractical because of our inability to describe the complex geometry and trace a large number of interfacial boundaries of the porous domain although by lattice gas or lattice Boltzmann method made such a description possible in some cases (Benzi et al. 1992; Rothman and Zaleski 1994). Moreover, at this level, we cannot measure physical quantities (Bachmat and Bear 1986). Therefore, the porous media models are often constructed through averaging the governing equations in continua at the microscopic level over a representative elementary volume (REV). The statistical averaging method is another commonly used approach which treats the porous media as a random structure. The intrinsic medium properties are represented by statistical functions. The amounts of needed data and statistical functions are large, which makes this approach impractical.

The terminology "representative elementary volume" was first used in (Bear 1972) which is defined as the minimum randomly selected volume, which keeps the porosity features of the entire volume of the site. In other words, if the volume is large enough, it should account for the spatial heterogeneity of the parameter of interest within the scale of interest. A continuum approach attempts to describe mass, momentum and energy balance laws at macroscopic scale using REV. To summarize, the general macroscopic balance equation governing transport phenomena in porous media can be formulated as

$$\frac{\partial \rho \Psi}{\partial t} + \nabla \bullet (\rho v \Psi) - \nabla \bullet J - \rho F - \rho G = 0 \tag{16.1}$$

where

| | |
|---|---|
| $\rho$ | mass density function |
| $\Psi$ | intrinsic thermomechanical property |
| $v$ | velocity |
| $J$ | flux |
| $F$ | external supply |
| $G$ | rate of production |

The equation is volume averaged over REV as illustrated in Fig. 14. For example,

$$\rho_\alpha = \frac{1}{U} \int_{\mathrm{U}^\alpha} \rho_{\mathrm{local}_\alpha} d(\mathrm{U}^\alpha) \tag{16.2}$$

is the $\alpha$-phase density function, $\rho_{local}$ is the microscopic density function, U denotes the volume of REV, $\mathrm{U}^\alpha$ is the subset of U occupied by the $\alpha$-phase. At each spatial point within the porous medium, the transport properties such as density and conductivity are averaged which reflect the corresponding microscopic properties. Details of the presentation of various averaging rules can be found in (Bachmat 1972; Hassanizadeh and Gray 1979; Whitaker 1966, 1967, 1969, 1973, 1985; Bachmat and Bear 1986; Bear 1972). In the following, we present some of the commonly used fluid heat and moisture transfer properties.

**Fig. 14** Illustration of representative elementary volume

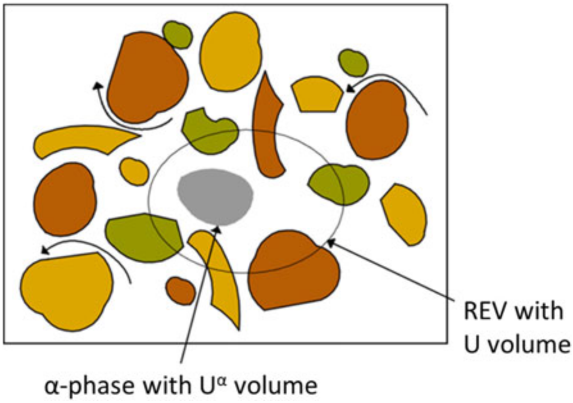
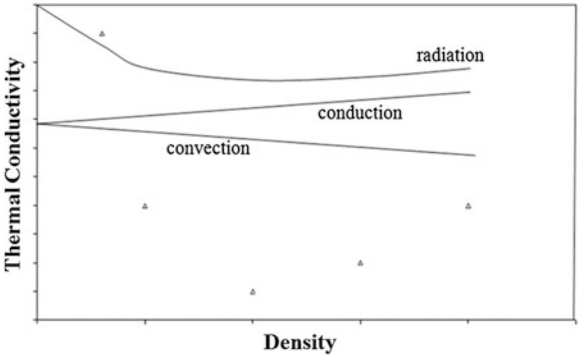


**Fig. 15** Contributions of the three main heat transfer modes for mineral wool



### 5.2.1 Heat Transport

Over the decades, significant process has been made in understanding the energy transport properties of fibrous materials (Daryabeigi 2000; Lee and Cunnington 2000; Verschoor et al. 1952; Hager and Steere 1967; Larkin and Churchill 1959). Heat transport through fibrous insulation involves multiple heat transfer mechanisms of conduction, natural convection and radiation. The relative contributions of the various modes of heat transfer vary during re-entry. In high temperature, radiation dominates which is complicated because of the complex structures of the fibres and the inherent complexities associated with the transport mechanism itself (Zhang et al. 2008). Figure 15 illustrates the contributions from all three major heat transfer modes for mineral wool (RIL 155, 1984).

### 5.2.2 Heat Transport: Conduction

The conduction is described by the first Fourier's law which shows that the energy transport at the microscopic scale tends to flow from regions of high concentration of internal energy to regions of low internal energy. The macroscopic heat flux can be formulated as

$$Q_{\text{conduction}} = \lambda \nabla \bullet T \tag{16.3}$$

where

| | |
|---|---|
| $T$ | temperature |
| $\lambda$ | conductivity |
| *subscript* | heat transfer mode |

A simple heat balance equation can be expressed as

$$(\rho C_p)\frac{\partial T}{\partial t} = -\nabla \bullet (\lambda \nabla \bullet T) \tag{16.4}$$

known as the second Fourier's law. For a fibrous material, if it has a low fibre volume fraction, heat conduction through its solid phase is often neglected. Therefore, only conduction through gaseous media is considered. The conductivity depends on the Prandtl number, Knudsen number and the free path of air's molecules which is the function of temperature, air's collision diameter and the pressure (Evseeva and Tanaeva 2004). Karamanos et al. (2008) show a picture, Fig. 16, about how each transfer mode plays in the total heat transfer for stone wool fibre.

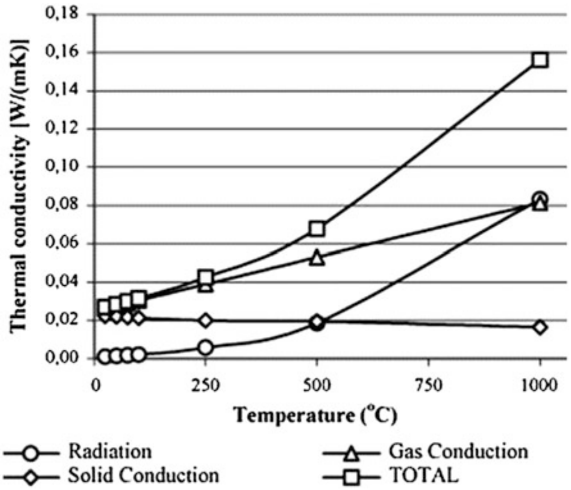


**Fig. 16** Contributions from major heat transfer modes for stone wool, adapted from (Karamanos et al. 2008); with kind permission of Elsevier, 2013

### 5.2.3 Heat Transport: Convection

By this mode, heat is transferred via the movement of fluid. It can be classified according to its nature as natural convection and forced convection. Both forced and natural types of convection may exits together. Natural convection results from thermal buoyancy effects. Forced convection is typically driven by wind pressure and HVAC equipment. The Rayleigh number is a dimensionless number which is associated with buoyancy-driven airflow and can be regarded as a measure of the driving forces of natural convection. The Nusselt number is another dimensionless number which is associated with forced convection and a function of wind velocity and the shape of the fibrous insulation. In a fibrous material, convection exists due to the air movement in the pores between the fibres. But due to the small dimensions of the pores, convection is often neglected without losing in accuracy (Karamanos et al. 2008; Milandri et al. 2002).

### 5.2.4 Heat Transport: Radiation

Radiation is the transfer of energy by electromagnetic wave motion. It travels at the speed of light and does not require a medium to carry it. The radiative heat flux depends mainly on the absolute temperature of the emitting body based on the Stefan-Boltzmann law (Holman 1997). For general porous media, the calculation of radiative heat transfer commonly requires solving the radiative transfer equation (Holman 1997; Larkin and Churchill 1959; Siegel et al. 1992; Batycky and Brenner 1997; Webb 1994 Klemens and Kim 1985). But for fibrous materials, the prediction of radiative heat transfer means not only solving of radiative transfer equation but also requiring of the knowledge of the radiative properties of the concerned material due to its absorbing and scattering capabilities. Hence, the transport process of radiation in the fibrous insulation is complicated because of both its complex morphology and the inherent complexities associated with the transport mechanism itself. Such complexity of the heat transfer makes the analysis and the design of insulation quite difficult.

There has been extensive research on this topic in fibrous materials theoretically, experimentally and empirically (Tien 1988; Hendricks et al. 1994; Singh and Kaviany 1992; Lee and Cunnington 2000; Lee 1991). The refractive index, the scattering and absorption coefficients are critical in determining the radiative properties. Viskanta and Menguc (1989) and Baillis and Sacadura (2000) rigorously reviewed methodology applied to the calculation of radiative transfer and properties in dispersed media. Two basic methods are principally used: theoretical model and identification approaches. Assuming that the media are composed of spherical particles and starting from the properties of the basic components such as the optical indices, the theoretical model, based on the Mie’s theory, describes the interaction of an electromagnetic wave to predict the radiative properties of a fibrous material (Baillis and Sacadura, 2000). These models can provide the understanding of the physical side of the material. However, with the increasing complexity of, for example, the geometry of the fibrous material, theoretical models become sophisticated and are not very suitable. Therefore, on the experimental front, an alternative way has been proposed to determine the radiative properties of a medium of which radiative behaviour would not be easily modelled with theoretical method (Baillis and Sacadura 2000).

Radiative heat flux in a partially opaque is often expressed in the form of Klemens and Kim (1985)

$$Q_{\text{radiation}} = 4\sigma n^2 T^3 l \nabla \bullet T \tag{16.5}$$

where

$\sigma$ Stefan-Boltzmann constant

$n$ average index of refraction

$l$ free path of photons

The mean free path of photons are calculated by absorption and scattering inside the medium, as well as by the finite dimensions of the medium. Very often, the scattering and absorption coefficients are functions of frequency $f$. Mathematically, the mean free path is expressed as

$$l(f) = \frac{1}{\frac{1}{l_a(f)} + \frac{1}{l_s(f)} + \frac{1}{l_b}} \tag{16.6}$$

where $l_a$ is the absorption coefficient, $l_s$ scattering coefficient and $l_b$ the boundary mean free path (Klemens and Kim 1985).

The transport process of radiation in the fibrous insulation is complicated with increasing temperature. Very often, to simplify the calculation, surface film coefficients are used to transpose the radiation into equivalent conduction through a fictitious surface layer. For example, the equivalent conductivity for radiation in fibre can be calculated as

$$\lambda_{\text{radiation}} = \frac{16\sigma}{3\beta} T^3 \tag{16.7}$$

where $\beta$ is the extinction coefficient depending on the materials' density and the specific extinction coefficient (Karamanos et al. 2008).

### 5.2.5 Moisture Transport

Moisture transport in fibrous materials can be due to several different modes. Primary three models are molecular diffusion for gases, capillary for liquids, and pressure-induced convection or Darcy flow.

### 5.2.6 Moisture Transport: Molecular Diffusion

Molecular diffusion is the transport of molecules from a region of higher concentration to one of the lower concentrations. Gases such as water vapour and air in fibrous media can move by molecular diffusion. Analogous to the heat conduction, the molecular diffusion is described mathematically by the second Fick's law. The macroscopic mass flux of gases is

$$J_{\text{diffusion}}^{\text{gas}} = -D_{\text{gas}} \nabla \bullet C_{\text{gas}} \tag{16.8}$$

where

| | |
|---|---|
| $C$ | concentration |
| $D$ | diffusivity |
| *subscript* | gas or liquid |
| *superscript* | gas or liquid |

The molecular diffusivity $D$ can be related to the molecular diffusivity of gas in bulk in that

$$D_{\text{gas}} = \frac{D_{\text{bulk}}}{\tau} \varepsilon \tag{16.9}$$

where

$D_{\text{bulk}}$ diffusivity in bulk

So the mass conservation equation can be expressed as

$$\frac{\partial C_{\text{gas}}}{\partial t} = -\nabla \bullet (D_{gas} \nabla \bullet C_{\text{gas}}) \tag{16.10}$$

which is the second Fick's law.

### 5.2.7 Moisture Transport: Darcy Flow

In pressure-driven gas transport, Darcy's law is often used in calculating the mass flux in the form of

$$J_{\text{pressure}}^{\text{gas}} = -\rho_{\text{gas}} \frac{k_{\text{gas}}}{\mu_{\text{gas}}} \nabla \bullet P \tag{16.11}$$

where

$$k_{\text{gas}} = k.\, k_{\text{relative}}^{\text{gas}}$$

| | |
|---|---|
| $k$ | intrinsic permeability |
| $k_{\text{relative}}$ | relative permeability |
| $\mu$ | viscosity |

### 5.2.8 Moisture transport; Capillary flow

Capillary flow is induced by capillary attraction force that governs the action of a liquid against solid surfaces in small and confined areas. Darcy's law also describes the transport of liquid due to pressure. However, capillary attraction creates a negative pressure; therefore, the mass flux of liquid is written as

$$J_{\text{pressure}}^{\text{liquid}} = -\rho_{\text{liquid}} \frac{k_{\text{liquid}}}{\mu_{\text{liquid}}} \nabla \bullet (P - p_c) \tag{16.12}$$

where

| | |
|---|---|
| $p_c$ | capillary pressure |

The capillary pressure is defined as the pressure difference between the liquid and the gaseous phase.

### 5.2.9 Moisture Transport: Swelling

Vegetable fibres absorb large amounts of moisture which may lead to swelling. Studies have shown that the amount of water retained by swollen fibres varies from 6 to 100 % of dry weight of fibres and swelling in water could reach 22 % of the initial fibre volume (Rowell et al. 1998). Swelling changes the structure and molecular arrangement of the fibres, such as the capillary pore, the porosity and the permeability (Chatterjee and Gupta 2002). Swelling is an important issue in modelling flow transport in vegetable fibres. Swelling of vegetable fibres is a time-dependent process and a function of micro- and macro-structure of the porous fibres.

There are two commonly used models for simulating swelling fibres. One is based on the Lucas–Washburn approach assuming that the porous medium is a bundle of aligned capillary tubes of the same radii (Greenkorn 1983). Another one is based on the modified Darcy's law and continuity equation that include the swelling effects in the model (Masoodi et al. 2010). A time-dependent function for permeability is adopted. The mass flux takes the form of

$$\nabla \bullet J_{\text{pressure}}^{\text{waters}} = -S - \frac{\partial \varepsilon}{\partial t} \tag{16.13}$$

where $S$ presents sink source which is assumed to be linearly proportional to the water rate.

### 5.2.10 Heat and Moisture Transport with Swelling Effect

Material’s thermal conductivity is an inherent property that is dependent on its temperature, density and moisture content. When vegetable fibre swells, the structure changes to some external deformation leading to the changes of its size, shape and density. Its conductivity, therefore, increases and consequently thermal resistance decreases. When modelling the effective thermal conductivity as a function of the moisture content and for vegetable fibres, swelling effect should be accounted for and addressed. Extensive research has been reported in the literature, for example, Hatta and Taya (1986) and Charoenvai et al. (2005) with theoretical, numerical and experimental methods. Some analytical investigations are also available based on idealized bundle of tubes models of fibres. Using these models, Chadiarakou theoretically studied the effect of water content on the thermal behaviour fibrous materials by assuming four modes of heat transfer in a fibrous material: (1) conduction through the solid medium, i.e., the fibres (2) conduction through the gas medium, i.e., the air trapped between the fibres (3) convection due to the air in the space between the fibres (4) radiation interchange between fibres and air (Charoenvai et al. 2005). The conclusion is that the diffusion of water in the material can cause a significant increase in its thermal conductivity which will lead to a significant failure of the insulation. An example shows that 1 % moisture content by volume can increase by up to 107 % conductivity. Most importantly, the swelling problem is also associated with the decomposition of fibres, which is not rare in the case of industrial insulation (Karamanos et al. 2004).

### 5.2.11 Model Applications

Mass and heat transfer through vegetable fibrous materials can be modelled based on the above-described mechanisms. In recent years, extensive research has been performed on fibrous materials which broadly includes vegetable fibrous materials and is reviewed below. Depending on the level of detail desired, various macroscopic models have been proposed in the literature.

In the earlier literature, Bankvall (Banklvall 1973) conducted detailed experimental and theoretical research on the relative contribution of the three modes of heat transfer through fibrous insulation. He found that conduction in the gas phase was the most important heat transfer model in fibres. Radiation heat transfer was considerable at high porosities. The relative contribution of each type of heat transfer model with respect to critical porosities is proposed. Wijeysundera et al. (1996) set up an experiment to study thermal conductivity across a range of moisture contents using one-dimensional transient vapour diffusion and heat conduction in an insulation slab. It was found that thermal conductivity had a linear relationship with the moisture content, and its magnitude increased with increasing mean slab temperature and temperature difference.

Modi and Bennes (1985) studied spray-applied fibreglass and cellulose and found that the rate of moisture gain and the total moisture gain increased with the relative humidity and the temperature difference. Moisture in the cellulose increased slightly more than that in the fibreglass under the same conditions. Hokoi and Kumaran (1993) studied heat and moisture transport through glass fibre insulation experimentally and analytically. They reported that for a medium density glass fibre insulation (about 50 kg/m3), the value of the local moisture content at the fully saturated moisture state may reach 20 kg/kg of dry insulation material. Ogniewicz and Tien (1981) got a semi-analytical solution for solving a quasi-steady one-dimensional forced convective problem with convective boundary conditions. They found that the rate of condensation, though relatively small, increased with external humidity, temperature levels and overall temperature differences. Motakef and El-Masri (1986) demonstrated the existence of a wet region sandwiched between two dry zones in a porous slab. Chen et al. (1997a) and (b) investigated a transient two-dimensional forced convective case with a warm plate at the top and a cold plate experimentally and numerically. The total mass of moisture and frost accumulation on the insulation slab and cold surface was 0.0156 kg was found for one case which was 50 % of the total vapour that flowed through the system in a 3.5-h test. A 20 % decrease in the effective thermal conductivity was predicted to cause temperature, moisture and heat flux variations over 3–5 h of up to 1.5 K, 0.5 and 11 %, respectively.

Vafai and Sarkar (1986) conducted two-dimensional simultaneous heat and mass transfer in porous insulation. Gas pressure was assumed to be constant. They demonstrated that condensation occurred at any point in the insulation where the water vapour concentration became greater than the saturation concentration corresponding to the temperature at the point. Vafai and Whitaker (1986) studied condensation effects in fibrous insulation slab and concluded that the condensation process was significantly affected by the thermophysical properties of the insulation, the infiltration velocity and the humidity levels. Condensation was a serious problem for large Peclet numbers. Tao et al. (1991a, b) developed frost model for studying the motion of the frozen boundary which started at a cold plate (sink) at subzero temperature a fibrous insulation slab.

In the recent literature, Fan et al. (2004) developed a coupled heat and moisture transfer model with phase change and mobile condensates in fibrous insulation. A super-saturation state in condensing region, the dynamic moisture absorption of fibrous materials and the movement of liquid condensates were considered. Foss et al. (2003) presented a simultaneous heat and mass transfer model through a porous material for investigating transient moisture sorption by paper sheets from humid air. The model showed nonlinearities of the moisture content isotherm and heat of sorption. Charoenvai et al. (2005) reported the result on heat and moisture transport in durian (Durio zibethinus)-fibre-based lightweight construction materials composed of cement, sand and waste fibre from durian peel. The results showed that the weekly mean water content on the surface of material was quite low. The effect of moisture on the apparent thermal performance of the composite was higher as water absorbed in the pore structure contributed to higher thermal conductivity than the air it replaced. However, the mean value of thermal conductivity in material is still rather low as the mean value of water content in material is low. An anisotropic 3D geometric fibre model was used in studying 2D transient heat and moisture transport behaviour through fabric. The mass and energy conservation as well as capillary phenomenon was considered in the model (Luo and Xu 2006).

Zhao et al. (2009) presented a numerical model of combined radiation and conduction heat transfer to predict the effective thermal conductivity of fibrous insulation at various temperatures and pressures. Effective thermal conductivities of the fibrous insulation were measured over a wide range of temperature and pressure. Using different mathematical models of heat flow, Roy et al. (2006) studied the porosity dependence of heat flux through glass fibre insulation. Karamanos et al. (2008) developed a model for evaluating the performance of stone wool under varying temperature and humidity conditions. Bao and Yee (2002) studied moisture absorption and hygrothermal ageing in a woven and woven/uni-weave composites. The short-term absorption curves of the uni-weave/woven/uni-weave and woven/uni-weave/woven composites were described by Fickian diffusion and the dual-diffusivity model, respectively.

In the experimental literature, (Fan et al. 2003) presented an experimental result on the temperature and water content distribution within the porous fibrous battings sandwiched by an inner and outer layer of thin covering fabrics using a novel sweating, guarded hot plate. It was found that most of the changes in temperature distribution took place within 1/2 h of the tests and moisture absorption by the hygroscopic fibres affected the temperature distribution. Higher water content, a combined result of moisture absorption, condensation and liquid water movement, was found at the outer regions than that at the inner regions of the battings.

For more general heat and moisture transfer model equations for hygroscopic fabrics or porous materials, please refer to (Lu 2002a; b; Osanyintola 2006; Wu et al. 2007). Very often, the obtained model equations are complex which do not permit simple analytical solutions. Therefore, different approaches like finite element method, finite difference method, and finite volume method are used to solve the equations. For more literature, refer to Pan and Gibson (2006) and Oduor (1999).

In this chapter, the macroscopic model configuration is presented in Fig. 17. The moisture transport is divided into liquid and vapour flow. The liquid transport is based on Darcy and capillary flow equations. The vapour flow is driven by

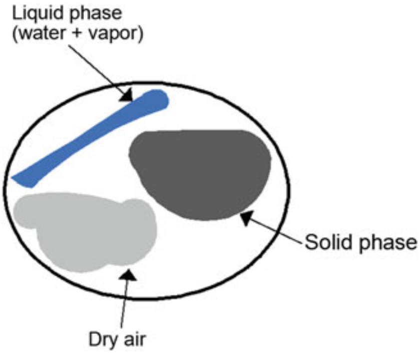


**Fig. 17** Macroscopic model configuration

vapour pressure gradient and depends on the material's permeability coefficient. We assume that no air transfer occurs. The model is mainly based on one developed for fibrous material (Karamanos et al. 2008).

### 5.3 Mechanics Models

Besides heat and mass transfer, many attempts have made for modelling mechanical properties of fibrous materials and their composites. Specifically, (Rao et al. 2012) extended the micromechanical models in the literature to conduct micro- and macro-analysis of sisal fibre composites hollow core sandwich panels and to evaluate the feasibility of using short sisal fibres as reinforcements in the composites. The stress relaxation behaviour of the composites was examined experimentally. A steady-state finite element analysis in the linear range was performed in ANSYS environment to examine flexural properties of the panels, and the shear strength of the hollow cores (Rao et al. 2012). For fibrous materials, there is a strong need of micromechanical models because the global nonlinear material response to loading is defined by the microscopic constituents (Syerko et al. 2012). The micromechanical models predict elastic modulus which generally lump the composite's properties together into constitutive relationship using different parameters, see also Halpin and Kardos (1976) and Cox (1952) for the models.

## 6 Applications

The building and construction industry constitutes one of the largest sectors to employ fibrous materials in a wide range of products, including light structural walls, insulation materials, wall and floor coverings, geotextiles and thatch roofing. We don't distinguish fibrous materials and vegetable fibrous materials here because their applications are very similar, if not same. on, etc. The purpose of insulation is to provide a thermal barrier to minimize heat flow through the components of the buildings.

### 6.1 Thermal Insulators

Fibrous materials have been extensively used as thermal insulators with a variety of applications ranging from interior or exterior walls, roofs, foundations, cavity walls, unheated garages, band joists, storm windows, seal around all windows, doors and heating system and hot and cold water services. Insulating the attic is a very important measure as the greatest heat loss occurs through the roof which can be verified by noting the length of time required for snow on the roof to melt.

Warm air goes up and the temperature in the upper air layers of heated rooms is always higher, which may cause a loss of heat through the roof. Insulating the basement is also a very effective way to add energy efficiency. Insulating exposed ductwork that runs through unheated areas, such as crawl spaces and attic, is equally important (Extension 2001).

Youngquist et al. (1994) has made an extensive review of vegetable fibres for building materials and panels. The review covered a wide range of issues including the methods for efficiently producing building materials and panels from vegetable fibres, mechanical and physical properties of products made from them, use of vegetable fibres as stiffening agents in cementitious materials and as refractory fillers and cost-effectiveness of using materials. Many different kinds of vegetable fibrous materials have been surveyed and grouped, by type of raw material, into five major sections: panel boards including acoustical and thermal materials, cement/clay/gypsum/plaster materials, moulded masses, miscellaneous, and material used in natural state.

In addition to general thermal properties described above, the appropriate degree of insulation depends on local climate, building construction type, and many other factors. Soubdhan et al. (2005) studied the influence of radiant barriers on conductive and radiative heat transfers when they are integrated to a building envelope and compared their efficiency to traditional insulation material (mineral wools and polystyrene) under tropical climate. Different tests were performed to evaluate the influence of parameters such as roof absorptivity and roof air layer ventilation on the heat flux reduction through the roof. Pervaiz and Sain (2003) reported the environmental performance of hemp-based natural fibre mat thermoplastics (NMT) by quantifying carbon storage potential and $CO_2$ emissions and comparing the results with commercially available glass fibre composites. Nonwoven mats of hemp fibre and polypropylene matrix were used to make NMT samples by film-stacking method without using any binder aid. They showed that hemp-based NMT have compatible or even better strength properties as compared to conventional flax-based thermoplastics and their impact energy values are also promising. Hens and Janssens (1998) examined the performance of self-drying roof in cool and cold climates.

With regard to structural behaviour, Bojic et al. (2002) studied the insulation effects of including a thermal insulation layer in the fabric components that separate cooled spaces from the outdoors and from nonair conditioned spaces in high rise residential buildings. The simulation results showed that the highest reduction in the yearly cooling load and in the maximum cooling demand would be achieved when a 50-mm-thick thermal insulation layer was placed at the indoor side of the walls that enclose the cooled spaces. Fibre-based composite insulators have been very popular for decades due to their good mechanical and thermal properties. Abdou et al. (1996) investigated the thermal insulation characteristics of the prefabricated, interlocking fibreglass composite panel system in the construction of building envelope systems. The experiments showed that such envelope system could be a potential candidate for wider use in energy-conscious commercial buildings.

Besides the traditional application of these fabrics, randomly mixed palmyra fibre and glass fibre hybrid composites have been proposed as an eco-friendly composite and their mechanical properties and moisture absorption have been studied in Velmurugan and Manikandan (2007). It showed that the mechanical properties of the composites are improved due to the addition of glass fibre along with palmyra fibre in the matrix. Addition of glass fibre with palmyra fibre in the matrix decreases the moisture absorption of the composites. Furthermore, the mechanisms of fibrous insulation where the fibre nanofibre technology (fibre diameter less than 1 micrometre) have been investigated (Gibson et al. 2007). However, very little research has been done on this topic. It has been found that fibres below 1 μm in diameter are not thermally efficient at low fibre volume fractions and performance gains in existing thermal insulation materials may be possible by incorporating a proportion of nanofibres into the structure, but large diameter fibres would still be necessary for durability and compression recovery.

## *6.2 Reinforced Composites*

The principal advantages of natural vegetable fibres over traditional fibres, such as glass and carbon fibres, are their good specific strengths and modulus, low density, economical viability and biodegradability. They have good thermal resistance. However, due to some disadvantages that vegetable fibres possess, industry of vegetable-fibre-reinforced composites has been substantially developed and active for decades. Indeed, vegetable fibre composites have a long history dating back to 200 BC in China where straw-reinforced bricks were used in the wall structures of tha Great Wall of China. Composites research has also a long history at technologies to create building products.

Composite is a microscopic or macroscopic combination of two or more distinct materials with an interface between them. Most composite materials are said to have two phases: the reinforcing phase and the matrix phase. The reinforcing phase can be, for example, the vegetable fibres, that are embedded in the matrix phase. The matrix material can be, for example, ceramic or polymer. The aim is to rectify some specific shortcomings of the materials and to improve the overall performance. For example, concrete, cement and mortar are the most widely used construction materials in building industry. These materials are all intrinsic brittle. Cracks or other flaws in them will quickly propagate when they are stretched in tension. The use of fibre reinforcement systems can help brittle materials to resist the tensile forces. As described previously, vegetable fibres have composite like structures which make them suitable as reinforcing materials in the composites. Composites take advantage of the properties of vegetable fibres that they contain cellulose, a kind of natural polymer, for reinforcing materials. The fundamental design concept of composites is that the matrix phase accepts the load over a large surface area and transfers it to the reinforcement material. Three main types of vegetable fibrous composites can be categorized: (1) composites in which the fibre serves as a filler in commodity thermoplastics. (2) composites in which longer fibres enhanced with compatibilizers and other additives to obtain additional strength and toughness in thermoplastics. (3) composites in which fibres are used with thermosetting resins as designed elements within engineered components (Suddell 2008). Composites using natural fibres and bio-based resins will see explosive development within the next ten years (Suddell 2008). As extensive reviews are available in the literature which covers in great detail of the raw materials, manufacturing methods, properties of composites reinforced by vegetable fibre, this subsection, therefore, provides a brief summary of the outcome research in vegetable fibrous composites.

Tradition reinforcement by fibres is often for structural strength purposes for providing load carrying capacity, toughness, flexural strength and resistance to cracking and defections. Some vegetable fibres present good tensile strength which can be integrated in the materials to carry the load and to produce high stiff, high strength and good thermal fibre-reinforced composites suitable for different building purposes. The greatest advantage of using vegetable fibres as reinforcement in polymer matrix is that they can promote new classes of biodegradable composites with improved mechanical properties.

Moreover, modern technologies for vegetable-fibre-reinforced composites modify the properties of the material in more predictable, measurable and economical ways for specific applications in technological and environmental advantages and challenges (Vassilev et al. 2013). For example, oil palm fibre has been used to improve thermal, hygroscopic and insulation property of laminate composite (Hariharan and Khalil 2005). Abdul Khalil et al. (2012) provided a critical review of the most recent developments of bamboo-fibre-based reinforced composites with low cost.

Despite various purposes and modern technologies, the major contribution of the vegetable fibres has always been towards increasing the mechanical strength of the materials. The mechanical behaviour of the composite is greatly depending on the fibre properties and the percentage of fibre added as well as the manufacturing process. The main goal of fibre processing is to remove pectin and lignin and separate fibre bundles. This will increase the contact surface area of the fibre for chemical and/or mechanical bonding with matrix phase. The degree of chemical and/or mechanical bonding between fibre and matrix determines the strength of the overall composite (Agopyan et al. 2005; Khalil et al. 2012; Li et al. 2000b; Jawaid and Khalil 2011; Graupner et al. 2009; Merta and Tschegg 2013; Pacheco Torgal and Labrincha 2013a, b; Pacheco Torgal et al. 2013). The final manufactured products largely depend on process parameters used to process the fibres and manufacture the composites. The composites can be produced in various ways using hot pressing, extrusion, injection moulding, compression moulding, etc. Broadly speaking, there are two approaches and the products fall into two groups: The first one is based on the production of thin sheets or mats. The second is based on the production of composites for different types of building components, such as load-bearing wall, roofing tiles and ceiling plates (Agopyan et al. 2005). Details can be found in the above-described reviews. In brief, utilizing natural fibres for the insulation of buildings has become one of the increasingly practiced techniques in building industry in recent years.

Natural vegetable fibres, traditionally for filling and reinforcing buildings composites, have attracted increasingly more attention for building insulations due to their superior thermal and acoustic insulation properties, high flexural and tensile modulus, low density, low thermal expansion coefficient and added environmentally preferable properties, such as renewable recycled, low manufacturing cost among many others. Various environment-friendly insulations and building constructions have been developed and favourably investigated using various vegetable fibres, for example, cotton stalk fibres (Zhou et al. 2010), date palm wood (Agoudjil et al. 2011), hemp (Le et al. 2010), straw bale (Ashour et al. 2010), combined jute, flax and hemp (Korjenic et al. 2011), sugar cane bagasse fibres (Onesippe et al. 2010), banana (Paul et al. 2013), banana/sisal hybrid fibre (Idicula et al. 2010), banana and coir (Sathishkumar et al. 2012).

In fact vegetable fibres provide all manners of reinforced materials in building constructions, such as bricks, cement, aggregates, steel, aluminium, wood, cladding, partitioning materials. Examples of vegetable fibres that have been invested and reported in the literature are sisal, wood, barley straw, flax, hemp, jute, pinewood fibre, rice husk, sawdust, luffa sponge, paper sludge, coconut, kenaf, kapok/ cotton, pineapple leaf, basalt, vetiver, bio flour, bamboo, date palm, cotton waste, dried sludge collected from an industrial wastewater treatment plant, rice husk ash, granulated blast furnace slag, wood sawdust, processed waste tea and waste forms from different vegetable fibres (Kazragis 2005; Pacheco Torgal et al. 2011; Raut et al. 2011; Madurwar et al. 2013), to cite a few reviews. Bouhicha et al. (2005) investigated the usage of composite soil reinforced with chopped barley straw and soils acting as a thermal insulation for indoor temperature under extreme weather conditions. More reviews of the cellulosic-based materials in composites were given by Bledzki and Gassan (1999) and Malkapuram et al. (2008).

Despite significant increases in production, application and development of vegetable-fibre-reinforced composites remain many challenges. Glass fibres still dominate the composites industry.

The main disadvantages of using natural fibres, in general, are their high hydrophilic behaviour and incompatibility between them (hydrophilic fibres) and hydrophobic matrices, which demand appropriate physical and chemical treatments to enhance the adhesion between them, and which in turn will ultimately affect the overall properties of the composites. The large variation in the properties of natural vegetable fibres is another important disadvantage. For example, concerns have been raised over the years for the durability of the fibres in the composites with alkaline since alkaline weakens vegetable fibres. The composites may undergo a reduction in strength and toughness as a result of the weakened fibres. Another major drawback of composites from vegetable fibres is the reduced processing and practical temperatures, such as product extrusion and injection temperatures due to sensitivity of the composite from both fibre and matrix. The thermal degradation of composites with vegetable fibres and their improvement have been studied in Moriana et al. (2011).

These challenges have provided a boost to vegetable-fibre-reinforced material research. Binici et al. (2005) has investigated the mechanical properties of certain combinations of fibrous waste materials and some stabilizers and proposed that these materials can be used as earthquake-resistant materials due to their high compressive strength. They concluded that the interface layers of fibrous materials increased the compressive strength and a certain geometrical shape of these layer materials gave the best results. Lignocellulosic agricultural by-products are a copious and cheap source for cellulose fibres. Agro-based biofibres have the composition properties and structure that make them suitable for uses such as composite. Reddy and Yang (2005) reviewed the production processes, structure, properties and suitability of biofibres for various industrial applications. Ardente et al. (2008) presented a life cycle assessment of a kenaf-fibre insulation board following the international standards of the ISO 14040 series. Each life cycle step has been checked, from kenaf production and board manufacture, to use and disposal. A comparison among various insulating materials was carried out also. Hyvarinen et al. (2002) investigated whether fungal genera and actinobacteria were associated with seven types of moisture-damaged building materials by systematically describing the mycobiota and enumerating fungi and bacteria in these materials. They found the highest median concentrations of fungi were observed in wooden and paper materials, and lowest in samples of mineral insulation, ceramic products, and paints and glues. Concentrations of viable bacteria in mineral insulation materials were significantly lower than in wood, paper, ceramic products and plastics. A rich variety of fungi was found in wooden materials.

Vegetable fibrous materials that span the nano-to-mesoscales have potentially broad applications. The review by Woolfson and Ryadnov (2006) focused on potential applications of bioinspired fibrous materials and centred on the developments in the design of peptide-based fibres and particularly those using the alpha-helix and the collagen triple helix as building blocks for self-assembly. Neethirajan et al. (2009) reviewed the background on plant silica bodies, silica uptake mechanisms and applications and suggest possible ways of producing plant silica bodies with new functions for nanotechnology.

Energy use in buildings covers a large share of world's total end-use of energy. A challenging task of building professionals today is to design and promote NZEB/ZEB energy buildings in a cost effective and environmentally responsive way, keeping that in mind that large portion of existing buildings were not designed to meet NZEB/ZEB requirements. It has been reported that as for the NZEB-related technologies, the current market for insulation materials should grow by about two to three times (Boermans 2011). There is no doubt that the design principles of eco-friendly insulation will play an increasingly important role alongside the uses of vegetable fibres will gain their importance in insulation industry.

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## References

RIL (1984) *Lämmön ja kosteudeneristys,* Helsinki, Finland (in Finnish), Suomen Rakennusinsinöörien Liitto

The Directive 2010/31/EU of the European Parliament and Council of 19 May 2010 on the energy performance of buildings. In: UNION, O. J. O. T. E. (ed.)

ISO 6946:2007 (1996) Building components and building elements—Thermal resistance and thermal transmittance—Calculation method. Berlin, Germany

EC (2005) Biomass: green energy for Europe

NMAB (1994) Hierarchical structures in biology as a guide for new materials technology, The National Academies Press, Washington DC

Abdou OA, Murali K, Morsi A (1996) Thermal performance evaluation of a prefabricated fiber-reinforced plastic building envelope system. Energ Build 24:77–83

Agopyan V, JR HS, John VM, Cincotto MA (2005) Developments on vegetable fibre–cement based materials in Sao Paulo, Brazil: an overview. Cement and Concrete Composites, 27, 527–536

Agoudjil B, Benchabane A, Boudenne A, Ibos L, Fois M (2011) Renewable materials to reduce building heat loss: characterization of date palm wood. Energ Build 43:491–497

Agriculture U. S. D. O. (2000) Harvesting, retting, and fiber separation. Industrial Hemp in the United States. United States Department of Agriculture Economic Research Service

Ardanuy M, Antunes M, Velasco JI (2012) Vegetable fibres from agricultural residues as thermo-mechanical reinforcement in recycled polypropylene-based green foams. Waste Manage (Oxford) 32:256–263

Ardente F, Beccali M, Cellura M, Mistretta M (2008) Building energy performance: A LCA case study of kenaf-fibres insulation board. Energ Build 40:1–10

Ashour T, Georg H, Wu W (2010) Performance of straw bale wall: a case of study. Energ Build 43:1960–1967

Bachmat Y (1972) Spatial macroscopization of processes in heterogeneous systems. Israel J Tech 10:391–403

Bachmat Y, Bear J (1986) Macroscopic modelling of transport phenomena in porous media, 1: the continuum approach. Transp Porous Media 1:213–240

Baillis D, Sacadura J-F (2000) Thermal radiation properties of dispersed media: theoretical prediction and experimental characterization. J Quant Spectrosc Radiat Transfer 67:327–363

Banklvall CG (1973) Summary of Heat Transfer in Fibrous materials. Document D4. J Testing Eval 1:235–243

Bao L-R, Yee AF (2002) Moisture diffusion and hygrothermal aging in bismaleimide matrix carbon fiber composites: part II-woven and hybrid composites. Compos Sci Technol 62:2111–2119

Batycky RP, Brenner H (1997) Thermal macrotransport processes in porous media. Rev Adv Water Res 20:95–110

Bear J (1972) Dynamics of fluids in porous media. USA, Elsevier, New York

Beckwith SW (2003) Natural fiber reinforcement materials: lower cost fiber technology for composites. Applications. Composites Fabrication, November/December, 12–16

Benzi R, Succi S, Vergassola M (1992) The lattice Boltzmann equation: theory and applications. Phys Rep 222:145–197

Binici H, Aksogan O, Shah T (2005) Investigation of fibre reinforced mud brick as a building material. Construct Build Mat 19(4):313–318

Bisanda ETN (1993) The manufacture of roofing panels from sisal fibre reinforced composites. J Mater Process Technol 38:369–380

Bisanda ETN, Ansell MP (1992) Properties of sisal–CNSL composites. J Mater Sci 27:1690–1700

Bismarck A, Mishra S, Lampke T (2005) Plant fibers as reinforcement for green composites. In: Mohanty AK, Misra M, Drzal LT (eds) Natural fibers biopolymers and biocomposites. Boca Raton Taylor and Francis

Bledzki AK, Gassan J (1999) Composites reinforced with cellulose based fibers. Prog Polym Sci 24:221–274

Boermans T, Bettgenhauser K, Hermelink A, Schimschar S (2011) Cost optimal building performance requirements. Calculation methodology for reporting on national energy performance requirements on the basis of cost optimality within the framework of the EPBD, eceee, May 2011,http://www.eceee.org/

Bojic M, Yik F, Leung W (2002) Thermal insulation of cooled spaced in high residential buildings in Hong Kong. Energy Convers Manage 43:165–183

Bouhicha M, Aouissi F, Kenai S (2005) Performance of composite soil reinforced with barley straw. Cement Concrete Compos, 617–621

Charoenvai S, Khedari J, Hirunlabh J, Asasutjarit C, Zeghmati B, Quenard D, Pratintong N (2005) Heat and moisture transport in durian fiber based lightweight construction materials. Sol Energy 78:543–553

Chatterjee PK, Gupta BS (2002) Absorbent technology. Elsevier, Amsterdam

Chen H, Besant RW, Tao Y (1997a) Two-dimensional air exf iltration and heat transfer through fiberglass insulation 1: numerical mode1 and experimental facility. HVAC R Research 3:197–213

Chen H, Besant RW, Tao Y (1997b) Two-dimensional air exf iltration and heat transfer through fiberglass insulation 2: comparisons between simulations and experiments. HVAC R Research 3:215–232

Cheng X, Fan J (2004) Simulation of heat and moisture transfer with phase change and mobile condensates in fibrous insulation. Int J Therm Sci 43:665–676

Cox HL (1952) The elasticity and strength of paper and other fibrous materials. Br J Appl Phys 3:72–79

Cristaldi G, Latteri A, Recca G, Cicala G (2010) 17 Composites based on natural fibre fabrics. In: Dubrovski PD (ed) Woven Fabric Engineering. In Tech

Crosson N (2012) Going natural means more than just insulation. Modern Methods of Construction [Online]

Dam JEGV (1999) Optimisation of methods of fibre preparation from agricultural raw materials. Agrotech Res Ins, Wageningen

Daryabeigi K (2000) Design of high-temperature multi-layer insulation for reusable launch vehicles. Ph.D. University of Virginia, Virginia

Desideri U, Leonardi D, Arcioni L (2012) Analysis of different typologies of natural insulation materials with economic and performances evaluation of the same in building. Proceedings of ECOS 2012—the 25th international conference on efficiency, cost, optimization, Simulation and environmental impact of energy systems. Perugia, Italy

Dufresne A (2008) Chapter 19–Cellulose-based composites and nanocomposites. In: Belgacem MN, Gandini A (eds) Monomers, polymers and composites from renewable resources. Elsevier

Energy U. S. D. O (2010) Genomics: GTL Roadmap. In: U.S. Department of energy, O. O. S. (ed)

Evseeva LE, Tanaeva SA (2004) Influence of impregnation on the thermal properties of heat-insulating fibrous materials. J Eng Phys Thermophys 77:99–102

Extension E (2001) Engineering extension

Fan J, Cheng X, Chen Y-S (2003) An experimental investigation of moisture absorption and condensation in fibrous insulations under low temperature. Exp Thermal Fluid Sci 27:723–729

Fan J, Cheng X, Wen X, Sun W (2004) An improved model of heat and moisture transfer with phase change and mobile condensates in fibrous insulation and comparison with experimental results. Int J Heat Mass Transf 47:2343–2352

Farnworth B (1983) Mechanisms of heat flow through clothing insulation. Text Res J 53:717–725

Forgacs J JS, In: Kadis S, Ciegler A, Ajl SJ (eds), Microbial Toxins. Academic Press, New York Inc vol 8 pp 95–128

Foss WR, Bronkhorst CA, Bennett KA (2003) Simultaneous heat and mass transport in paper sheets during moisture sorption from humid air. Int J Heat Mass Transf 46:2875–2886

Gibson LJ (2012) The hierarchical structure and mechanics of plant materials. J R Soc Interface 9:2749–2766

Gibson PW, Lee C, Ko F, Reneker D (2007) Application of nanofiber technology to nonwoven thermal insulation. J Eng Fibers Fabr 2:32–40

Graupner N, Herrmann AS, Mussig J (2009) Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: An overview about mechanical characteristics and application areas. Compos A Appl Sci Manuf 40:810–821

Greenkorn RA (1983) Flow phenomena in porous media. Marcel Dekker, New York

Abdul Khalil HPS, Bhat IUH, Jawaid M, Zaidon A, Hermawan D, Hadi YS (2012) Bamboo fibre reinforced biocomposites: A review. Materials Design, 42, 353–368

Hager NE, Steere RC (1967) Radiant heat transfer in fibrous thermal insulation. J Appl Phys 38:4663–4668

Halpin JC, Kardos JL (1976) The Halpin–Tsai equations: a review. Polym Eng Sci 16:344–352

Hariharan ABA, Khalil HPSA (2005) Lignocellulose-based hybrid bilayer laminate composite: part I—studies on tensile and impact behavior of oil palm fiber–glass fiber-reinforced epoxy resin. J Compos Mater 39:663–684

Hassanizadeh SM, Gray WG (1979) General conservation equations for multi-phase systems 1. averaging procedure. Adv Water Resour 2:131–144

Hatta H, Taya M (1986) Equivalent inclusion method for steady state heat conduction in composites. Int J Eng Sci 24:1159–1172

Hendricks TJ, Howell JR (1994) Absorption/Scattering coefficients and scattering phase functions in reticulated porous ceramics. In: Bayazitoglu Y (ed)

Henriksson G, Akin DE, Rigsby LL, Patel N, Eriksson K-EL (1997) Influence of chelating agents and mechanical pretreatment on enzymatic retting of flax. Tex Res J 67:829–836

Hens H, Janssens A (1998) Application of a new type of air and vapor retarder in a self-drying sloped roof with a cathedral ceiling. Thermal Perf Exte Env Build 7:15–27

Hill CAS, Khalil HPSA, Hale MD (1998) A study of the potential of acetylation to improve the properties of plant fibres. Ind Crops Prod 8:53–63

Hokoi S, Kumaran MK (1993) Experimental and analytical investigations of simultaneous heat and moisture transport through glass fiber insulation. J Thermal Insul Bldg Envs 16:263–292

Holman JP (1997) Heat transfer. McGraw-Hill, Inc, New York

Home T. C. C. E (2012) Fibre reinforced concrete

Hyvarinen A, Meklin T, Vepsalainen A, Nevalainen A.(2002) Fungi and actinobacteria in moisture-damaged building materials — concentrations and diversity. Int Biodeter Biodegrad 49(1):27–37

Idicula M, Joseph K, Thomas S (2010) Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites. J Reinf Plast Compos 29:12–29

INFOLINK (2011) Natural fibre insulation—benefiting the built and natural environment [Online]. Australia's Architecture, Building

Jawaid M, Khalil HPSA (2011) Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review. Carbohydr Polym 86:1–18

Karamanos A, Hadiarakou S, Papadopoulos AM (2008) The impact of temperature and moisture on the thermal performance of stone wool. Energ Build 40:1402–1411

Karamanos A, Papadopoulos AM, Aravantinos D (2004) Heat transfer phenomena in fibrous insulating materials. In: Proceedings of 2004 WSEAS/IASME international conference on heat and mass transfer. Corfu, Greece

Kazragis A (2005) Minimization of atmosphere pollution by utilizing cellulose waste. J Environ Eng Landscape Manage 13:81–90

Khalil HPSA, Bhat IUH, Jawaid M, Zaidon A, Hermawan D, Hadi YS (2012) Bamboo fibre reinforced biocomposites: a review. Mater Des 42:353–368

Klemens PG, Kim N (1985) Radiative heat transfer in inhomogeneous media and insulations. Thermal Conductivity 19:453–458

Korjenic A, Petranek V, Zach J, Hroudova J (2011) Development and performance evaluation of natural thermal insulation materials composed of renewable resources. Energ Build 43:2518–2523

Kymalainen H-R, Sjöberg A-M (2008) Flax and hemp fibres as raw materials for thermal insulations. Build Environ 43:1261–1269

Larkin BK, Churchill SW (1959) Heat transfer by radiant through porous insulations AIChE J. 4:467–474

Lazko J, Dupre B, Dheilly RM, Queneudec M (2011) Biocomposites based on flax short fibres and linseed oil. Ind Crops Prod 33:317–324

Le ADT, Maalouf C, Mai TH, Wurtz E, Collet F (2010) Transient hygrothermal behaviour of a hemp concrete building envelope. Energ Build 42:1797–1806

Lee SC, Cunnington GR (2000) Conduction and radiation heat transfer in high porosity fiber thermal insulation. J Thermophys Heat Transfer 14:121–136

Lee SM (1991) International encyclopedia of composite. VCH, New York

Li Y, Mai Y, Ye L (2000a) Sisal fibre and its composites: a review of recent developments. Compos Sci Technol 60:2037–2055

Li Y, Yan Y-W, Ye L (2000b) Sisal fibre and its composites: a review of recent developments. Compos Sci Technol 60:2037–2055

Lotz B (2006) A brief history of thermal insulation. *RSI report*

Lu X (2002a) Modelling heat and moisture transfer in buildings: (I) Model program. Energ Build 34:1033–1043

Lu X (2002b) Modelling heat and moisture transfer in buildings: (II) Application to indoor thermal and moisture control. Energ Build 34:1045–1054

Luo X, Xu Q (2006) A new numerical implementation on 2D heat and moisture transfer through fabric. Appl Math Comput 174:1135–1150

Madurwar MV, Ralegaonkar RV, Mandavgane SA (2013) Application of agro-waste for sustainable construction materials: a review. Constr Build Mater 38:872–878

Malkapuram R, Kumar V, Yuvraj SN (2008) Recent development in natural fibre reinforced polypropylene composites. J Reinf Plast Compos 28:1169–1189

Masoodi R, Tan H, Pillai KM (2010) Numerical simulation of liquid absorption in paper-like swelling porous media. AIChE J 56:2257–2267

Merta I, Tschegg EK (2013) Fracture energy of natural fibre reinforced concrete. Constr Build Mater 40:991–997

Milandri A, Asllanj F, Jeandel G, Roche JR (2002) Heat transfer by radiation and conduction in fibrous media without axial symmetry. J Quant Spectrosc Radiat Transfer 74:585–603

Mishra SP (2000) A text book of fibre science and technology New Age International

Modi DB, Bennes SM (1985) Moisture gain of spray-applied insulations and its effect on effective thermal conductivity—Part 1. J. Thermal Insulation 8:259–277

Moriana R, Vilaplana F, Karlsson S, Ribes-Greus A (2011) Improved thermo-mechanical properties by the addition of natural fibres in starch-based sustainable biocomposites. Cpmposites: Part *A,* 42, 30–40

Motakef S, El-Masri MA (1986) Simultaneous heat and mass transfer with phase change in a porous slab. Int. J. Heat Mass Transfer 29:1503–1512

Mussig J (2010) Industrial applications of natural fibres-structure. Properties and Technical Applications, Wiley

Neethirajan S, Gordon R, Wang L (2009) Potential of silica bodies (phytoliths) for nanotechnology. Trends Biotechnol 27(8):461–467

Oduor SO (1999) Simultaneous air, heat and moisture transfer in fibrous building insulation. Ph.D. University of Alberta, Alberta

Ogniewicz Y, Tien CL (1981) Analysis of condensation in porous insulation. Int J. Heat Mass Transfer 24:421–429

Olesen PO, Plackett DV Perspectives on the performance of natural plant fibres [Online]

Onesippe C, Passe-Coutrin N, Toro F, Delvasto S, Bilba K, Marie-Ange A (2010) Sugar cane bagasse fibres reinforced cement composites: thermal considerations. Composites Fabrication 41A:549–556

Osanyintola OF, Simonson CJ (2006) Moisture buffering capacity of hygroscopic building materials: Experimental facilities and energy impact, Energ Build 38(10):1270–1282

Pacheco Torgal F, Jalali S (2011) Cementitious building materials reinforced with vegetable fibres: A review. Construction and Building Materials, 25

Pacheco Torgal F, Labrincha JA (2013a) Biotech cementitious materials: some aspects of an innovative approach for concrete with enhanced durability. Constr Build Mater 40:1136–1141

Pacheco Torgal F, Labrincha JA (2013b) The future of construction materials research and the seventh UN Millennium development goal: a few insights. Constr Build Mater 40:729–737

Pacheco Torgal F, Miraldo S, Ding Y, Labrincha JA (2013) Targeting HPC with the help of nanoparticles: an overview. Constr Build Mater 38:365–370

Pan N, Gibson P (2006) Thermal and moisture transport in fibrous materials. UK, Woodhead Publishing Ltd, Cambridge

Papadopoulos AM (2005) State of the art in thermal insulation materials and aims for future developments. Energ Build 37:77–86

Pasila A (2004) The dry-line method in bast fibre production. University of Helsinki, Ph.D

Paster M, Pellegrino JL, Carole TM (2003) Industrial bioproducts. Today and Tomorrow, Washington DC

Patel BC, Acharya SK, Mishra D (2012) Environmental effect of water absorption and flexural strength of red mud filled jute fiber/polymer composite. Int J Eng Sci Technol 4:49–59

Paul V, Kanny K, Redhi GG (2013) Formulation of a novel bio-resin from banana sap. Ind Crops Prod 43:496–505

Pervaiz M, Sain MM (2003) Carbon storage potential in natural fiber composites. Resour Conserv Recycl 39:325–340

Pietak A, Korte S, Tan E, Downard A, Staiger MP (2007) Atomic force microscopy characterization of the surface wettability of natural fibres. Appl Surf Sci 253:3627–3635

Rao S, Jayaraman K, Bhattacharyya D (2012) Micro and macro analysis of sisal fibre composites hollow core sandwich panels. Compos B Eng 43:2738–2745

Raut SP, Ralegaonkar RV, Mandavgane SA (2011) Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks. Constr Build Mater 25:4037–4042

Reddy N, Yang Y (2005) Biofibers from agricultural byproducts for industrial applications. Trends Biotechnol 23:22–27

Roberts K (2007) Handbook of plant science, Wiley

Rode C (1998) Organic insulation materials: effect on indoor humidity and necessity of a vapor barrier. Thermal performance of the exterior envelopes of buildings VII, Clear water Beach, Florida, USA 109

Rong MZ, Zhang MQ, Liu Y, Yang GC, Zeng HM (2001) The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. Compos Sci Technol 61:1437–1447

Rothman DH, Zaleski S (1994) Lattice-gas models of phase separation: interfaces, phase transitions, and multiphase flow. Rev. Modern Phys 66:1417–1479

Roy S, Junk M, Sundar S (2006) Understanding the porosity dependence of heat flux through glass fiber insulation. Math Comput Model 43(5):485–492

Rowell RM (1992) Property enhancement of wood composites, Chapter 14. In: Rowell RM, Vigo T, Kinzig B (eds) Composite applications—the role of matrix, fibre and interface. VCH Publishers, New York

Rowell RM (1997) Chemical modification of agro-resources for property enhancement. Paper and Composites from Agro-based Resources

Rowell RM, Stout HP (1998) Jute and Kenaf

Saheb ND, Jog JP (1999) Natural fiber polymer composites: a review. Adv Polym Tech 18:351–363

Sathishkumar T, Navaneethakrishnan P, Shankar S, Kumar J (2012) Mechanical properties of randomly oriented snake grass fiber with banana and coir fiber-reinforced hybrid composites. J Comp Mater

Satyanarayana KG, Arizaga GGC, Wypych F (2009a) Biodegradable composites based on lignocellulosic fibers—an overview. Prog Polym Sci 34:982–1021

Satyanarayana KG, Guimaraes JL, Wypych F (2007) Studies on lignocellulosic fibers of Brazil. Part I: Source, production, morphology, properties and applications. Compos A Appl Sci Manuf 38:1694–1709

Sharma HSS, Mercer PC, Brown AE (1989) A review of recent research on the retting of flax in Northern Ireland. International Biodeterioration 25:327–342

Siegel R, Howell JR (1992) Thermal radiation heat transfer, Washington, Hemisphere

Singh BP, Kaviany M (1992) Modeling radiative heat transfer in packed beds. Int. J. Heat Mass Trans 35:1397–1405

Siqueira G, Bras J, Dufresne A (2010) Cellulosic bionanocomposites: a Review of preparation, properties and applications. Polymers 2:728–765

Soubdhan T, Feuillard T, Bade F (2005) Experimental evaluation of insulation material in roofing system under tropical climate. Sol Energ 79:311–320

Suddell BC (2008) Industrial fibres: recent and current developments. Proceedings of the Symposium on Natural Fibres, Rome

Sukumaran K, Satyanarayana KG, Pillai SGK, Ravikumar KK (2001) Structure, physical and mechanical properties of plant fibres of Kerala. Met Mater Process 13:121–136

Sumere CFV (1992) Retting of flax with special reference to enzyme retting. In: Sharma HSS, Sumere CFV (eds) The biology and processing of flax, M Publications. Belfast, UK

Syerko E, Comas-Cardona S, Binetruy C (2012) Models of mechanical properties/behavior of dry fibrous materials at various scales in bending and tension: a review. Compos A Appl Sci Manuf 43:1365–1388

Tao Y-X, Besant RW, Rezkallah KS (1991a) Modelling of frost formation in a fibrous Insulation slab and on an adjacent cold plate. Int Comm Heat Mass Trans 18:609–618

Tao Y-X, Besant RW, Rezkallah KS (1991b) Unsteady heat and mass transfer with phase changes in an insulation slab: frosting effects. Int J Heat Mass Trans 34:1593–1603

Thompson NS (1993) Hemicellulose as a biomass resource, Academic Press

Tien C-L (1988) Thermal radiation in packed and fluidized beds. ASME J Heat Trans 110:1230–1242

Turner WC, Malloy JF (1981) Thermal insulation handbook. Robert E. Krieger Publishing Co & McGraw Hill

Vafai K, Sarkar S (1986) Condensation effects in a fibrous insulation slab. J Heat Trans 108:667–675

Vafai K, Whitaker S (1986) Simultaneous heat and mass transfer accompanied by phase change in porous insulation. Trans ASME 108:132–140

Wallenberger FT, Weston N (2004) Natural fibers, Plastics and composites Springer

Vassilev SV, Baxter D, Andersen LK, Vassileva CG (2013) An overview of the composition and application of biomass ash.: Part 2. Potential utilisation, technological and ecological advantages and challenges. Fuel 105:19–39

Webb RL (1994) Principles of enhanced heat transfer. Wiley, New York

Weinberger CB (1996) Synthetic fiber manufacturing, Departmant of Chemical Engineering, Drexel University

Velmurugan R, Manikandan V (2007) Mechanical properties of palmyra/glass fiber hybrid composites. Compos A 38:2216–2226

Verschoor JD, Greebler P, Manville NJ (1952) Heat transfer by gas conduction and radiation in fibrous insulation. J Heat Transfer 74:467–474

Whitaker S (1966) The equation of motion in porous media. Chem Eng Sci 21:291–300

Whitaker S (1967) Difision and dispersion in porous media. AIChE J 13:420–427

Whitaker S (1969) Advances in theory of fluid motion in porous media. Lndustr Eng Chem 61:14–28

Whitaker S (1973) The transport equations for multi-phase systems. Chem Eng Sci 28:139–147

Whitaker S (1985) A simple geometrical derivation of the spatial averaging theorem. Chem Eng Educ 19:18–52

Wijeysundera NE, Zheng BF, Iqbal M, Hauptmann EG (1996) Numerical simulation of the transient moisture transfer through porous insulation. Int J Heat Mass Trans 39:995–1004

Woolfson DN, Ryadnov MG (2006) Peptide-based fibrous biomaterials: Some things old, new and borrowed. Current opinion in chemical biology. 10(6):559–567

Viskanta R, Menguc MP (1989) Radiative transfer in dispersed media. *ASME*. Appl Mech Rev 42:241–259

Wu H, Fan J, Du N (2007) Thermal energy transport within porous polymer materials: effects of fiber parameters. J Appl Polym Sci 106:576–583

Youngquist JA, English BE, Scharmer RC, Chow P, Shook SR (1994) Literature review on use of non-wood plant fibers for building materials and panels. United States Department of Agriculture

Zhang B-M, Zhao S-Y, He X-D (2008) Experimental and theoretical studies on high-temperature thermal properties of fibrous insulation. J Quant Spectrosc Radiat Transfer 109:1309–1324

Zhao SY, Zhang BM, He XD (2009) Temperature and pressure dependent effective thermal conductivity of fibrous insulation. Int J Therm Sci 48:440–448

Zhou X, Zheng F, Li H, Lu C (2010) An environment-friendly thermal insulation material from cotton stalk fibers. Energ Build 42:1070–1074

# High-Performance Insulation Materials

**Hans-Peter Ebert**

**Abstract** Improving the thermal efficiency of the existing building stock is one of the key measures to deliver a substantial contribution to reduce $CO_2$ emissions of our society. Novel high-performance insulation materials with superior low thermal conductivity values offer several advantages in comparison with conventional insulation products. Following a brief introduction of the principles of heat transfer in thermal insulations, two classes of superinsulations will be discussed in detail: vacuum insulation panels (VIP) and microporous thermal insulations. The special features of these thermal insulations will be pointed out and best practice examples are presented. Finally, a general summary and a discussion on future trends in R&D for thermal insulation will complete this topic.

## 1 Introduction

Thermal insulation of buildings is one of the most effective ways to save energy resources for heating and cooling and providing comfortable temperatures in living and working rooms. Techniques for thermal insulation were historically always applied in regions with harsh conditions by using natural materials like straw, hay, cork or felts. The physical principle behind these efforts that were empirically optimised with time and passed down generations is to generate a volume of still air within a porous structure and to avoid convection effects. Thus, the thermal conductivity of still air, i.e. 0.026 $Wm^{-1}K^{-1}$ at ambient conditions, comes significantly into effect and provides a reasonable thermal insulation. Thermal insulation materials or systems, which show effective thermal conductivity values far below the conductivity value of still air at ambient conditions, are known as so-

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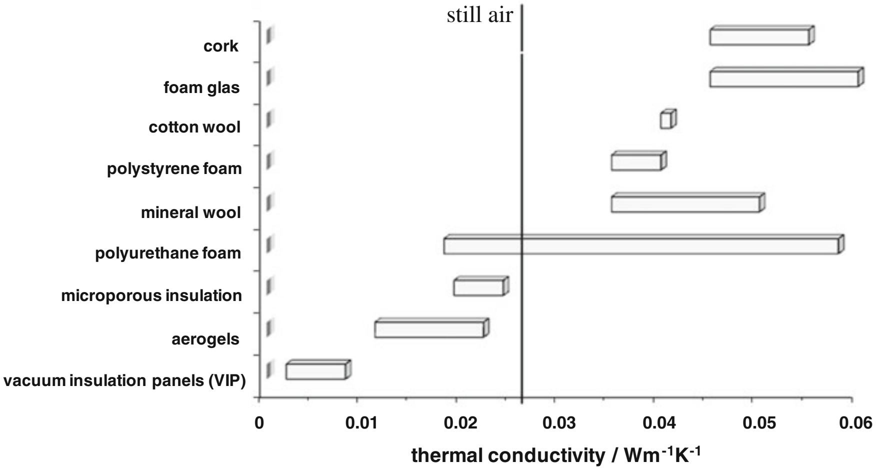


**Fig. 1** Typical thermal conductivity values of thermal insulation materials at ambient conditions

called superinsulations. An overview of thermal insulation materials is depicted in Fig. 1.

Against the backdrop of the climate change and the necessary actions to limit its impacts on the environment, the reduction in greenhouse gas emissions by implementing energy-saving technologies is a key issue of international efforts. In this context, the improvement in the thermal insulation of our building stock is one of the most effective ways to reduce the energy consumption. In Europe and the United States, about 40 % of the total energy consumption is from buildings, especially to old ones. In Germany, for example, about 2/3 of the building stock that was constructed before 1977 consumes about 95 % of the energy in the building sector. Concerning the development of thermal insulation products for building industry, a lot of existing customary insulation products were optimised in the past. One example is the opacification of expanded polystyrene foams with pigments, i.e. opacifier, which reduces heat transfer within these low-density foams by absorbing thermal radiation and therefore leading to a lower total thermal conductivity of the thermal insulation product. However, the use of classical insulation materials (e.g. mineral wool, foam products) has the effect that the thicknesses of insulation layers for façades have to be quite large to fulfil the requirements of the building codes and current regulations. Thus, insulation thicknesses of more than 10 cm are not unusual. For extremely well-insulated façades with U-values of about 0.015 $Wm^{-1}K^{-2}$, insulation thicknesses of more than 20 cm are needed. In respect to refurbishment of buildings, these additional thick insulation layers could lead to problems in implementation (cf. Fig. 2). Of course the remaining space at the insulated area will be reduced. In the case of internal thermal insulation, e.g. considering the insulation of an attic, the usable space will be reduced and might affect the quality of living. Also in some cases,

**Fig. 2** *Left* A thick insulation layer influences the façade view at the interface façade/window. *Right* Not completed insulation due to the fact that the insulation had to be mounted close to the surrounding property

where the thermal insulation layer had to be mounted close to surrounding property, the required insulation thicknesses could often not be applied because of legal regulations. Last but not least due to the later attachment of a thermal insulation, the proportions of the building will be shifted, which often influences architecture, especially the façade, in a negative way, and diminishes the aesthetic general impression.

These above-mentioned facts initiated a lot of new developments in the field of thermal insulations with the objectives to provide a customised product with extremely low thermal conductivity values, the superinsulation. International coordinated research activities took place within IEA working groups (Binz et al. 2005; IEA 2012) and various public and non-public research projects in Europe (Berge and Johansson 2012; Stahl et al. 2012), America (Mukhopadhyaya et al. 2008; Kosny et al. 2013) and Asia (Wen et al. 2009; Kwon et al. 2009).

## 2 Heat Transfer within Thermal Insulations

Within a porous insulation material, heat is transported by three different mechanisms: conductive heat transfer via the solid backbone, heat conduction within the gas phase and radiative heat transfer (cf. Fig. 3). Convection, i.e. the transport of energy by free or forced convective gas flow, does not occur in thermal insulations

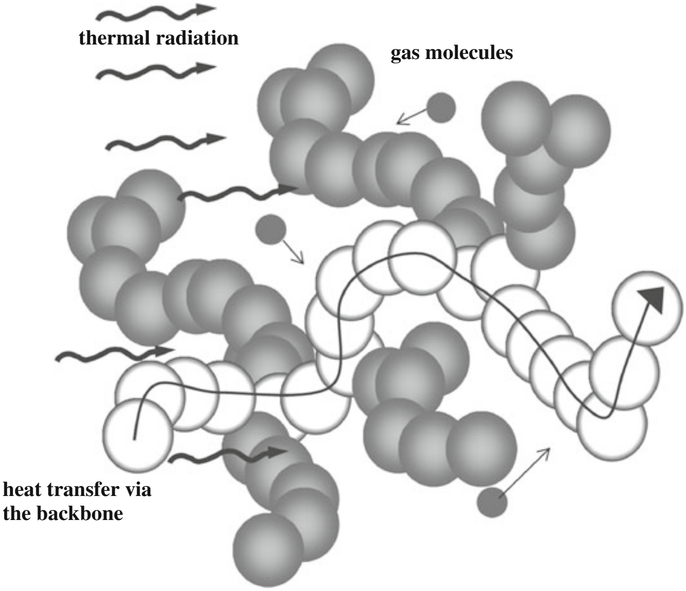


**Fig. 3** Heat transfer mechanisms within thermal insulations. Heat transfer takes place by heat conduction via the solid skeleton and the gas phase and by thermal radiation

because of the limited free space, the relatively low temperature and non-existent pressure differences in building applications.

The thermal insulation properties of an insulation material are determined by the total effective thermal conductivity $\lambda_{\text{eff}}$, which is a temperature-dependent material property and is defined by Fourier's law. In the case of a one-dimensional insulation layer, Fourier's law is given by (Fourier 1822)

$$q = -\boldsymbol{\lambda}(T)\frac{T_h - T_c}{\Delta x} \tag{1}$$

where $q$ the heat flux density in $\mathrm{Wm}^{-2}$, $\lambda$ the thermal conductivity in $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$ and $T_h$ and $T_c$ the local temperatures at the hot and cold side of the thermal insulation layer with the thickness $\Delta x$. The total effective thermal conductivity could be described in a good approximation by the sum of the solid thermal conductivity, $\lambda_s$, the thermal conductivity of the gas within a given porous structure, $\lambda_g$, and the radiative thermal conductivity, $\lambda_r$, which reflects the involved heat transfer mechanisms (Ebert 2011):

$$\lambda_{\text{eff}}(T, p_g) = \lambda_s(T) + \lambda_g(T, p_g) + \lambda_r(T), \tag{2}$$

where $T$ the temperature and $p_g$ the gas pressure. The solid thermal conductivity depends on the chemical composition of the solid backbone, its structure (e.g. powder, fibre, foam structure) and the effective density of the insulation material, $\rho$ (Lu 1991; Scheuerpflug et al. 1991):

$$\lambda_s(T) = G(\rho) \cdot \lambda_0(T), \tag{3}$$

where $\lambda_0$ the thermal conductivity of the backbone material and $G$ the geometry factor which depends on the density. The geometry factor $G$ shows in many cases weak nonlinear density dependence, i.e.

$$G \propto \rho^{\alpha}, \tag{4}$$

with typical values of $\alpha = 1\ldots2$.

Energy within the gas phase is transported by the interaction of the gas molecules with itself and with the surrounding solid backbone via collisions. Therefore, the conductive heat transfer in the gaseous phase depends on the ratio of the mean free path $l_g$ of the gas molecules to the effective pore dimension $D$ which is characteristic for the porous structure of the insulation material. This ratio is also known as Knudsen number Kn:

$$\mathrm{Kn} = \frac{l_g}{D} \tag{5}$$

For $\mathrm{Kn} \gg 1$, i.e. the average pore size is significantly smaller than the mean free path of the gas molecules, the gas molecules collide predominantly with the solid backbone of the insulation material and the resulting thermal conductivity contribution is proportional to the number of gas molecules, i.e. the gas pressure. The contrary extreme is the case where the mean free path of the gas molecules is much smaller than the average pore size, i.e. $\mathrm{Kn} \ll 1$. The gas molecules collide predominantly with each other, which is the classical case of diffusive heat transfer. The resulting thermal conductivity of the gaseous component equals the thermal conductivity of the free gas, which is independent of the gas pressure for ambient and moderate pressures. For $\mathrm{Kn} \approx 1$, the gas molecules collide with both the walls and each other. An analytic expression of the gas pressure dependence of the effective thermal conductivity of a pore gas, $\lambda_g$, which considers all three regimes, is provided by Kaganer (1969):

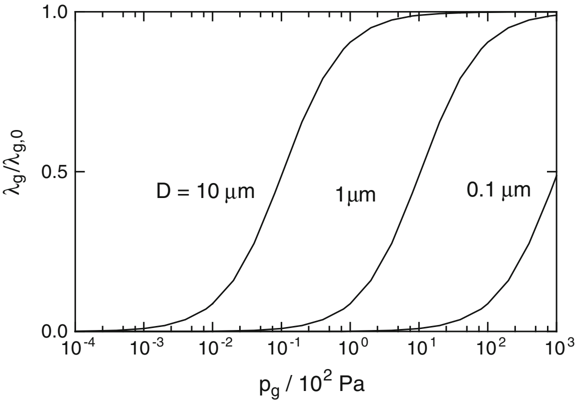
$$\lambda_g(p_g, T) = \frac{\Pi \cdot \lambda_{g,0}(T)}{1 + 2 \cdot \beta(T) \cdot \mathrm{Kn}(T)} = \frac{\Pi \cdot \lambda_{g,0}(T)}{1 + \frac{p_{1/2}(T)}{p_g}} \tag{6}$$

where $\Pi$ the porosity of the insulation material, $\beta$ the coefficient, dependent on the type of gas and temperature, $p_{1/2}$ the gas pressure at which the thermal conductivity is one-half of $\lambda_{g,0}$ and $\lambda_{g,0}$ the thermal conductivity of the non-convecting free gas.

Figure 4 shows the ratio $\lambda_g/\lambda_{g,0}$ as a function of the gas pressure for different pore diameters $D$ and $\Pi = 1$.

The curves in the regime of molecular heat transfer increase linearly with the gas pressure, which is hard to see in Fig. 4, followed by the transition regime where the gaseous thermal conductivity increases significantly until the saturation regime is reached. In this case, the thermal conductivity is independent of the gas pressure. The plot also shows that with decreasing Knudsen number, i.e. increasing

**Fig. 4** Gas pressure dependence of the effective thermal conductivity of the pore gas nitrogen in relation to the thermal conductivity of the free gas according to Eq. (6) for different pore diameters $D$ and $\Pi = 1$. Typical $s$-shaped curves can be observed in the log-linear representation



pore diameter $D$, the half-width pressure $p_{1/2}$ is shifted to higher values of the gas pressure.

For thermal insulation materials at ambient temperatures, radiative heat transfer could be described by the diffusion of photons and a radiative conductivity can be defined as (Siegel and Howell 1972):

$$\lambda_r(T) = \frac{16}{3} \cdot \frac{n^2 \cdot T_r^3}{\rho \cdot e_R^*(T)} \tag{7}$$

where $\lambda_r$ the radiative conductivity, $n$ the effective index of refraction, $\rho$ the density, $e_R{*}(T)$ the temperature-dependent effective specific extinction and $T_r$ the mean radiative temperature. It is important to realise that the higher the density, i.e. the more material can interact with the thermal radiation, and the higher the effective specific extinction, the lower the radiative conductivity. Since in general higher densities will be avoided because in this case the solid thermal conductivity could increase, it is highly preferable to use so-called infrared opacifier. These opacifiers consist of pigments, e.g. oxides, carbides or carbon blacks, which absorb or scatter thermal radiation very efficiently and therefore reduce radiative heat transfer. The effective specific extinction $e_R{*}$ is a material property and depends on the chemical composition, the material size and shape.

In Fig. 5, the gas pressure-dependent thermal conductivity of typical insulation materials is depicted. For materials, like glass fibres and foams with large pores in comparison with the mean free path of the gas molecules (for nitrogen at ambient conditions about 70 nm), the saturation region where the diffusive heat transfer occurs can be clearly observed for gas pressures above 10 mbar. Here, the thermal conductivity is nearly independent of gas pressure. For microporous materials, like precipitated and fumed silica with pore sizes in the range of the mean free path of nitrogen, the thermal conductivity of the pore gas is already reduced and a total effective thermal conductivity below or in the range of the thermal conductivity of still air could be seen. The thermal conductivity values for the gas pressure-

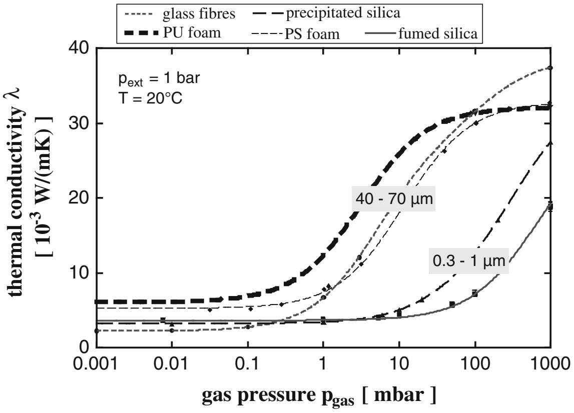


**Fig. 5** Thermal conductivity of porous insulation materials as function of gas pressure for an external load of 1 bar and at 20 °C. The typical range of the average pore size of the investigated materials is also given. For microporous materials, e.g. precipitated or fumed silica, the average pore size is below 1 μm

independent regime at low gas pressures indicate the sum of the solid thermal and radiative conductivity, $\lambda_s + \lambda_r$.

From Fig. 5, also two obvious directions for the realisation of superinsulation could be recognised. Firstly, the possibility to evacuate porous insulations would lead to effective thermal insulation systems with thermal conductivity values about 10 times lower as they are known for conventional insulation materials. This effect leads to the development of vacuum insulation panels for building applications. Secondly, the reduction in pore size below 1 μm would have the effect that even at ambient conditions thermal insulation products would have thermal conductivity values below those of still air. This effect was well known since the invention of silica aerogels in 1932 by Kistler (1935). However, only in the last years, new research activities were launched to develop such microporous insulation materials for building applications.

## 3 Vacuum Insulation Panels

### 3.1 *Construction and Physical Properties*

The possibility to use vacuum insulation panels (VIP) for thermal insulation of buildings was first investigated by ZAE Bayern in the years 1998–2003 (Schwab et al. 2004). The challenge at that time was to develop a flat more or less vacuum tight panel with a lifetime durability of more than 50 years. Vacuum insulation was well known for technical insulations, e.g. storage of cryogenic liquids and for the vacuum flask for more than 100 years. However, the storage devices had a cylindrical shape to withstand the atmospheric pressure of 1 bar, which corresponds to 10 t/m$^2$. In a vacuum flask, no insulation material is used. The hollow space between two concentric glass cylinders is evacuated to such a low gas pressure that heat conduction via the gas phase is negligible. A detailed discussion of the history of vacuum insulation is given in Fricke et al. (2005, 2008). VIP technology for building application is described in literature in detail (Binz et al. 2005; Simmler and Brunner 2005; Baetens et al. 2010).

For flat insulation panels, which are applicable for building insulation, a microporous kernel is used, which consists of a pressed silica powder in the most cases (cf. Fig. 6). Additionally, an infrared opacifier is added to the silica powder to reduce the radiative heat transfer. The pressed silica core is embedded in a core bag to enable a further dustless manufacturing of the final VIP. The filled core bag will be enfolded by a multilayer envelope film. This package will be evacuated down to 1 mbar and sealed within a vacuum chamber. The advantage of a kernel made of fumed silica, which is evacuated at gas pressure of about 1 mbar, could be seen in Fig. 5. While for conventional insulation kernels like glass fibres or foams, the effective thermal conductivity would immediately increase with gas pressure of 1 mbar, for the microporous fumed silica only at a gas pressure of about 100 mbar, a significant increase could be recognised. This is a safety margin of 100 mbar considering a typical gas pressure increase of 1 mbar per year by penetrating nitrogen and water molecules through the high-barrier laminate and the sealing rims.

In Fig. 7, a typical design of a high-barrier laminate that used VIP is depicted. The polyethylene (PE) layer is necessary to enable the thermal welding of the laminate at VIP rims. The aluminium (Al) layers work as barrier layers against penetrating air gas molecules, e.g. nitrogen, oxygen and water vapour. It is important to use more than one thin Al layer in the range of several nanometres, e.g. two or three, to reduce thermal heat transfer via these layers and therefore a thermal bridge at the VIP rims. The minimum thickness of the adhesive layer embedded between the two metal layers is also important. If pinholes, i.e. defects

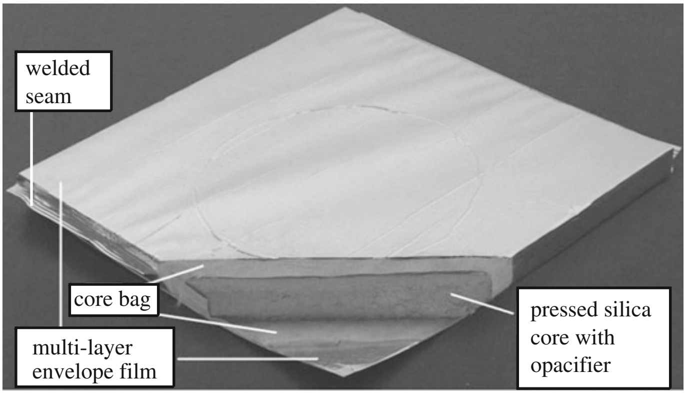


**Fig. 6** Construction of a vacuum insulation panel (VIP) used for building insulation: a pressed silica core is embedded in a core bag to enable a further dustless manufacturing of the final VIP. The filled core bag will be enfolded by a multilayer envelope film. This package will be evacuated and sealed within a vacuum chamber

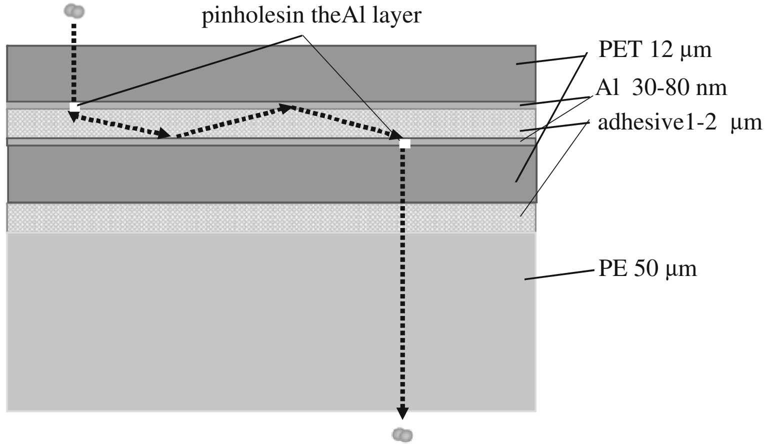


**Fig. 7** Construction of a high-barrier laminate for a VIP

which could not be avoided, occur in the Al layers, the penetrating gas molecules have to diffuse parallel to the pressure gradient until they hit upon a further pinhole in the next Al layer (cf. Fig. 7).

A typical thermal conductivity value for VIP used in building application is about 0.005 $\mathrm{Wm^{-1}K^{-1.}}$ In principle, this value only yields for the core material evacuated at a certain gas pressure. Because a vacuum insulation panel has a finite dimension and thickness, there is always an influence of an enhanced heat flux via the rims of a VIP. The heat flux depends on the effective in-plane thermal conductivity of the used laminates and the length and thickness of the rims. This is the reason why a VIP has to be regarded as an insulation system, and in a more correct way, a heat transfer coefficient, the U-value, should be provided for VIP for a certain dimension. The U-value in $\mathrm{Wm^{-2}K^{-1}}$ is defined by

$$q = -\lambda(T) \cdot \frac{T_h - T_c}{\Delta x} = -U(T) \cdot (T_h - T_c) \tag{8}$$

and describes the heat flux per unit area flowing through an insulation layer of thickness Δx. The influence of the laminate type and panel size is depicted in Figs. 8 and 9. From Fig. 9, it could be concluded that for VIP using high-barrier laminates with an overall thickness of about 80 nm or less, thermal boundary effects are negligible except for very small panels.

A further special property of a vacuum insulation panel is the fact that the VIP envelope cannot be absolute vacuum tight. As mentioned above, gas molecules could penetrate through pinholes and through the sealing areas into the VIP, and as a consequence, the gas pressure will increase with time (Schwab et al. 2005c). Therefore, preferable microporous silica as kernel material (cf. Fig. 5) in combination with high-barrier laminates is used to establish a long service time where the gas pressure increases but not the thermal conductivity (Schwab et al. 2005a, b).

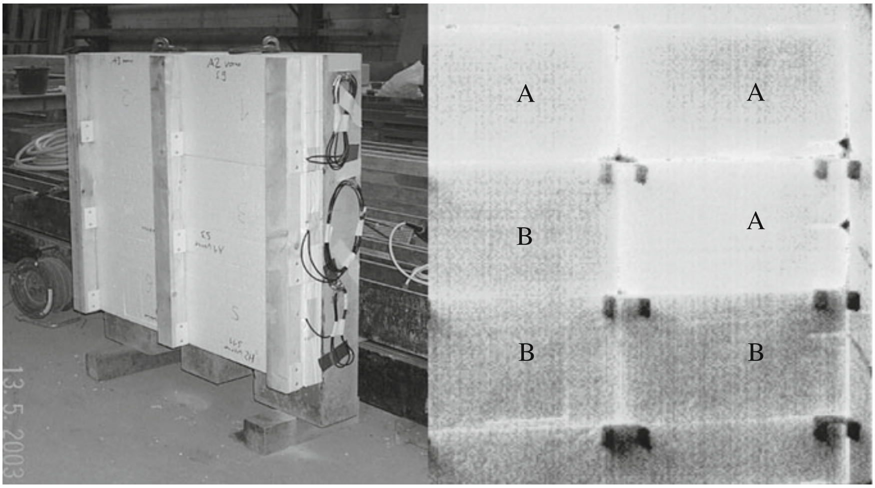


**Fig. 8** Test construction for the investigation of thermal bridge effects while using VIP with different envelope laminates. In a first group, the VIP laminates include a 7-µm aluminium layer (A), and in a second group, VIP-applied laminates for the envelope contain only a 30-nm aluminium layer. *Left* 6 VIP were mounted on a temperature-controlled concrete wall and covered with 20-mm polystyrene foam insulation. *Right* The thermal image shows enhanced temperatures for VIP with the pure aluminium enclosure

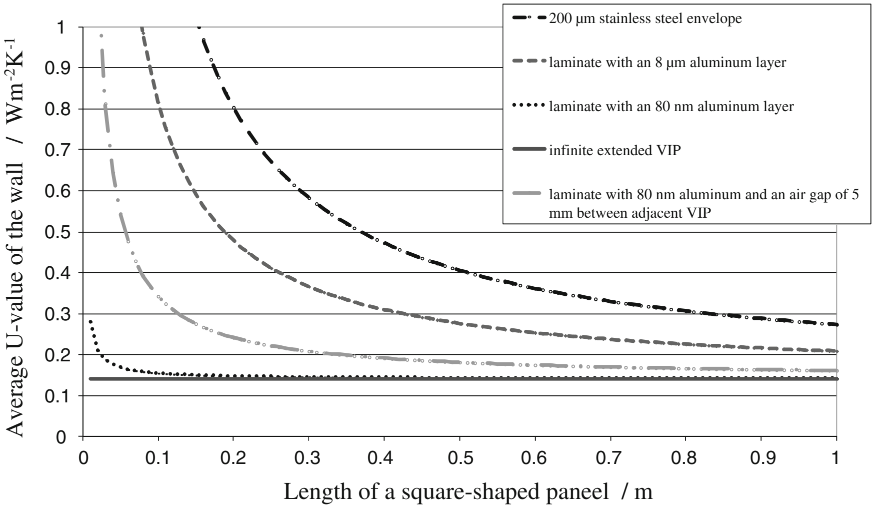


**Fig. 9** Calculated average U-value of vacuum insulation panels (VIP) as a function of panel size for different laminate types. The values for the infinite extended VIP (*full line*) represent the U-value for the core material not taken into account thermal boundary effects

This ageing effect depends on climate conditions, and therefore, many producers of VIP run accelerated ageing tests under different climatic conditions to provide reliable thermal performance data.

In order to adapt the VIP for rough construction site conditions or special application (direct finishing with plaster), the VIP could be enclosed by additional layers, e.g. fibre, fleece or foam.

## *3.2 Experiences in Practice*

Nowadays, VIP insulation technology becomes more and more known and a significant number of buildings were insulated with VIP. In the most cases, this relatively expensive insulation technique in comparison with standard insulation products, e.g. PS foam or glass wool, was used as ‘problem solver’. The VIP technology offers special advantages where limited construction space does not allow conventional insulation measures, e.g. low storey heights or surrounding property, or when living space is extremely expensive, e.g. in city centres. Of course the highly insulation panels also offer the possibility for an aesthetical slim architecture.

Findings and experience in the use of VIP in the daily practice on construction sites were gained from various research projects. In this context, the projects ‘VIP Gebäude’ (Schwab et al. 2005d) and ‘VIP PROVE’ (Heinemann and Kastner 2010) conducted by the ZAE Bayern for the period 2000–2010 can be mentioned. Within the project ‘VIP PROVE’ 29 commercially realised buildings with a total area of 8,206 $m^2$ of installed VIP from different producers were investigated. It is worthwhile to mention that in this project, buildings were investigated where no scientific institutes were involved during the construction and the implementation of VIP. Therefore, more or less the daily construction work was reflected.

### 3.2.1 Retrofitting of Façades and Roofs

One of the very first façades insulated with vacuum insulation panels belongs to a 200-year-old protected building. VIPs were used in combination with conventional polystyrene foam insulation for the thermal insulation of the façade on the gable side because it was the only possible way to preserve the characteristic of the façade with the low roof overhang and to provide an excellent U-value of 0.19 $Wm^{-2}K^{-1}$. The U-value of the historic brickwork was about 0.7 $Wm^{-2}K^{-1}$. The wall structure is depicted in Fig. 10.

Figure 11 shows the mounting of the VIPs at the construction site. The VIPs were positioned on the profile rails. After this, the polystyrene rendering panels were mounted. It is important to avoid air gaps between the VIP to reduce thermal bridges. Existing air gaps were filled with insulation foam.

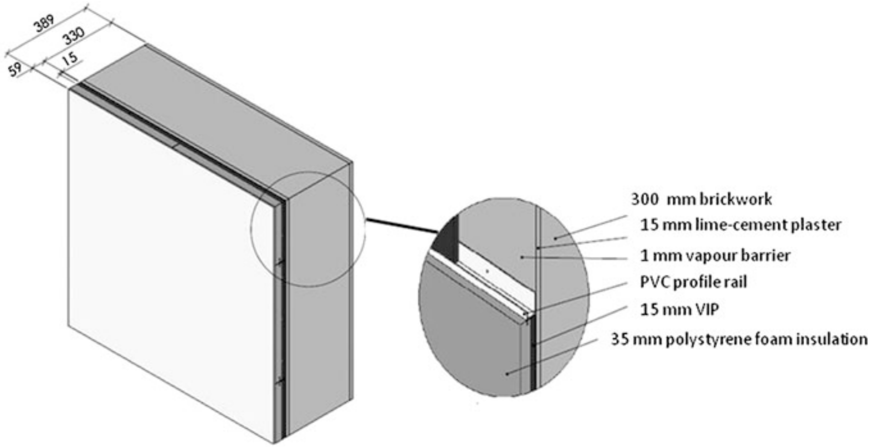


**Fig. 10** Wall structure of the renovated wall. Finally, a finish of 3 mm of reinforcement plaster and 3 mm of synthetic resin plaster were applied

**Fig. 11** Installation of the VIP on the *top* of the vapour barrier. In the edge regions, *triangular-shaped* VIPs were used

A view of the façade before and after refurbishment is depicted in Fig. 12. It could be stated that due to the slim VIP, the refurbishment could be successfully finished in full accordance with department for the protection of historical monuments. Figure 13 shows a thermal image, which was taken 1 year after refurbishment. As can be seen, the rim of the VIP acts as thermal bridges. This effect is damped by the application of an additional insulation layer with polystyrene foam. Additionally, the thermal image indicates that at least three VIPs are vented, which means that the effective thermal conductivity increases for these panels up to approximately 0.025 $\mathrm{Wm^{-1}K^{-1}}$. This fact was detected shortly after the completion of the refurbishment. Since this time, no further degradation could be

**Fig. 12** View of a historic building before and after refurbishment with vacuum insulation panels. It was a prerequisite to preserve the roof overhang in order not to change the façade characteristic. The U-value could be reduced from a value of 0.7 to 0.19 $\mathrm{Wm^{-2}K^{-1}}$

**Fig. 13** Thermal image of the renovated wall one year after refurbishment

observed, where the last investigation with an infrared camera was in November 2008.

Another striking example is the refurbishment of terraced house (year of construction 1956). VIPs were used for the thermal insulation of the façade and the

**Fig. 14** View of a refurbished terraced house. *Left picture* photography and *right picture* thermal image. The *dark colours* of the thermal image correspond to low surface temperatures and therefore are an indicator for an excellent thermal insulation

roof. The external wall consists of 0.34-m brickwork with a U-value of 1.0 $\mathrm{Wm^{-2}K^{-1}}$. Due to the application of VIP layer with a thickness of 30 mm, the U-value was improved to a U-value of 0.16 $\mathrm{Wm^{-2}K^{-1}}$. Concerning the thermal insulation of the roof, the areas between the rafters were packed with cellulose insulation material with an additional layer of 20-mm-thick VIPs at the interior side of the roof construction. Thus, an overall U-value of 0.13 $\mathrm{Wm^{-2}K^{-1}}$ could be achieved.

Due to the application of vacuum insulation technology, the contours of the refurbished building seamlessly fit in the front of the row of houses (cg. Fig. 14). However, the use of conventional insulation materials with a required thickness of 200 mm would have lead to significant visible jumps of the front along the three buildings shown.

A particular challenge is the energy-related renovation of historical buildings. In this context, the refurbishment of Rosslyn Chapel at the village Rosslyn close to Edinburgh is noteworthy. Rosslyn Chapel is a listed building of the highest category in Great Britain and was constructed between 1446 and 1484. During the refurbishment work in 2010, the church roof was thermally insulated by using vacuum insulation panels. At this time, about 152-$\mathrm{m}^2$ VIPs of the Typ 'va-Q-vip B' from the company va-Q-tec, Germany, with a thickness of 30 mm were installed to achieve a U-value of the roof construction of less than 0.23 $\mathrm{Wm^{-2}K^{-1}}$ (cg. Figs. 15, 16 and 17). With this slim and highly thermally insulating roof sealing, the specific character of the building could be maintained.

**Fig. 15** View of the enclosed church roof of Rosslyn Chapel just before the refurbishment measure

**Fig. 16** Preparation of the support structure containing the VIP panels. The used VIPs of type 'va-Q-vip B' have an additional protection layer, which is responsible for the *blackish colour* of the VIPs

### 3.2.2 VIPs for Interior Thermal Insulation

In many cases, the only possible way to improve the insulation properties is the application of an interior insulation. This applies, in particular, if a historical façade with visible framework should be refurbished. Vacuum insulation panels

**Fig. 17** Mounted VIP construction with wooden framework for the final metal roof sheets

offer the advantage that less living space is exhausted for thermal insulation and even an acceptable thermal standard could be provided.

In the following two examples, the application of an interior insulation will be given. The requirement for a space saving thermal insulation of an attic is frequently the case in practice. Figures 18 and 19 show the realisation of such insulation for a building that was constructed in 1929. The already-existing stone wool insulation in between rafters was supplemented by a layer of vacuum insulation panels with results in a final U-value of about 0.13 $\mathrm{Wm^{-2}K^{-1}}$. According to a given laying plan, roofing laths were mounted on the existing vapour barrier which covers the stone wool insulation and the rafters. The VIPs were placed between the roofing laths. The rims of each VIP were covered with a self-adhesive compression tape to avoid air gaps between adjacent VIPs.

The second example deals with the energy-related refurbishment of a school in the southern part of Germany (cf. Fig. 20). The school was constructed in 1972. After refurbishment in 2011, the energy required for heating could be reduced to a value of 13.3 $\mathrm{kWhm^{-2}}$ per year which is fifteen times lower than the average consumption of German schools (Kluttig et al. 2001). For the thermal insulation of the floor slap, vacuum insulation panels were used with the advantage that the floor height was only slightly higher than before. In total, 1,230 $\mathrm{m^2}$ VIPs of the type Vacupor RP-B2-S (thickness 30 mm, U-value 0.23 $\mathrm{Wm^{-2}K^{-1}}$), Porextherm-Dämmstoffe GmbH (Germany), were installed. The panels were covered with a building protective mat. Figure 21 shows the installation of the VIPs.

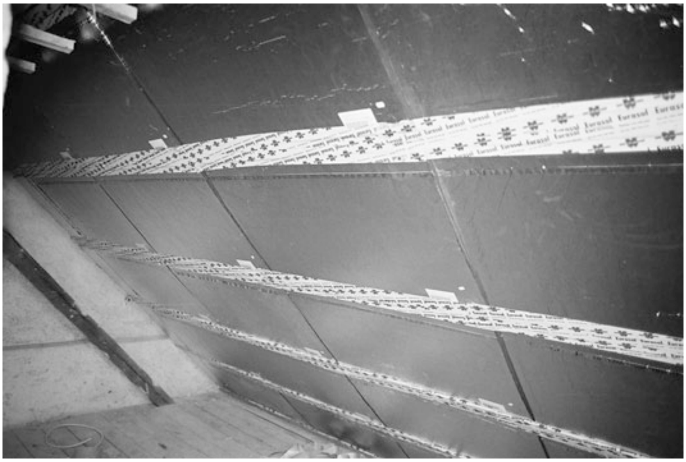


**Fig. 18** Attic with VIPs for thermal insulation. The horizontal discontinuities are covered with a self-adhesive sealing tape

**Fig. 19** Same attic as in Fig. 18. Also, the vertical discontinuities are sealed and a wooden framework is mounted for the installation of gypsum plaster boards

### 3.2.3 General Aspects Regarding Application

Vacuum insulation panels are a powerful thermal insulation system with specific features which have to be considered by planers, craftsmen and house owner. These peculiarities start with the planning process:

**Fig. 20** View of a refurbished school using VIP for the insulation of the base slap

**Fig. 21** Installation of the VIP at the floor at the *top* of a vapour barrier. The VIPs of the type Vacupor RP-B2-S were laminated with a building protective mat

The effective U-value of a VIP panel depends on the VIP type and size (cf. Fig. 9). Since the thermal resistance of VIP is high even for a small panel thickness, special care has to be taken to avoid thermal bridges in constructions.

The VIP itself acts as a vapour barrier. Therefore, the gaps between VIPs have to be tightened by vapour-barrier foils.

VIP layers within constructions have to be protected against damage, e.g. drilling, knocking in a nail.

Even if the VIP is damaged and the U-value is increased (approximately by a factor 3), it should be acceptable regarding aspects of building physics.

VIPs are not designed to be in constant exposure to water, UV radiation and high temperatures.

Because VIPs are evacuated systems, cutting of a VIP after production is not possible. Planers have to develop an installation diagram and parts list to know how many panels of which size are needed. The use of standard sizes helps to decrease costs by avoiding the production of VIP with special dimensions.

Logistic is also of important: site-specific packing of the VIPs, punctual delivery to avoid a long storage period at the construction site, installation only on clean and smooth surfaces.

Last but not least, it is important that the companies commissioned to carry out work related to the installation of VIP have sufficient experience with this technology and are aware about the special technical features.

## 4 Microporous Insulation Materials

### *4.1 Types and Thermal Properties*

Microporous insulation materials are porous materials with an effective average pore size below 1 μm. This fact results in the physical effect that the mean free path of gas molecules is reduced even at ambient atmospheric conditions and the effective thermal conductivity of the pore gas is below the thermal conductivity of still air, i.e. 0.026 $\mathrm{Wm^{-1}K^{-1}}$ (cf. Fig. 5).

Typical microporous materials used for thermal insulation in building applications are silica aerogels (Aegerter et al. 2011; Fricke 1988), pyrogenic silica, i.e. fumed silica and precipitated silica and mixtures and blends from those. Since the pure materials are fragile and brittle, often blends with fibres are used to enhance the mechanical stability in products. In general, the products are hydrophobic in order to avoid the absorption of water. Additionally, also infrared opacifiers are added to reduce the heat transfer by thermal radiation. A picture of silica aerogel as monolith and granulate is shown in Fig. 22. Monolithic silica aerogel is a material which shows one of the lowest thermal conductivity values of the world at ambient conditions, which could be in the range of 0.010 $\mathrm{Wm^{-1}K^{-1}}$. In comparison with this value, the effective total thermal conductivity increases for silica aerogel powder to about 0.013 $\mathrm{Wm^{-1}K^{-1}}$ and above 0.02 $\mathrm{Wm^{-1}K^{-1}}$ for silica aerogel granulate, because more and more large pores between the particles increase the contribution of the pore gas.

A relative small number of microporous insulation products for building application are commercially available since years. This number will certainly increase in future because a lot of research activities are currently under way. An obvious disadvantage of this group of thermal superinsulation is the high prize

**Fig. 22** Monolithic silica aerogel (on the *left side*) and silica aerogel granulate (*right side*)

which focus the field of application to such cases where the superior thermal insulation properties are needed to save space and to provide solution where classic insulation materials fail.

## *4.2 Applications*

### 4.2.1 Microporous Thermal Insulation for Thermal Separation

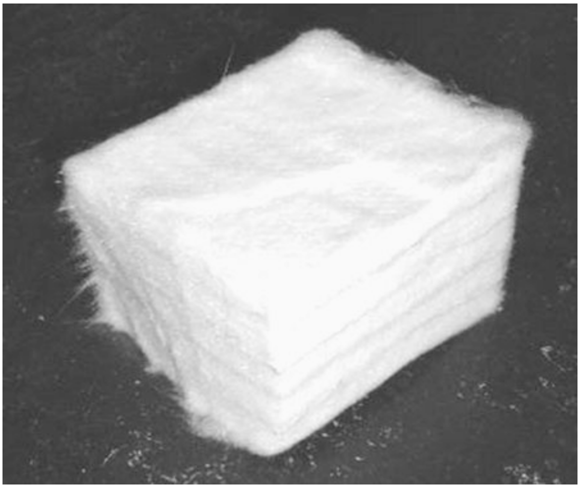
The Fraunhofer Institute for Solar Energy Systems ISE, Freiburg (Germany), conducted a research project for the energetic refurbishment of a multistorey residential building which was build in 1968 (cf. Fig. 23) (Schneider 2012). A main challenge was the thermal separation of the balcony construction. The existing construction with massive concrete ballast and cantilevering concrete slabs as balconies required a technical solution of the thermal bridges. As a substantial measure, the existing balconies were integrated within the thermal building shell and replaced by new thermally separated balconies which had also the advantage that additional living space could be provided. For thermal insulation at the thermal dividing line, a microporous insulation product based on silica aerogel was used. The hydrophobic product ‘Spaceloft 10 mm’ from aspen aerogels, USA (cf. Fig. 24), offers a remarkable low thermal conductivity value of 0.013 $\mathrm{Wm^{-1}K^{-1}}$ at 10 °C. However, the product is very dusty and the use of personal protection equipment (gloves, safety goggles and overalls) is recommended. The technical solution of the thermal separation is presented in Fig. 25. After refurbishment of the building, the heat demand could be reduced by 80 % to a value of 15 kWh $\mathrm{m^{-2}a^{-1}}$.

### 4.2.2 Microporous Thermal Insulation for Internal Insulation

In the autumn of 2011, a 150-year-old farmhouse in the southern part of Germany was refurbished (cf. Fig. 26). For the building owner, it was substantial that the

**Fig. 23** Multistorey residential building in Freiburg, Germany, before (*left picture*) and after (*right picture*) refurbishment

**Fig. 24** Silica aerogel-based superinsulation material 'Spaceloft 10 mm' from aspen aerogels, USA, used for the thermal separation of the balcony slabs from the façade construction



historical architecture could be preserved and in the same time to achieve a maximum of thermal efficiency. Therefore, it was decided to apply a pure mineral, open porous interior insulation of 8 cm thickness, which could be easily mounted on the 50-cm-thick brick walls. The insulation board consists of a microporous

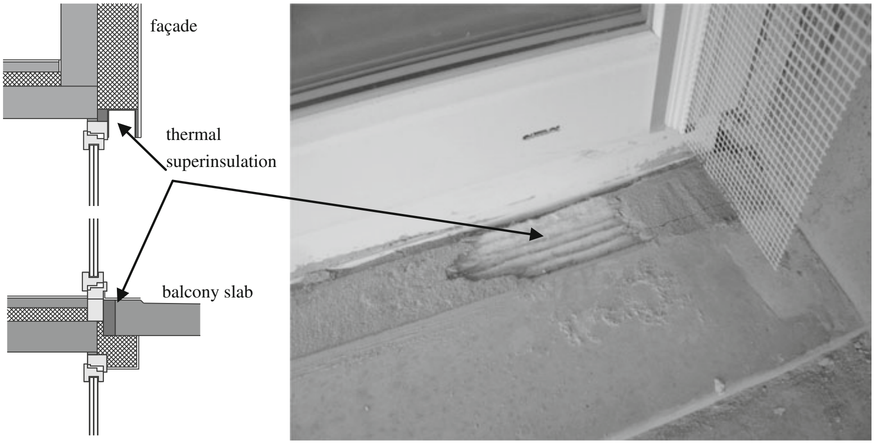


**Fig. 25** Construction details of the application of the 'Spaceloft 10 mm' insulation product

**Fig. 26** Prospect of the farm house which was refurbished by using an internal thermal insulation to keep the historical identity of the building

highly insulating hydrophobic kernel, i.e. CALOSTAT® from Evonik Industries, Germany, with a thermal conductivity of 0.019 $\mathrm{Wm^{-1}K^{-1}}$. This kernel is embedded in an open porous, capillary active calcium silicate structure. Finally, a highly efficient insulation system was installed, which provides a comfortable climate also in respect to room humidity (Figs. 27 and 28).

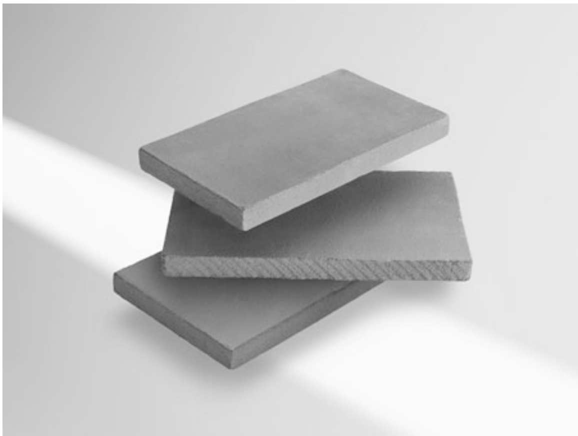


**Fig. 27** Hydrophobic microporous insulation material CALOSTAT® with a thermal conductivity of 0.019 $Wm^{-1}K^{-1}$

**Fig. 28** Installation of the interior thermal insulation with CALOSTAT® in combination with a calcium silicate insulation material (*left picture*). *Right picture* The calcium silicate board with microporous insulation kernel, i.e. CALOSTAT®, allows a time and cost-efficient installation and an individual adjustment at the construction site

# 5 Conclusions and Outlook

High-performance insulations being presented here offer new possibilities to improve the thermal performance of buildings. The given practice examples are convincing regarding the thermal performance achieved, the implementation of planning and architecture. It should be mentioned that the presented products for vacuum insulation panels and microporous insulation materials are examples of a variety of products and product combinations. In many cases, these products were used in prefabricated building components. Also, there exists of course a certain variety in respect to quality and physical properties of superinsulation materials. Actually, some specific trends in the development of thermal superinsulation could be observed: the efforts to synthesise microporous insulation foams, to combine the insulation properties of microporous insulation materials with other physical properties, e.g. enhancement of heat capacity, and of course to reduce manufacturing costs for superinsulations. Future progress in material science and chemistry will certainly help to achieve the ambitious goals and therefore make a substantial contribution for the establishment of a sustainable, well-insulated building stock.

## References

Aegerter MA, Leventis N, Koebel MM (eds) (2011) Aerogels handbook, Springer Science+Business Media, New York

Baetens R, Jelle BRP, Thue JV, Tenpierik MJ, Grynning S, Uvslã KKS, Gustavsen A (2010) Vacuum insulation panels for building applications: a review and beyond. Energ Build 42:147–172

Berge A, Johansson P (2012) Literature review of high performance thermal insulations. Report in building physics. Chalmers University of Technology, Gothenburg, Sweden

Binz A et al (2005) Vacuum insulation in the building sector—systems and applications. IEA/ECBCS Annex 39

Ebert HP (2011) Thermal properties of aerogels. In: Aegerter MA, Leventis N, Koebel M (eds) Aerogels Handbook 1st edn, Springer

Fourier JBJ (1822) Théorie Analytique de la Chaleur. F. Didot, Paris

Fricke J (1988) Aerogels. Sci Am 256:92–97

Fricke J (2005) From dewars to VIPs—one century of progress in vacuum insulation technology. 7th international vacuum insulation symposium. Zürich-Dübendorf

Fricke J, Heinemann U, Ebert H-P (2008) Vacuum insulation panels—from research to market. Vacuum 82:680–690

Heinemann U, Kastner R (2010) VIP PROVE Ergebnisse der wissenschaftlichen Begleitforschung Project Final Report. Bavarian center for applied energy research (ZAE Bayern)

IEA (2012) International symposium on superinsulating materials. Brussels, Belgium

Kaganer MG (1969) Thermal insulation in cryogenic engineering. IPST Press, Jerusalem, Israel

Kistler SS (1935) The relation between heat conductivity and structure in silica aerogel. J Phys Chem 39:79–86

Kluttig H, Dirscherl A, Erhorn H (2001) Energieverbräuche von Bildungsgebäuden in Deutschland. Gesundheits-Ingenieur 122:221–233

Kosny J, Fallahi A, Shukla N (2013) Cold climate building enclosure solutions. In: Program BT (ed), U.S. department of energy

Kwon J-S, Jang CH, Jung H, T-H S (2009) Effective thermal conductivity of various filling materials for vacuum insulation panels. Int J Heat and Mass Transfer 52:5525–5532

Lu X (1991) Transport properties of porous media. Physics department. Germany University, Würzburg

Mukhopadhyaya P, Kumaran MK, Normandin N, van Reenen D, Lackey JC (2008) High performance vacuum insulation panel: development of alternative core materials. J Cold Reg Eng 22:103–123

Scheuerpflug P, Morper HJ, Neubert G, Fricke J (1991) Low-temperature thermal transport in silica aerogels. J Phys D-Appl Phys 24:1395–1403

Schneider B (2012) On route to a low-energy urban district. FIZ Karlsruhe Germany

Schwab H, Heinemann U, Beck A, Ebert HP, Fricke J (2005a) Permeation of different gases through foils used as envelopes for vacuum insulation panels. J Therm Envelope Build Sci 28:293–317

Schwab H, Heinemann U, Beck A, Ebert HP, Fricke J (2005b) Prediction of service life for vacuum insulation panels with fumed silica kernel and foil cover. J Therm Envelope Build Sci 28:357–374

Schwab H et al (2005c) Predictions for the increase in pressure and water content of vacuum insulation panels (VIPs) integrated into building constructions using model calculations. Journal of Thermal Envelope and Building Science, 28, 327–344

Schwab H, Stark C, Wachtel J, Ebert HP, Fricke J (2005c) Thermal bridges in vacuum-insulated building facades. J Therm Envelope Build Sci 28:345–355

Schwab H (2004) Entwicklung und Anwendung von evakuierten höchsteffizienten Dämmungen für Gebäude (vakuumdämmung für Gebäude). Würzburg, Bayerisches Zentrum für Angewandte Energieforschung e.V. (ZAE Bayern)

Siegel R, Howell JR (1972) Thermal radiation heat transfer. McGraw-Hill Kogakushka, Ltd, Tokyo

Simmler H, Brunner S (2005) Vacuum insulation panels for building application: basic properties, aging mechanisms and service life. Energ Build 37:1122–1131

Stahl T, Brunner S, Zimmermann M, Ghazi wakili K (2012) Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications. Energ Build 44:114–117

Wen Y-G (2009) Development status of vacuum insulation panel technology in china. International vacuum insulation symposium 2009. London

# Thermal Energy Storage Technologies

**R. Parameshwaran and S. Kalaiselvam**

**Abstract** Energy, the lifeline of all activities is highly regarded to be conserved at every step of the growing engineering and the stupendous technological activities for ensuring the congruent economic development of a country. The gap present between the energy generation and the energy consumption keeps expanding with a precipitous increase in the demand for the energy, especially in the infrastructure and construction sectors. From this perspective, the incessant value-added engineering designs from the scheme inception to the construction are to be primarily necessitated, for enhancing the energy savings potential and energy efficiency in the new as well as in the refurbishment of building structures. Albeit there are several measures available to minimize the net energy consumption in buildings, there is still a need for an efficient system which can shift the thermal load demand during the on-peak to off-peak conditions, without losing energy conservative potential. In this context, the thermal energy storage (TES) systems are primarily intended for enhancing the performance of the cooling and heating systems in terms of storing and releasing heat energy on short-term or diurnal or seasonal basis, depending on the thermal load requirements experienced in buildings. The incorporation of renewable energy-based seasonal TES systems can collectively contribute for achieving enhanced energy performance on a long term, which would take forward the new and the existing building refurbishment designs towards the nearly zero-energy concepts.

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## 1 Introduction

Increased green house gas (GHG) emissions from fossil fuel combustion for power generation and emission of halogenated substances from vapour-compression-based refrigeration, air-conditioning and heat pump systems contribute significantly to the global warming potential, worldwide. The increased concerns over the energy security and GHG emissions among the world nations have paved way for bringing out useful and breakthrough research efforts towards achieving the energy conservation potential, in almost all the engineering systems. A possible way of reducing the GHG emissions can be achieved by using environment-friendly, energy-efficient systems and technologies.

In addition, the growing energy demands and environmental concerns worldwide have provided impetus to the development of many energy-saving measures during the last couple of decades, especially applied to the buildings sector. In recent years, the architects, engineers and consultants related to the building services engineering have shown great interest in planning, designing and developing energy-efficient buildings that are either newly constructed or being subjected to the refurbishment.

The inherent vision lying behind the state-of-the-art technological advancements taking place in the construction sector is to sustain the energy efficiency in both existing and newly developed buildings on a long-term basis. The existing building envelopes which may seem to be consuming more energy can be refurbished in such a way that the energy consuming elements of the buildings can be upgraded towards saving the energy, considerably. It is in the hands of the design engineers and architects, whose value-added efforts put forth in identifying and implementing the proper and suitable energy management technologies in buildings, particularly in the case of refurbishment, would result in a substantial savings in the energy being spent so far.

It is being made a mandatory requirement and task worldwide that the heating, ventilation and air-conditioning (HVAC) systems to be installed in the imminent building architectures must conform to the energy standards and have to be highly energy efficient. This means that, the future constructions will definitely result in the development of high-performance buildings. But, as far as the present energy demand and the energy security issues are concerned, the existing buildings or the building envelopes that are near to the refurbishment must also to be transformed as the high-performance buildings, globally.

In the spectrum of a variety of energy conservative techniques being tailored to make the building structures energy efficient, they still depend upon the primary energy sources for enabling them to effectively function during the thermal load demand occasions. In this context, a realistic question may arise in the sense that, is it possible for a system to make itself function with literally no input energy or a quantum of which is being supplied? This might replicate the case of a perpetual motion machine of first kind, but this condition can be achieved by the other way.

Factually, when the HVAC systems are engaged in providing comfort to occupants in indoor environments of a building through cyclic cooling and heating processes, the excess thermal energy that is available from these systems can be effectively stored during specific time periods of the design day operations.

Precisely, the cooling or the heating energy demand in buildings can be shifted from the on-peak to the part-load conditions; thereby the levelling of the load demand is achieved in a much efficient way. The storing of the useful energy in a particular operating period (part-load conditions) of the cooling/heating system and retrieving back the same amount of energy at a later time period (on-peak conditions) gives rise to the well-established concept of the thermal energy storage (TES).

Thermal energy can be stored as a change in internal energy of a material in the form of sensible heat, latent heat and thermochemical or combination of these. The TES systems can be sensible heat storage (SHS) or latent heat storage (LHS) or combination of both. In the SHS, the temperature of the storage material increases as the energy is stored, while the LHS makes use of the energy stored when a substance changes from one phase to another. Thermochemical energy storage also forms a part of the TES, wherein the heat energy can be stored and released by virtue of the reversible chemical reactions occurring between two or more reactive components or materials.

TES systems are more suitable for buildings requiring refurbishment, wherein they can act as an interface between different building elements or components for conserving the useful energy being spent on cooling/heating requirements. Thermal energy can be stored as part of the building structures as well as in a separate enclosure, which purely depends on the method of cooling/heating being provided in the existing building envelope. For instance, TES systems can be incorporated in the fabric elements such as bricks, concrete wall, ceiling and floor slab components, roof structures, glazing and so on.

The TES systems are basically classified into two broad segments, namely, the passive and the active TES systems. In the passive TES systems, the heat energy is stored and retrieved by the heat interactions between the heat storage elements of the building and the indoor air or the ambient air, without the aid of any mechanical equipment like fans, blowers, pumps, etc. On the other hand, the active TES systems utilize the mechanical assistance of equipments to transfer the heat and to store or release the thermal energy based on the fluctuating load demand in buildings.

The other forms of TES systems includes the diurnal, short-term and long-term storage, which basically depends upon the thermal load demand persisting in the building as well as on the type and availability of the energy source. The diurnal and short-term TES systems are preferred for sharing the energy requirements between the TES system and the cooling/heating system only for a short duration of time, the thermal load peaks would occur in the conditioned spaces.

On the other hand, the long-term storage systems makes use of the seasonal conditions for capturing and releasing the thermal energy, depending upon the heat load conditions existing in buildings. In short, the seasonal TES systems utilize the heat energy from the environment or from other renewable energy sources (e.g. solar energy) for storing during one season and retrieving it back during the other seasonal condition.

In addition, the energy redistribution requirements can be effectively met by using the TES systems integrated with the dedicated cooling and heating systems in the existing buildings. Energy efficiency in buildings is intensely coupled with high-performance-materials-based energy redistribution and energy conservation, which would glean in creating a pleasant and comfortable indoor environment to occupants. In particular, the assessment of reducing energy consumption using materials that are thermally efficient and stable on long-term stands vital in building cooling applications.

From this perspective, research interests towards developing the TES systems incorporating efficient phase change heat storage materials (PCM), which would offer energy redistribution requirements, are increasingly popular. Organic PCMs are highly pronounced in modern times because of their good thermophysical properties, operating temperature limits, high latent heat capacity, congruent phase transition, good heat storage capabilities, low supercooling, non-toxic effects, thermochemical stability and reliability on long-term usage.

However, the successful use of organic PCMs in veracity primarily depends on their thermal conductivity and heat transfer mechanisms exhibited in charging (freezing) and discharging (melting) cycles. Incorporation of thermally conductive materials into the pure (base) PCM would enhance the thermal conductivity, heat storage or release density, thermal stability and reliability of PCMs. However, the increased proportion of additives at macrosize may at times descend the heat storage density of composite PCMs which in turn would produce nonlinear heat storage characteristics during phase transformation.

As a step forward to the above achievements, research efforts have been equally put forth to enhance the operational performance of organic PCMs using nanomaterials. The relatively high surface-to-volume ratio of nanomaterials enables them to effectively promote nucleation and heat transfer in PCM. The proper selection and preparation of nanomaterials paves way for attaining enhanced thermal conductivity, latent heat capacity and heat transfer performance of PCMs. Nanomaterials prepared in different structures including nanotubes, nanorods, nanoparticles, etc., would exhibit distinct thermophysical aspects when dispersed in pure PCM.

The nucleus of this chapter is devised in a way to provide an outlook of a variety of the TES systems and with an objective of giving good understanding on the integration of the TES systems with the existing building architectures, for achieving enhanced energy savings potential and energy efficiency on a long-term basis. A brief discussion on the operational strategy and the design aspects of the TES systems with the relevant information are summarized and presented.

## 2 Classification of TES Technologies

Thermal energy can be stored as a change in internal energy of a material in the form of sensible heat, latent heat and thermochemical or combination of these. In the SHS, the temperature of the storage material increases as the energy is stored, while the latent thermal energy storage (LTES) makes use of the energy stored when a substance changes from one phase to another. On the other hand, energy being stored by virtue of the process reactions between the chemical constituents is referred under the thermochemical energy storage.

## 2.1 Sensible Thermal Energy Storage

As the name signifies, thermal energy is stored in the material through sensible heat supply, which in turn would raise the temperature of the material considerably. In this kind, the thermal energy stored by the material is directly quantified to its mass ($m_s$), specific heat capacity ($c_{ps}$) and the temperature gradient ($\Delta T$) of the material which is given by

$$Q_s = m_s c_{ps} \Delta T \tag{1}$$

or,

$$Q_s = m_s c_{ps} (T_h - T_i) \tag{2}$$

where $T_h$—maximum temperature attained by the material in (K) and $T_i$—initial temperature of the material in (K). It can be observed that the energy storage capacity of such materials largely depends on their density and specific heat. The relatively low thermal capacities of these materials are usually compensated by their large temperature gradient experienced during heat storage or release processes.

For high-temperature applications, SHS materials can be a good choice for the aforementioned reasons. Thermal energy can be stored or released upon demand by exchanging the heat energy by virtue of the temperature difference being experienced within these materials.

## 2.2 Latent Thermal Energy Storage

In recent years, the usage of LTES systems has received increased interest. LTES systems have been recognized as one of the effective measures for reducing the energy consumption, especially applied to the HVAC systems in buildings. As stated earlier, LTES system utilizes a heat storage material which is capable of storing and releasing the thermal energy by changing its phase either from solid to liquid or vice versa, at isothermal conditions. For instance, during freezing process, the material would undergo a phase change process by absorbing the energy from the heat source at constant temperature.

Likewise, in a melting process, the thermal energy stored would be released by the material to the surrounding heat transfer medium with phase change process taking place within the material at constant temperature. Precisely, the usage of terminologies pertaining to freezing and melting varies with the literatures, but in this chapter, the convention followed for the freezing and melting is being referenced to the process by which transfer of heat energy takes place between the heat storage material and the heat transfer medium. Besides, the terms like charging or solidification and discharging would also mean the same as that of freezing and melting processes, respectively.

In reality, the LTES systems offer a huge potential to store thermal energy, when compared to the SHS systems for building cooling and heating applications. This is due to the fact that, the heat storage material in an LTES system possess good thermophysical characteristics in terms of freezing and melting, which provides more flexibility to store or release the thermal energy on demand.

Moreover, the volumetric capacity and handling of heat storage materials in LTES systems would also benefit for its preference in modern building HVAC applications. Both the sensible and latent thermal storage systems are capable of offsetting the thermal load demand and can satisfy the energy redistribution requirements in buildings. The forthcoming sections are dedicated to the SHS and LTES systems, which would clearly highlight their effective contribution towards meeting nearly zero energy in buildings that are being newly constructed or refurbished.

## *2.3 Thermochemical Energy Storage*

In the spectrum of TES technologies, the concept of utilizing the chemical potential of certain materials for storing and releasing the heat energy on a long-term basis has been gaining momentum in recent years. Basically, the thermal energy can be stored or released by virtue of the reversible chemical reactions occurring between the reactive components (or chemical compounds or materials) with negligible thermal loss.

The endothermic reactions of the chemical compounds can be initiated by supplying the thermal energy that is being captured from any heat source (solar energy). For instance, the heat energy that is required to be stored and released over time using two chemically reactive components can be defined by

$$C_1C_2 + \text{Heat input} \Leftrightarrow C_1 + C_2 \tag{3}$$

Herein, the pair of chemical components ($C_1$, $C_2$) has got dissociated into individual components with the supply of heat, which can be stored separately. On the other hand, if they are combined together, the same paired components are produced with the release of heat energy (exothermic reaction). The International Energy Agency (IEA) during the Task 32 SHC programme proposed a prototype system working on the principle of thermochemical reaction for storing heat energy using the hydrates of magnesium sulphate.

The desorption–adsorption reaction of hydrates of magnesium sulphate which is capable of storing 2.8 GJ/m3 of energy was identified during the aforementioned Task 32 of IEA. The associated reaction is as follows:

$$MgSO_4 \cdot 7H_2O(s) + \text{heat input} \Leftrightarrow MgSO_4(s) + 7H_2O(g) \tag{4}$$

The term ‘sorption’ usually refers to the phenomenon of capturing of a vapour or a gas by a substance that is available in the condensed state (either in solid or liquid state). The former is known as ‘sorbate’, and the latter is called as ‘sorbent’. The phenomenon of sorption generally comprises of both thermochemical and thermophysical criteria, which also includes the aspects related to the absorption and adsorption processes. The absorption in terms of TES literally means the process of absorption of a gas into the liquid medium (or the absorbent). Likewise, adsorption refers to the binding of a gas or vapour on the surface of the solid or porous material.

The aspects of adsorption are more related to the surface phenomenon of one or more materials undergoing reactions either through the physical (physisorption) or chemical (chemisorption) routes. The physisorption is more pronounced, when the reaction occurs due to the effects of Van der Waals forces, but the chemisorption is realized by virtue of the valence forces. The heat of sorption is usually high for the chemisorptions when compared to the physisorption, but the reaction may be sometimes irreversible for the former case.

Sorption processes for acquiring TES can be further divided into the open-loop and closed-loop systems. In the open-loop systems, the working fluid vapour (water vapour) is usually exhausted to the open atmosphere, whereas in the closed-loop systems, the working fluid is separated out from the neighbourhood subsystems. The circulating working fluid capable of catering higher heat storages would characterize the operating efficiencies of the closed-loop systems.

The energy density of various storage methods (N’Tsoukpoe et al. 2009), the volume reduction in the storage containment using various TES technologies (Pinel et al. 2011), classification of the chemical storage (Pinel et al. 2011) and the combination of working materials of thermochemical energy storage (Gores et al. 2012) are depicted in Fig. 1 a–d.

## 3 Incorporation of TES in Buildings

The increasing energy demand and security of energy supply worldwide has indubitable necessities for conserving energy at every step of economic development of a nation. The buildings are identified to be one of the major sectors, which would account for 30–40 % of primary energy consumption. The construction of value-added building structures would in one way help to elevate the economy and societal status of a country, but on the other hand, they would have a higher proportion of energy consumption being derived from primary energy sources.

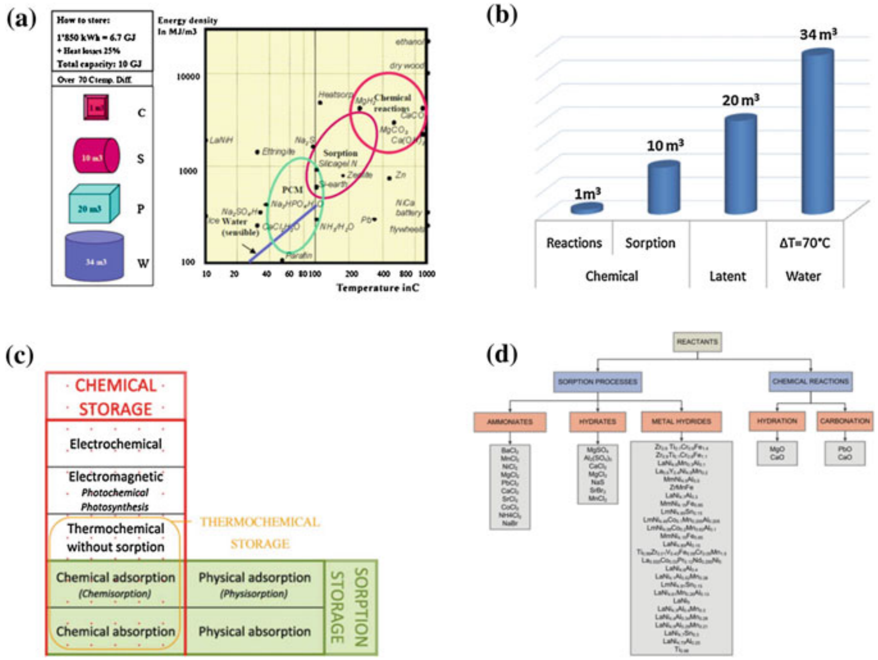


**Fig. 1** **a** Energy density of high-energy storage methods, **b** volume required to store 6.7 MJ, **c** chemical storage and sorption storage classification and **d** overview of working pairs tested in prototypes under practical conditions

From this perspective, the implementation of energy-efficient TES systems would possibly contribute to achieving energy savings potential and energy efficiency in buildings. The broad categorization of TES technologies incorporated in buildings is presented in Fig. 2. The following section describes the operational strategies of a variety of TES systems dedicated to provide cooling and heating energy redistribution and energy conservation potential in buildings.

## *3.1 Thermal Energy Storage Using Building Fabrics*

The fabric materials including bricks, concrete or a combination of these can be utilized to store and release the heat energy upon thermal load demand in buildings. The building fabric materials used to construct wall, floor, ceiling and roof structures are good enough to capture the thermal energy in the form of heat or cold during off-peak hours and release the stored energy back to the conditioned space in on-peak load conditions. The energy stored by the building fabric materials may be classified into passive and active systems depending upon the operational strategies involved in these systems.

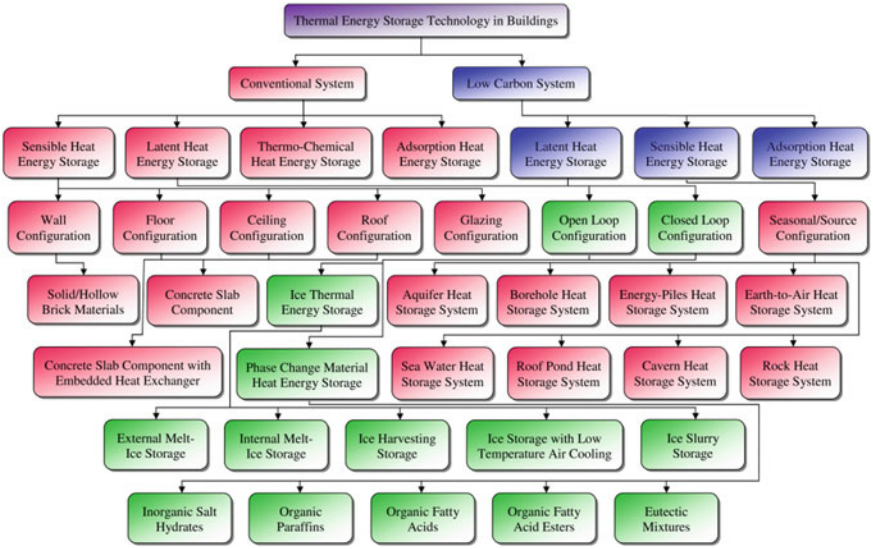


**Fig. 2** Broad classification of thermal energy storage technologies incorporated in buildings

In a passive system, the thermal energy is stored by virtue of temperature gradient between the fabric material and indoor space through the density difference in indoor air being aided by the natural convection process. On the other hand, active systems utilize mechanically assisted fan or blower units for distributing air over the building fabric materials in order to store or release the thermal energy. Some active systems are equipped with heat exchange coil elements being embedded inside the building fabric structures, wherein cold or hot water supplied through the coil elements effectively transfers the required heat energy to fabric materials. In short, the rate of heat transfer primarily depends upon the mass of the fabric material, specific heat capacity of fabric and heat transfer fluid (air or water), temperature gradient between the fabric structure and indoor air, volume flow rate of cool or warm water in heat exchange elements, thermal conductivity of fabric material and heat transfer fluid, thickness of fabrics, infiltration (moisture effects) through the building structure and so on.

### 3.1.1 Storage with Ceiling Slab Component

The most attractive and easy way of storing thermal energy in buildings is achieved using this technology. This storage system finds itself in place between conventional natural ventilation and mechanical ventilation systems. Typically, in the cooling mode, during night-time (or part-load conditions), by passing the cold air from the occupied zones over the surface of the ceiling slab, the desired cool thermal energy is trapped off and stored in the slab component.

During the daytime (i.e. when on-peak load conditions prevail in building), by circulating the warm air over the ceiling slab, the stored cold energy is dissipated to the indoor spaces to meet out the cooling and thermal comfort requirements. Factually, the temperature swings achieved inside conditioned zones using this storage system is estimated to be 2–4 °C.

The amalgamation of ceiling slab storage system with mechanically assisted fan unit can still improve the overall heat transfer performance of the combined system, especially when the heat exchange mechanism between the slab component and supply air is appreciable. With the condition of outdoor air being at a lower temperature than the indoor design set temperature, the cooling capacity of storage component can be increased significantly (both under passive and active modes of operation).

The free energy storage that is possible during night-time using the fresh air (outdoor/ventilation air) can enhance the storage capability of slab component on an average by 5–10 %. The ceiling slab can be made to expose directly to the indoor spaces or covered with a suspended ceiling arrangement. The suspended ceiling decouples the stratification effects of indoor air with the ceiling component to some extent, thereby providing good thermal comfort to occupants with enhanced energy efficiency.

Furthermore, the installation of longer ductwork air distribution systems are less pronounced, which further enhances the energy savings potential of this type of storage system. The floor slab storage system is much similar to the ceiling slab configuration, but the fabric slab material is arranged in conjunction with the floor component of the building. The operational strategy of this system is the same as that of ceiling slab system.

The main advantage of floor slab storage arrangement is that the cold air after transferring its energy to the slab is supplied from the floor level into the conditioned space. The vertical movement of air from the floor surface to the ceiling space can add value in effectively offsetting the heat load demand as well as maintain the temperature stratification in indoor environment much better than the ceiling slab configuration.

In intermediate seasonal conditions, both the storage systems are capable enough to capture any excess heat energy produced from the conditioned zones during daytime, thereby facilitating to compensate the additional heat losses in buildings that occur in night-time.

### 3.1.2 Storage with Hollow-Core Ceiling Slab Component

The next level of storing thermal energy using the fabric component is achieved through the implementation of hollow-core slab arrangement in buildings. The fabric structure made up of construction materials contains a series of hollow cores (or voids), wherein the low-temperature air flows across the slab structure through these cores. The pitch between the cores is maintained in such a way that the effective heat transfer taking place between the air and the structure is maximum throughout its operation.

In the cooling mode, during night-time, the low-temperature air is allowed to flow through the cores, which in turn releases its cold energy to the slab component. As the ceiling slab is exposed to the indoor space, during day-load conditions, the indoor air in contact with the surface of the slab cools down to the designed set temperature and meets out the required cooling load demand.

Storing of heating energy is also possible with this arrangement, wherein hot air in place of low-temperature air is allowed to flow through the hollow-core module. The overcooling or overheating of conditioned zones imposes for having control logic-like monitoring strategies for ensuring the effective functioning of such system on a long run.

### 3.1.3 Storage with Embedded Coil Elements

The fabric structures embedded with heat exchange coil inserts play a vital role in achieving good TES capabilities in buildings. The heat transfer fluid flowing through the heat exchange coil element serves as both cold and hot sources of energy. In the part-load conditions (cooling mode), the chilled water from cooling plant is diverted to flow across the serpentine-like coil structures being embedded with the building structure.

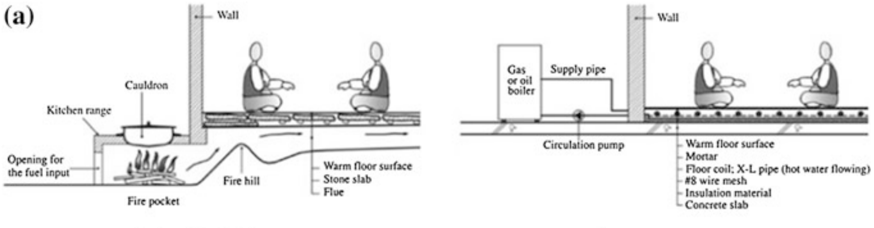
By this, the cool thermal energy being stored in the fabric structure during off-peak load conditions are retrieved back by the supply air flowing over the building structure during on-peak load conditions. Likewise, in the heating mode, hot water supply through the coil element facilitates to store heat energy in the building structure, which is then is utilized for providing heating in occupied zones during daytime operation in winter seasonal conditions.

The mass flow rate, specific heat capacity, temperature difference and viscosity of the heat transfer fluid are the influencing parameters that would determine the overall heat transfer performance of such system, in addition to their inherent frictional pressure losses.

### 3.1.4 Storage with Underfloor Slab Component

Thermal energy in the form of heat or cold can be stored and redistributed using the underfloor slab component in buildings. The heat transfer fluid (hot water or chilled water) pipe elements embedded into the fabric structure underneath the floor of the room serves as the heat transport source for charging the building fabric component. Typically, the cooling capacity that can be experienced using this system is accounted to be in the range of 25–35 W/m$^2$ (Seaman et al. 2000).

Since, the mode of heat transfer is largely by radiation means, the net heat output delivered by this system is appreciable. The indoor air which comes into contact with the floor surface traps off the heat or cold energy and dissipates them



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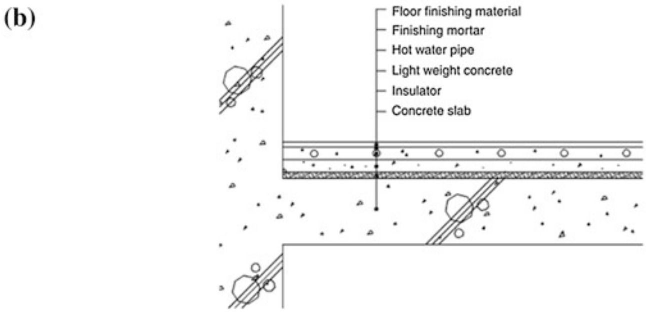


**Fig. 3** **a** The radiant floor heating system and **b** standard floor formation for the Korean Ministry of Land (Jeon et al. 2013)

through natural convection effects. The schematic representation of the radiant floor heating system and the standard floor formation (Jeon et al. 2013) are shown in Fig. 3 a–b.

It should be noted that for the buildings that are located in moderate to cold regions and equipped with this system, the floor surface temperature has to be maintained above 15–17 °C, which will prevent from any condensation of room air onto the floor surface. On the other hand, the same system can be tuned for providing heat energy storage to the building floor structure during winter seasons. By supplying the hot water (either derived from waste heat source or water heating) through the embedded underfloor pipe lines, the slab structure is heated, and the energy is then stored sensibly.

The rate of energy stored in the slab component depends mainly on the thermal conductivity, diffusivity, specific heat capacity and thickness of the ingredient building materials. The merits of the underfloor slab storage system include the effective redistribution of thermal energy into conditioned spaces, increased heat transfer rate between floor surface and indoor air through radiation, reduced condensation risks and lower operating costs. Providing proper control mechanism would help to adjust the set-point temperature fluctuations as well as the flow rate of heat transfer fluid throughout the operation of the storage system in buildings.

### 3.1.5 Sensible Heat Storage Using Electric Heating

The electric heating of building fabric component (mainly hollow-core bricks) during off-peak hours with good electricity tariff plan is a feasible method to store the thermal energy significantly. The hollow-core bricks made up of either magnetite or magnesite material suitably encased by a metal container when subjected to electrical resistance heating would capture and store the desired heat energy during part-load conditions. The stored heat energy is then dissipated to the individual or centralized zones during on-peak load conditions in building using passive or active air movement across the brick components.

Typically, the room air circulating over the heated bricks during daytime picks up and transmits the heat energy to the indoor spaces. For passive system operation, the room air by natural convection transfers the required heat energy into the room, whereas active systems utilize air circulation by fan or blower to meet out the heating load demand.

The temperature of brick components can be increased up to 760 °C during part-load conditions. Besides, the outer surface of the brick heater can still remain at temperatures below 80 °C. The TES capacity of the brick components can vary from 49 to 216 MJ (ASHRAE Handbook 2012). The charging (heat storage) period of these bricks approximately varies between 6 and 7 h, and the rate of discharging (heat release) into indoor spaces can vary on an average from 4 to 5 h.

Also, the thermal energy discharging efficiency of bricks depends on the room size, space heating load demand during the entire day’s operation and the heat loss effects in addition to climatic variations. Brick heaters can also cater the intermediate or fluctuating heating load conditions that might occur in buildings with variation in the outdoor air temperature. The heat energy that is transferred by the electrically heated hollow-core bricks to the room air can possibly supplement the heating load demand without losing the thermal comfort to occupants in indoor environment.

The heat storage capacities for residential equipment and large commercial/industrial systems vary from 310 to 864 MJ and 3,460 MJ, respectively. Likewise, the electric power input to the above systems varies from 14 to 46 kW and 53 to 160 kW, respectively. On the other hand, the radiant hydronic heating storage system utilizes a separate air-to-water heat exchanger, wherein the heat energy stored in the brick components is transferred to the heat transfer fluid through the heat exchanger module.

This module can be integrated to an air-handling system or room-heating systems (underfloor or ceiling unit) for effectively discharging the thermal energy into the conditioned space. The electric power input to radiant hydronic heating system varies from 20 to 46 kW, and their heat storage capacity range from 430 to 865 MJ.

## *3.2 Passive Solar Heating Storage*

The passive heating using the solar energy is a type of thermal storage technique highly suitable for buildings that are being newly constructed or refurbished. The term passive implies enabling the heating storage without the use of additional mechanical equipments such as circulation pumps, fans or blower units. The buildings intended for passive solar heat storage must be designed in such a way to take full advantage of the solar radiation.

Albeit the building fabric components as discussed in earlier sections are capable of absorbing and releasing the thermal energy to indoor environment, the alternative component, that is, the glazed envelopes are considered most essential and useful components to trap more solar radiation in buildings.

The solar glasses serve dual purposes by providing good aesthetics to the building and capturing solar radiation that is required for heating the occupied zones upon demand. The buildings that are oriented towards south to about 30° are generally considered energy efficient in this regard, which would absorb more sunlight during daytime hours. The glazed structures on such buildings allows solar radiation to infiltrate through them to enter the occupied spaces, but simultaneously prevents the infrared radiations from getting transmitted back to the ambient, thereby creating heat spaces in indoor environments.

Generically, if the ratio of glazing to floor area is designed to be 7–10 %, it can serve to achieve better heating storage in buildings as well as to reduce any risks due to overheating of thermal zones in buildings. Passive solar heating storage systems are economical and include more sustainable aspects, which when incorporated in modern buildings can enhance their energy efficiency by 30–35 %.

## *3.3 Active Solar Heating Storage*

The active solar heating storage on the other hand utilizes a dedicated solar collector, storage tank, heat exchanger, associated mechanical pumps and control interfaces. In principle, the solar radiation being trapped by the solar collector gets converted to heat energy. This heat energy is first transferred to the heat transfer fluid flowing across the solar collector by means of efficient absorber materials of the solar collector. The absorbed heat energy is then transferred to the storage tank by the warm heat transfer fluid and the cooled fluid then travels back to the collector, and the process is repeated for several thermal cycles until the heat storage requirements are met.

The heat stored in the tank is then retrieved by the secondary heat transfer fluid and is supplied to the heat exchanger (radiator or air-handling unit) installed in rooms or zones depending upon the thermal load demand persisting in building. Solar radiation absorbed by the flat plate and evacuated tube collectors potentially converts the light radiation to heat energy and helps to increase the temperature of the heat transfer fluid in the range of 60–80 °C. However, the overall heat transfer of solar heat storage depends primarily on the net surface area of collector.

In addition, due to the inherent thermal stresses, related convective and radiation heat-loss effects, the solar radiation absorbed by the flat plate and evacuated collectors can be converted to useful heat energy to only some extent, which might not be sufficient to cater the heat duty in buildings during off-sunshine periods. Solar heat storage can be made effective in buildings by incorporating concentrated solar collector module using parabolic or conical reflectors that would enhance the total heat transfer process between the collector and the storage tank.

By pointing out the collected heat source on the receiver tubes, the temperature of heat transfer fluid is expected to elevate up by 130–140 °C. For improved performance of the solar heating storage system, the solar collector has to be aligned towards 30° due South face with appropriate latitude correction of the building. Installation of concentrated solar collector might have cost-related issues, but they are much efficient than the flat plate and evacuated tube collectors.

The thermal storage systems designed to cater both space heating and hot water supply in buildings can be effectively tuned for its maximum performance, if they are coupled with high-operating-temperature parabolic or conical type solar reflectors or collectors. In order to satisfy the heating load demand in buildings on year-round basis, the concentrated solar collectors with the thermal efficiency greater than 60 % is most viable when compared to the flat plate and evacuated tube receivers with the thermal efficiency of 40–50 %.

## 4 Seasonal (Source) Thermal Energy Storage Technologies

The seasonal or source TES offers a promising way of storing cold or heat energy that is chiefly available from the energy sources including aquifers, earth, geothermal, lakes, ponds, caverns, sea water, rock structures, waste heat, cogeneration, etc.

The intention behind the development of seasonal TES technologies in buildings is primarily to redistribute or shift the cooling/heating demand from on-peak load conditions to off-peak conditions, reduce the peak electricity demand issues, reduce GHG emissions and achieve economic feasibility in large installations including district cooling and heating systems. For brevity, only some of the aforementioned source-based TES technologies are explained in the forthcoming sections.

### *4.1 Aquifer Thermal Energy Storage*

The aquifer thermal energy storage (ATES) system basically works on the principle of extracting the enthalpy of thermal energy from the low-temperature groundwater to cater the cooling or heating load demand in buildings. The schematic representation of the ATES system is shown in Fig. 4. The ATES system essentially consists of aquifer well, heat exchangers, pumps and other necessary installation accessories.

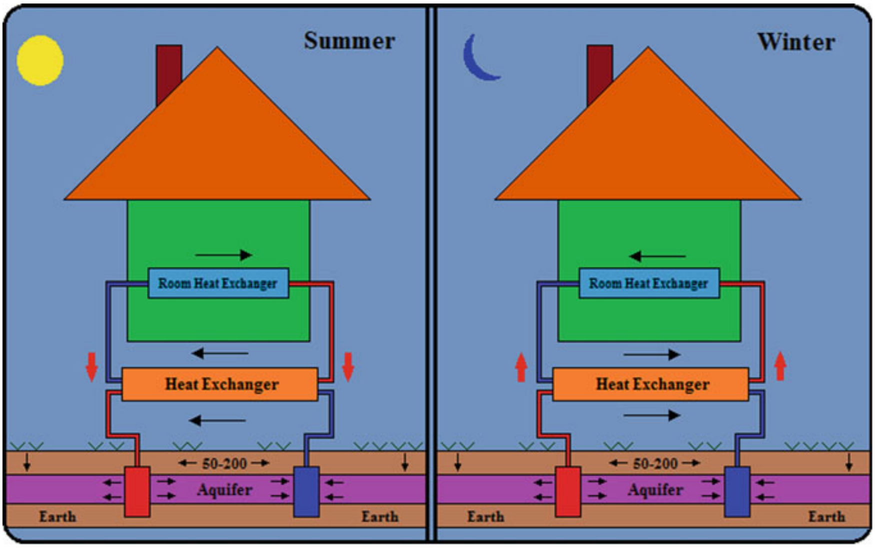


**Fig. 4** Schematic representation of the ATES system

During summer cooling mode, the ATES system retrieves the cold energy contained by the underground water (that is available around 8–10 °C) through the extraction well. The cold energy is then transferred to the heat exchanger unit coupled with the building thermal zone. The warm return water from the heat exchanger is then routed back into the underground water layers through the injection well.

There are essentially three types of ATES systems capable of storing heat or cold depending on the thermal load demand in buildings. They are single (mono)-source, double-source (doublet) and recirculation (year-round) ATES systems. Depending upon the constructional aspects related to extraction well, injection well, heat exchange mechanism, flow direction of heat transfer fluid, etc., these systems are preferred for the medium- to large-scale TES applications in buildings.

It is noteworthy that the ATES systems can achieve thermal storage capacity up to 15 kWh/m$^3$ (Lemmens et al. 2007). The coefficient of performance (COP) (the ratio of net cooling or heating effect to the electrical power input) of the ATES systems varies between 15 and 35, if the processes occur by natural cooling. At the same time, ATES systems if combined with a conventional chiller plant, the COP can be expected to achieve around 3.5–4.0 for a temperature gradient of 6–7 °C between the supply and return chilled water mains.

Similarly, the ATES integrated with a heat pump system is able to accomplish the COP ranging from 4.5 to 6.5 during heating process. ATES system also offers low operational and maintenance costs on a long-term basis and has a life expectancy of around 20–25 years.

In short, the ATES systems are more energy efficient in the sense that, on an average, they can reduce the primary energy and natural gas consumption by 50–60 % when compared to the conventional systems. There are some limitations observed in practice with the operation of the ATES systems, which includes destabilization of water quality in the underground levels, heat exchanger frictional pressure losses, scaling of extraction and injection wells, growth of algae, parasitic or bacterial agents in the heat exchanger surfaces, water table disturbances, etc. However, these limitations can be well resolved by implementing the value-added design principles for the energy-efficient commissioning of the ATES systems.

## *4.2 Borehole Thermal Energy Storage*

The another type of seasonal storage system being into practice is referred to as the borehole thermal energy storage (BTES) systems, which are basically similar to the ATES systems in operational characteristics, but are different from the ATES systems by their design configuration and installation. The schematic representation of the BTES system is depicted in Fig. 5. The BTES system utilizes the low-temperature source from the underground for effectively catering the cooling and heating requirements in buildings. The BTES systems essentially consists of high-density polyethylene pipe structures being embedded into a series of boreholes drilled underground, heat exchangers or heat pumps, heat transfer fluid and other necessary accessories.

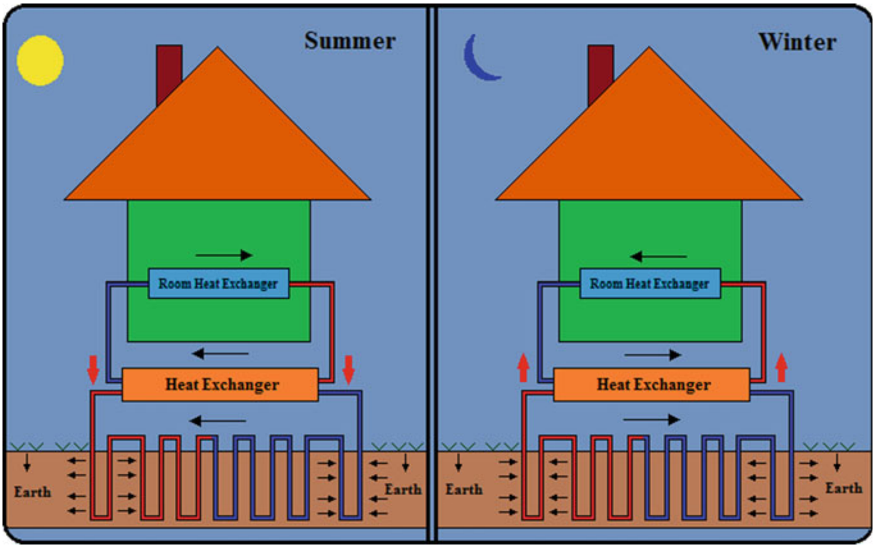


**Fig. 5** Schematic representation of the BTES system

The borehole structures are integrated to the building through the heat exchanger hydronic networks, which can be either an open-loop or a closed-loop configuration. In the open-loop configuration, the cold or heat energy being extracted from the underground through the heat transfer fluid (mostly underground water) is transferred to the indoor heat exchanger. The warm or cold water from the heat exchanger is routed back to the underground through the same borehole structure.

The water that is used for energy extraction is discharged into the underground and is not reused again for the next cycle of system operation. On the other hand, the closed-loop system utilize the brine solution (glycol or antifreeze) as heat transfer medium for extracting the heat energy from the underground, by which the overall thermal performance and heat exchange efficiency of the BTES system can be enhanced.

The heat transfer fluid remains always inside the system and can be reused for several thousand repeated thermal cycles. The BTES system with more borehole structures has a higher TES performance and heat transfer output.

The closed-loop BTES systems can be further classified into horizontal, vertical and slinky loop systems. These systems still offers a much better heat storage performance when compared to the ATES systems. For high-temperature thermal storage, the heat energy captured by efficient solar collectors can be stored in the ground during sun brilliance conditions (especially hot summer days).

During winter seasons, the stored heat energy can be retrieved back from the ground and supplied to the indoor environment, which offsets the net heating demand and heating losses in buildings. Thus, the BTES systems, like the ATES systems, are much favourable enough to store and release the thermal energy, based on the load requirements in buildings on a seasonal manner.

However, the initial capital costs involved in drilling boreholes of considerable depth, the thermal disturbances in hydrogeological structures and heat imbalances taking place in the underground thermal masses can collectively accentuate their consideration to the low- and medium-temperature-profile building cooling and heating applications.

### *4.3 Earth-to-Air Thermal Energy Storage*

The earth-to-air type of thermal storage system is relatively preferred for small residential and commercial buildings, where the temperature of earth is stable at specific depth from the surface of the ground. The earth-to-air energy storage system comprises of an array of plastic pipes or a single lengthy pipe, room air-handling unit or heat exchanger with necessary accessories. The functioning of this system takes place by energizing (charging) the earth soil material by the buried tubes at a depth of 3–4 m beneath the ground level.

During summer season, the outdoor cold air either at night-time or early morning period is directly fed into the room for accomplishing free cooling. In daytime, the outdoor air temperature, if sensed to be greater than the room air temperature, the indoor air is routed through the pipe structures embedded in the earth.

The cold energy contained by the earth is then trapped off by the air circulating through the pipe, and the cooling load demand in building can be effectively catered. The option of diverting the indoor air through the earth pipes depends on the outdoor air temperature variations experienced during seasonal conditions.

### *4.4 Energy Piles Thermal Energy Storage*

In recent years, the concept of introducing helical coil or spiral pipes into the building concrete pile structures is gaining momentum, because of its energy storage aspects related to the cooling and heating requirements in buildings. The schematic diagram of the energy piles TES system is shown in Fig. 6.

The coil elements are connected to the heat pump systems installed in the building, which transfers the heat or cold energy to the pile structure (beneath the ground surface). The design cooling or heating load demand in buildings is catered at ease with this system on a year-round basis.

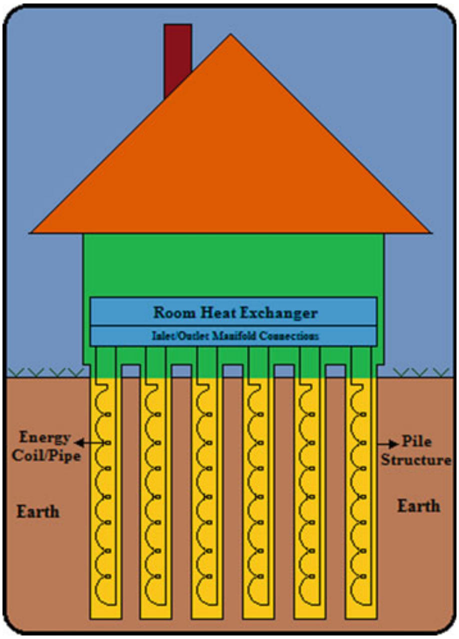


**Fig. 6** Schematic representation of the energy piles TES system

## 4.5 Sea Water Thermal Energy Storage

The sea water can act as an essential source for distributing the cooling energy to a large-district cooling facility, wherein the low-temperature sea water is fed to a series of chiller systems for producing the required cooling effect in buildings. The chiller or the heat exchanger cools down the temperature of sea water to around 5–6 °C, which is then pumped to the air-handling units to serve the cooling demand in buildings. The warm return sea water coming from the building side at a temperature of 12–15 °C is then pumped back to the chiller plant, and the process is repeated.

The volume flow rate of the sea water is maintained in such a way that the desired quantity of sea water only would be supplied to the district cooling plant, and the excess would be returned to the seabed. The issues of corrosion, salt deposition and other scale formation are of main concern in utilizing this system, but by providing proper corrosion-proof coatings, these challenges can be effectively confronted. The cooling capacity of the district cooling plant can be achieved in the order of 30–50 MW using the sea water cool thermal storage system.

## 4.6 Cavern Thermal Energy Storage

The cavern thermal storage is an attractive way of meeting the cooling/heating load requirements in the small- to medium-scale building construction. The schematic representation of the cavern TES system is illustrated in Fig. 7. Basically, this system performs the storage and distribution of heat energy using the underground water reservoirs on large landscape. There are two types of cavern energy storage systems, namely the hot water storage and gravel water storage.

In the hot water storage, huge volumes of water are filled inside the insulated cavity or the pit-like structure (tank) built underground, which in turn facilitate to take advantage of the underground heat energy, i.e. cool and heat energy in

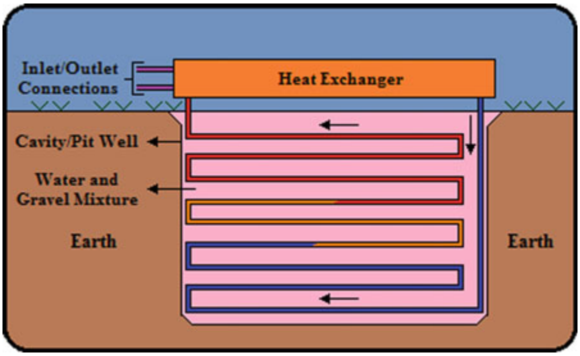


**Fig. 7** Schematic representation of the cavern TES system

**Table 1** Thermal properties of various earth materials (Yumrutaş and Ünsal 2012)

| Earth type | Thermal conductivity (W/mK) | Thermal diffusivity ($m^2/s$) | Specific heat (J/kg K) | Heat capacity ($kJ/m^3$ K) |
|---|---|---|---|---|
| Coarse gravelled | 0.519 | $1.39 \times 10^{-7}$ | 1,842 | 3,772 |
| Limestone | 1.3 | $5.75 \times 10^{-7}$ | 900 | 2,250 |
| Granite | 3.0 | $14.00 \times 10^{-7}$ | 820 | 2,164.8 |

summer and winter seasons, respectively. By integrating the water tank with the tubular heat exchanger in the building, the stored energy can be retrieved and redistributed to the zones requiring cooling or heating.

On the other hand, the gravel water storage makes use of the capillary and thermal conductivity aspects of rocks or pebbles for achieving the desired thermal storage in buildings. In general, cavern TES systems are comparatively expensive than the other type of seasonal storage systems, which is due to their site selection, constructional and operational aspects on long-term basis.

However, the facility installed in Chemnitz, DE, has an expected solar heat cost of 240 €/MWH for 8,000 $m^3$ of energy storage capacity (Schmidt et al. 2004). The thermal properties of various earth materials and the comparison of various heat storage systems are listed in Tables 1 and 2, respectively.

## *4.7 Rock Thermal Energy Storage*

As the terminology infers the utilization of rocks for TES, the thermal capacity, density and temperature of the rocks play a vital role in capturing and releasing the cold or heat energy depending upon the fluctuating load conditions in buildings during seasonal variations. The schematic diagram of the rock TES system is represented in Fig. 8.

The impermeable, buckle-free, strong rock structures capable of withstanding heat or cold energy on a long run are much preferred in this regard. The extraction of thermal energy from the rock structures is made possible by passing the heat transfer medium (air or fluid) through the long drilled holes in the rocks.

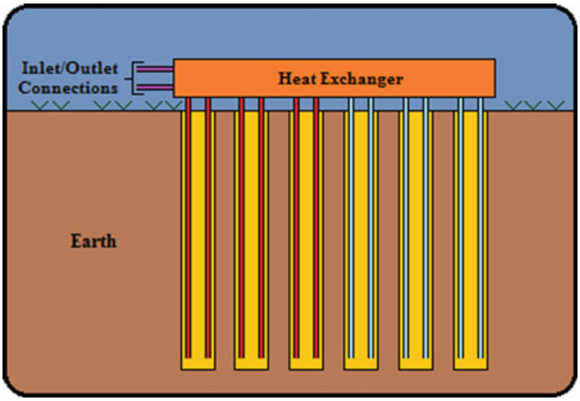
The absorbed heat energy is then transferred to the room spaces through the circulation of heat transfer medium in the room heat exchanger. In recent years, solar collectors are also used for charging (storing) the heat energy at elevated temperatures in the rock structures with the help of heat transfer fluid. The demonstration facility of a rock storage system with 10,000 kl has been installed in Sweden.

The rock TES systems are developed for catering the thermal energy redistribution needs for more than 1,000 dwellings on one stretch. The cost involved in drilling holes through the rocks, rock-site location, strength and reliability of rock structures subjected to frequent thermal cycles are the limiting factors to be addressed for their practical implementation.

**Table 2** Comparison of storage concepts (Novo et al. 2010)

| Storage concept | Hot water | Gravel water | Duct | Aquifer |
|---|---|---|---|---|
| Storage medium | Water | Gravel water | Ground material (soil/rock) | Ground material (sand/water–gravel) |
| Heat capacity (kWh/m3) | 60–80 | 30–50 | 15–30 | 30–40 |
| Storage volume for 1 $m^3$ Water equivalent | 1 $m^3$ | 1.3–2 $m^3$ | 3–5 $m^3$ | 2–3 $m^3$ |
| Geological requirements | Stable ground conditions<br>Preferably no groundwater<br>5–15 m deep | Stable ground conditions<br>Preferably no groundwater<br>5–15 m | Drillable ground<br>Groundwater favourable<br>High heat capacity<br>High thermal conductivity<br>Low hydraulic conductivity ($k\ f < 1 \times 10^{-10}$ m/s)<br>Natural groundwater flow < 1 m/a<br>30–100 m deep | Natural aquifer layer with high hydraulic conductivity ($k\ f > 1 \times 10^{-5}$ m/s)<br>Confining layers on top and below<br>No or low natural groundwater flow<br>Suitable water chemistry at high temperatures<br>Aquifer thickness 20–50 m deep |

**Fig. 8** Schematic representation of the rock TES system



## 4.8 Roof Pond Cool Thermal Energy Storage

In this storage system, the roof structure of the building contains water pond, which upon natural evaporation can create coolness inside the zones directly located below the roof of the building. The cooling effect caused by the evaporation of water can be enhanced by forced convection principle or else by filling the water with small rock-like structures. Due to the capillary action of the rocks, the water is raised above the surface level of the pond, thereby increasing the chance of evaporation to occur much better.

The rate of evaporation decides the level of cooling effects experienced inside the occupied space. Also, the cooling water can be pumped to the zone air-handling system or underfloor coil elements to provide indirect cooling to the conditioned spaces. On an average, the roof pond cooling system can achieve 1 kW energy storage/distribution potential per square metre of the pond with the cooling temperature ranging from 12 to 15 °C.

The formation of scales, dirt, fungal and other bactericidal activities may limit the usage of this system; however, ensuring periodic maintenance can help to facilitate the effective implementation of this kind of energy storage and distribution system.

## 4.9 Thermochemical Energy Storage

As explained in the earlier sections, the functional aspects of the thermochemical and sorption storage systems depend mainly on the rates of reversible chemical reactions. The reaction kinetics of the chemical components plays a vital role in absorbing or releasing the heat energy.

The absorption of heat energy in the reactive components takes place during desorption (or dissociation) process into individual components, which is

**Table 3** Potential materials for chemical reaction storage identified during IEA SHC Task 32 (Pinel et al. 2011)

| Material name | Dissociation reaction | | | Energy storage density of AB GJ/m$^3$ | Turnover temperature (°C) | Realization potential (%) |
|---|---|---|---|---|---|---|
| | AB ⇔ | B+ | A | | | |
| Magnesium sulphate | $MgSO_4 \cdot 7H_2O$ | $MgSO_4$ | $H_2O$ | 2.8 | 122 | 9.5 |
| Silicon oxide | $SiO_2$ | Si | $O_2$ | 37.9 | 4,065<br>+HF: 150 | 9.0 |
| Iron carbonate | $FeCO_3$ | FeO | $CO_2$ | 2.6 | 180 | 6.3 |
| Iron hydroxide | $Fe(OH)_2$ | FeO | $H_2O$ | 2.2 | 150 | 4.8 |
| Calcium sulphate | $CaSO_4 \cdot 2H_2O$ | $CaSO_4$ | $H_2O$ | 1.4 | 89 | 4.3 |

endothermic in nature. Similarly, when the individual components are combined together, the stored heat energy in them can be retrieved again, which is an exothermic reaction.

In the desorption process, the individual components obtained as the outcome can be stored separately, and when the energy demand arises, the working pairs can be combined together to form the parent chemical component. The thermodynamic properties and realization potential of some major thermochemical heat storage materials (or minerals) utilized in practice are summarized in Table 3.

For brevity, the operating characteristics of some closed and open adsorption/absorption types of the thermochemical energy storage systems are explained in the following section.

### 4.9.1 Closed Adsorption Energy Storage System

The modular high energy density heat storage (Modestore) prototype system was first developed by the AEE INTEC in Austria, which was integrated with the solar collectors of 20.4 m$^2$ intended for catering the heating and domestic water production purposes (N'Tsoukpoe et al. 2009). This system was classified under the closed adsorption energy storage, wherein the working pair or functional materials utilized for the chemical processing was silicagel/water. Silicagel, the well-known compound for adsorbing the moisture from vapour, was preferred as the adsorbent, and the water acts as the sorbate in this system. The operating principle of this system is depicted schematically in Fig. 9.

Factually, during the charging cycle, the heat energy trapped from the solar radiation is supplied to the silicagel through the dedicated heat exchanger arrangement. The temperature of the heat source is about 90 °C, which when added to the silicagel makes it to release the water vapour (through desorption principle).

The released water vapour then gets condensed in the condenser as shown, and the components (dry silicagel and water vapour) are stored separately for further usage. The time of storage of the reactive constituents may vary depending on the seasonal TES requirements on a long-term basis.

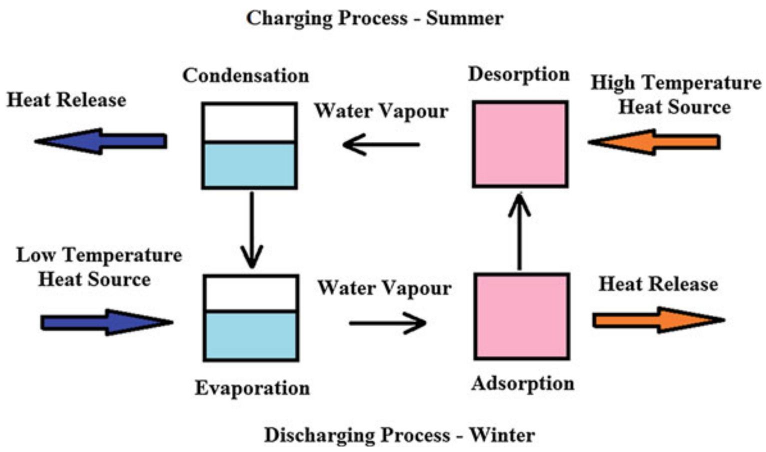


**Fig. 9** Operation principle of closed adsorption system

In the discharging cycle, based on the energy demand and the thermal load conditions prevailing in the evaporator, the stored water is evaporated, and the vapour is then mixed with the dry silicagel (adsorbent) in the adsorber store. By this, the silicagel captures the water vapour through adsorption phenomenon and eventually releases back the stored useful heat energy. Roughly, the storage density of this system was accounted to be 150 kWh/m$^3$ of silicagel.

### 4.9.2 Open Adsorption Energy Storage System

The open adsorption energy storage system also offers an attractive way for storing and releasing the heat energy upon energy demand requirements in buildings. The Institute of Thermodynamics and Thermal Engineering (ITW) in the University of Stuttgart (Germany) has proposed an open adsorption storage named as ITW Monosorp (N'Tsoukpoe et al. 2009). This system also utilizes the high-grade solar energy as the prime heat source for desorption process to take place in the adsorber store.

In principle, during the regeneration cycle (especially in summer), the solar heat energy being trapped using the evacuated tube solar collectors and which is available at a temperature of 180–190 °C is fed as the heat input to the incoming ambient air through a dedicated heat exchange as shown in Fig. 10.

The heated air is then passed over the zeolite 4A material which is filled inside the adsorber store. This enables desorption of zeolite 4A to take place by virtue of vaporizing the water content from the reactive compound. The return warm air is exhausted to the ambient after preheating the fresh incoming air.

During the discharging period (especially in winter), the wet/moist air from the indoor spaces is allowed to flow over the adsorbent store, wherein the water

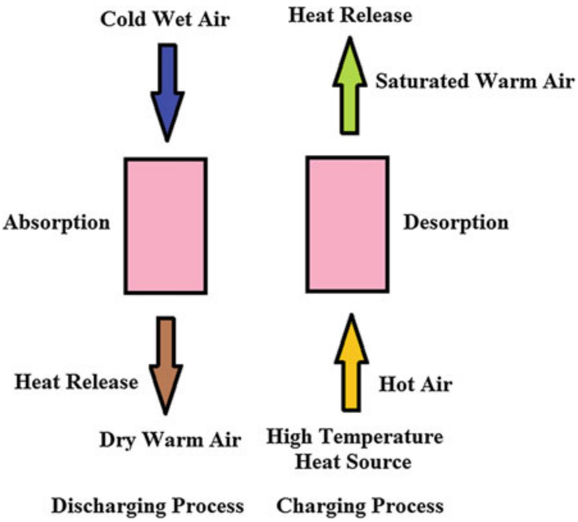


**Fig. 10** Operation principle of open adsorption system

content (humidity) present in the air is captured by the dry zeolite through the adsorption phenomenon.

At the same time, the zeolite discharges the stored heat energy to the flowing air stream, which in turn preheats the incoming ambient ventilation (or fresh) air stream. The honeycomb-like structure of the system design ensures acquiring improved adsorption or reaction kinetics and reduced pressure losses across the process length.

One major limitation of this system for practical realization is that the solar heat energy available at very high temperature in fact elevates the desorption temperature of the system. This in turn has a direct effect on the overall system performance and in the integration of the high-grade solar heat energy with this system.

The other form of open adsorption system that was studied by the ZAE Bayern (Center for Applied Energy Research) in Germany is not specifically meant for long-term seasonal TES applications, but can be considered to cater as a buffer or cushioning system in a district heating network dedicated for building heating applications (N'Tsoukpoe et al. 2009). This system is intended to store 1,300 kWh of energy for providing heating to a school building up to 14 h and with 130 kW of maximum power.

The charging of this system is usually performed during the off-peak load conditions through the district heating network and is almost independent of its operating criteria from the network, throughout the entire on-peak heating load conditions in buildings. The operating principle is very similar to the ITW Monosorp system operation, but with the difference in the heat energy source supply and the adsorbent used (herein, it is with district heating network and with zeolite 13X).

This system is expected to accomplish a storage density of 124 and 100 kWh/m$^3$ for heating and cooling applications, with the COP for the former and latter of 0.9 and 0.8, respectively.

### 4.9.3 Closed Absorption Energy Storage System

The solar-based seasonal heat energy storage system operating with the closed absorption concept was studied by the EMPA (Swiss Federal Laboratories for Materials Testing and Research in Switzerland) in 2006 (N'Tsoukpoe et al. 2009). The prototype of this system is intended for heat storage on a long-term basis using the seasonal thermal energy source. The absorbent utilized in this system is the commonly known caustic soda or sodium hydroxide (NaOH), and the water acts as the sorbate.

The working principle of this system is much similar to the closed adsorption system, wherein during the charging process, the solar heat is directly supplied to the regenerator containing the low-concentration solution (usually the NaOH solution). This heat input drives off the water content from the solution (desorption phase), thereby enabling the caustic soda to be concentrated for further utilization in the discharging cycle.

The water vapour thus generated is transferred into the condenser, where it gets cooled and condensed, and the condensate water as obtained is stored separately in the sorbate storage tank. The excess heat is routed to the ground heat exchanger for further utilization in winter season.

During the discharging cycle, by utilizing the low-temperature heat source from the ground heat exchanger, the stored water is evaporated from the storage tank. The water vapour thus obtained is absorbed by the concentrated caustic soda lye in the absorber tank, and the stored heat energy is thus retrieved back.

Furthermore, the evaluation of this system for a single-family home in accordance with the passive house standard of 120 m$^2$, heating demand of 15 kWh/m$^2$ at 35 °C, domestic hot water requirement of 50 l/day (approx.) at 60 °C and evaporator temperature of 5 °C yields a total storage volume of 7 m$^3$. This value includes the tanks and heat exchangers.

With this system, the maximum absorber temperature of 95 °C was attained, and the lowest temperature at the condenser was about 13 °C. These operating temperatures correspond to the 62 wt% concentration of the lye, which is 7 % higher than that was expected.

### 4.9.4 Thermo-Chemical Accumulator Energy Storage System

The importance of amalgamating the absorption storage and solar technologies with reduced system discrepancies has been achieved by the Solar Energy Research Centre, Sweden (SERC), and their industrial partner ClimateWell AB. This system is developed for catering the cooling requirements in buildings

**Table 4** Claimed performances of TCA' ClimateWell 10 machine (N'Tsoukpoe et al. 2009)

| Mode | Storage capacity[a] (kWh) | Maximum output capacity[b] (kW) | Electrical COP[c] | Thermal efficiency (%) |
|---|---|---|---|---|
| Cooling | 60 | 10/20 | 77 | 68 |
| Heating | 76 | 25 | 96 | 160 |

[a] Total storage capacity (i.e. including two barrels)

[b] Cooling capacity per barrel: 10 kW cooling is the maximum capacity. If both barrels are used in parallel (double mode), the maximum cooling output is 20 kW, and the heating output is 25 kW

[c] Coefficient of performance (COP) = cooling or heating output divided by electrical input

especially; however, it can be operated to fulfil either cooling or heating requirements in buildings. It can be seen that the condenser and evaporator are combined together in conjunction to the desorber and the absorber reactors in the TCA system.

During the charging phase, the weak concentration solution or the poor solution is pumped over the heat exchanger. As the poor solution attains the saturation point, the solid (salt) crystals present in the poor solution are dropped into the vessel by means of the gravity. The water vapour which is desorbed during this process is transferred to the condenser through the gas pipe arrangement.

By this, the heat of condensation and binding energy release are transferred to the building indoor spaces (heating mode) or to the ground-coupled heat exchanger (cooling mode). Likewise, during the discharging phase, the heat of evaporation is supplied by the low-temperature heat source, either from the building space heat exchanger or by the ground-coupled heat exchanger to the condensed water in the condenser. Herein, the condenser acts as the evaporator, which in turn produces the water vapour that flows back to the reactor heat exchanger.

The concentrated solution after absorbing the vapour turns into unsaturated solution by virtue of the dissolution of some salt crystals present in the reactor vessel. The heat storage density acquired by this system is 253 kWh/m$^3$ of LiCl salt. The cost factors involved in using the salt has limited the incorporation of this system for long-term heat storage applications. The important aspects of the TCA system are summarized in Table 4.

### 4.9.5 Solid/Gas Thermochemical Energy Storage System

The solar-energy-based sorption thermochemical energy storage system dedicated for solar air-conditioning application is being developed in recent times. This sorption system operates under two distinct phases, namely the diurnal period and the nocturnal period (Stitou et al. 2012). The schematic and the photographic views of the solid/gas thermochemical storage process pilot plant for solar air conditioning are depicted in Fig. 11.

During the diurnal period (or the daytime), the reactor in the system gets heated up by the solar thermal energy as retrieved through the solar collectors. This heat

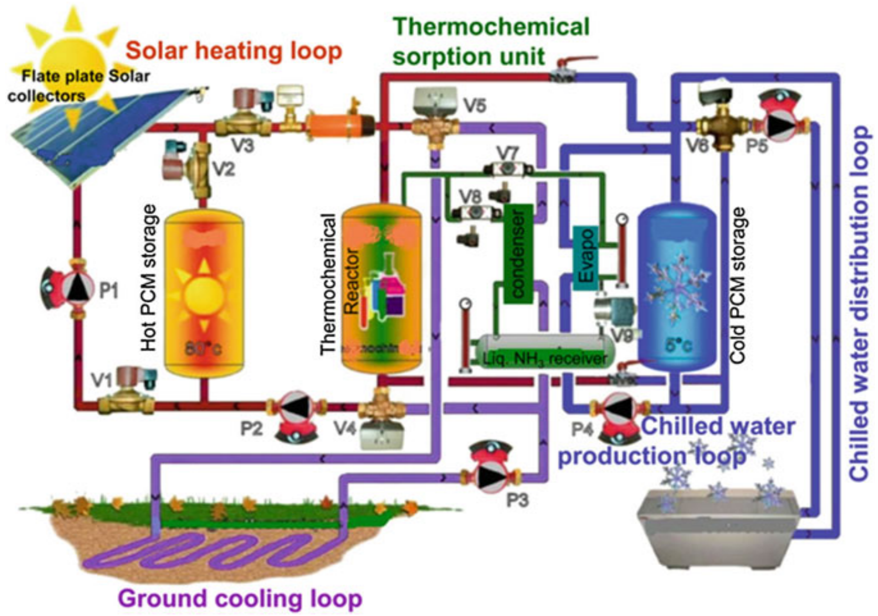


**Fig. 11** Schematic description of the solar air-conditioning thermochemical pilot plant (Stitou et al. 2012)

energy (as input) desorbs the reactive gas (ammonia) from the reactor to the condenser, where the gas gets condensed and collected in the condenser tank.

The condensation of the gas takes places, since the diurnal temperature (or the outdoor temperature) is higher than the nocturnal temperature. The condensation temperature of the reactive gas determines the highest possible operating pressure that could be attained by the system.

In the nocturnal period (or night-time), the reactor starts to absorb the reactive gas from the condenser, since the reactor is in the cooled state. Due to the pressure gradient between the reactor and the evaporator which are coupled together, the boiling and evaporation of the ammonia gas take place in the evaporator.

By this, the cooling effect is produced in the evaporator, which can be effectively stored using a separate cold storage facility integrated to this system. On the other hand, the evaporated reactive gas is absorbed by the reactor, producing heat of absorption at the nocturnal atmospheric temperature.

### 4.9.6 Floor Heating System Using Thermochemical Energy Storage System

The solar thermal long-term heat storage system using the composite of zeolite and salt materials has been developed by the CWS-NT (Chemische Wärmespeicherung—Niedertemperatur). This system essentially consists of a solar thermal combisystem integrated with the so-called thermochemical energy storage system (Mette et al. 2012). This system comes under the classification of open adsorption storage systems, which effectively utilizes the ambient or exhaust air for the discharge of the stored heat energy.

The collector loop heat exchanger bridges the solar thermal combisystem with the thermochemical energy storage system. The thermochemical energy storage system comprises of material storage (reservoir) and a reactor store, where the heat and mass transfer of the reacting components takes place during the charging and discharging processes. The material construction of the material reservoir and the reactor store are carefully designed to withstand the high temperature that may occur during the regeneration process. The provision for the external reactor concept in this system provides additional merit to separate out the storage material from the reactor.

This facilitates for the reaction to take place only on the required material in small quantities of the whole material store per unit time period. The storage material is transported between the material reservoir and the reactor by means of the vacuum conveying system, which allows the designed quantity of the material to get transported with reduced energy consumption.

The material from the storage is allowed to enter the cross-flow reactor from the top, which then moves through the reactor by the gravitational action. The ambient or exhaust air which enters in the lateral direction into the reactor transfers the heat energy and the moisture (or humidity) to the reactor.

During the heating cycle, the heat that is released by the air is transferred to the water loop through the air-to-water heat exchanger. On the other hand, the regeneration of the material takes place through the heat transfer between the flowing air stream and the reactor through the solar collector heat exchange interface.

### 4.9.7 Thermochemical Energy Storage Systems for Building Heating Applications

The attractive and a feasible route of achieving building floor heating using the thermochemical energy storage systems is increasingly attractive in modern times. The recent research work performed by (Caliskan et al. 2012) has signified the possible ways to provide floor heating in a newly constructed or a building subjected to refurbishment using the thermochemical energy storage system. The interesting feature of this system is that it is a combination of thermochemical and sensible energy storage facilities, capable of addressing the building heating demand.

In this system, the thermochemical energy storage is coupled with the aquifer thermal storage which together is operated for accomplishing better seasonal heat storage performance on a long-term basis. The combined system is schematically represented in Fig. 12.

During the charging process of the hot well of aquifer system, the heat energy retrieved from the solar collector is fed into the thermochemical storage system

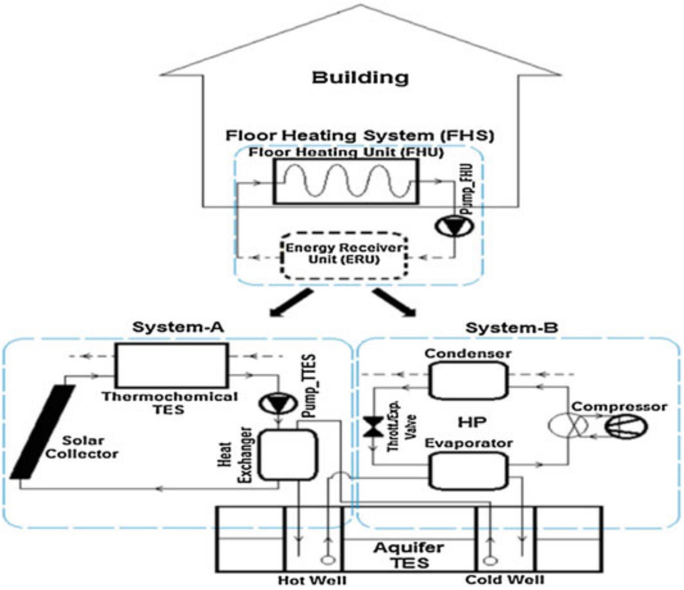


**Fig. 12** Schematic layout of the combined thermochemical and sensible thermal energy storage systems for building heating applications (Caliskan et al. 2012)

through the water loop; thereby the charging or dehydration of the reactive salt component of the thermochemical storage system occurs.

The water vapour in the reactor of the thermochemical storage system gets condensed and subsequently evaporated. Thus, the evaporated water vapour gets mixed with the concentrated salt; thereby the salt adsorbs the vapour and gets unsaturated with the release of stored heat energy (discharging or dehydration process).

This reversible chemical reaction helps the water entering from the building floor heating loop to the thermochemical heat storage system to gain the stored heat energy for achieving effective energy redistribution in buildings. The chemical reaction taking place in the proposed system is given below

$$\mathrm{SrBr_2 \cdot 6H_2O + Heat \rightarrow SrBr_2 \cdot H_2O + 5H_2O}\ \text{(charging process)} \tag{5}$$

$$\mathrm{SrBr_2 \cdot H_2O + 5H_2O \rightarrow SrBr_2 \cdot 6H_2O + Heat}\ \text{(discharging process)} \tag{6}$$

During the charging and discharging processes, the reactive components' $H_2O$ is in vapour phase, while $SrBr_2{\cdot}H_2O$ and $SrBr_2{\cdot}6H_2O$ are in the solid phase.

It is interesting to note that, simultaneous charging of the hot well of aquifer system as well as the offsetting of heating load demand in the building are achieved by this system. On the other hand, if the heat energy stored is insufficient to cater the load demand, the combined system is tuned in such a way that System-B is engaged to solve the purpose.

Herein, the water from the hot well is transported to the cold well of the aquifer system through the evaporator of the heat pump unit being integrated with the building floor hydronic heating system. The water loop of the heat pump picks up the heat from the evaporator, and it is then transferred to the condenser section.

The cumulative of heat energy gained by the water in the heat pump loop is then transferred to the floor hydronic water circuit from the building side. Hence, the overall heat load demand in the building is effectively catered by the combined seasonal thermochemical thermal energy storage systems. The major achievements in the Task 32 of the IEA programme dealing with the advanced storage concepts for solar and low-energy buildings are summarized in Table 5.

## 5 Ice Latent Thermal Energy Storage

The concept of ice TES has been into practice for many years, which by the principle satisfies the building energy redistribution requirements either in full or partial modes of operation. The cooling energy demand occurring in buildings during on-peak load conditions can be effectively met using ice thermal storage systems. The storage of cold thermal energy in the form of ice banks or ice-on-coil arrangements would possibly shift or level the fluctuating cooling load demand from on-peak to off-peak load conditions in buildings.

In principle, ice thermal storage systems effectively utilize the enthalpy of fusion of water to store or release heat energy based on demand load conditions. The chiller (or the cooling plant) installed in the building initially cools down the brine solution (typically glycol solution) during off-peak load conditions, which in turn is pumped through the cooling coil arrangement provided inside the storage tank filled with water.

During the course of time, the water over the coil absorbs the cold energy from the brine solution by combined conductive–convective modes of heat transfer and starts to crystallize over the surface of the coil in the form of thick ice layers. In the daytime, once peak load condition shoots up, warm water from the secondary loop being coupled with the storage tank is pumped through the ice coil; thereby the ice layers undergo melting process. By this, the cold energy stored can be effectively retrieved from the ice storage systems for catering the cooling energy requirements in buildings.

A standard chiller plant designed for low-temperature operating conditions can be configured with the ice storage for producing the required quantity of ice during the charging cycle. Generically, the functional aspects of an ice storage system depend on the latent heat of fusion of water, and so the volumetric storage capacity of such system is higher when compared to that of a standard chiller-based TES system.

Besides, the energy consumption of an ice storage system may vary from 15 to 20 %, since the COP of the chiller associated with the ice storage system would be less at the cost of incremental pumping power requirements. However, an ice

**Table 5** Main achievements in “Task 32: advanced storage concepts for solar and low-energy buildings” (N’Tsoukpoe et al. 2009)

| Parameter | TCA, 80–100 °C | NaOH, 95 °C test, 150 °C calculated | Modestore, 88 °C | SPF, 180 °C | Monosorp, 180 °C | ECN, 150 °C |
|---|---|---|---|---|---|---|
| Type of technology | Closed three phase absorption | Closed two phase absorption | Closed adsorption | Closed adsorption | Open adsorption | Closed thermo-chemical |
| Cost of material €/m$^3$ | 3,600 | 250 | 4,300 | 2–3,000 | [a]2,500–3,500 | 4,870 |
| Storage materials weight | LiCl salt 54 kg<br>Water 117 kg<br>Steel 47 kg | NaOH 160 kg<br>Water 160 kg | Silica gel 200 kg<br>Water 30 kg<br>Steel 100 kg<br>Copper 50 kg | Zeolite 13 × 7 kg | Zeolite 4A 70 kg<br>Steel 10 kg | $MgSO_4.7H_2O$ |
| Storage capacity for heat | 35 kWh | 8.9 kWh 12 | 13 kWh | 1 kWh | 12 kWh | – |
| Floor space required for prototype (m$^2$) | 0.46 | 2 | 0.4 | 0.09 | 0.4 | – |
| Energy density of material (NRJ4.1) (ratio to water 25/85 °C) | 253 kW h/m$^3$ (3.6) | 250 kW h/m$^3$ (3.6) | 50 kWh/m$^3$ (0.71) | 180 kWh/m$^3$ (∼ 3) | 160 kW h/m$^3$ (2.3) | 420 kW h/m$^3$ (6.1) |
| Energy density of prototype (NRJ4.1) (ratio to water 25/85 °C) | 85 kWh/m$^3$ (1.2) | 5 kWh/m$^3$ (0.07) | 33.3 kWh/m$^3$ (0.48) | 57.8 kWh/m$^3$ (∼1) | 120 kWh/m$^3$ (1.7) | – |
| Energy density of prototype—cold (ratio to water 7/17 °C) | 54 kWh/m$^3$ (4.7) | – | – | – | – | – |
| Charge rate (kW) | 15 | 1 | 1.0–1.5 | – | 2.0–2.5 | – |
| Discharge rate (kW) | 8 | 1 | 0.5–1.0 | 0.8/1.8 | 1.0–1.5 | – |
| Estimated size for 70 kWh (ratio to water 25/85 °C) | 0.64 m$^3$ (1.6) | 1.3 m$^3$ (0.75) | 1.7 m$^3$ (0.59) | 1.2 m$^3$ (∼1) | 0.54 m$^3$ (1.9) | [b]0.4 m$^3$ (2.5) |
| Estimated size for 1,000 kWh (ratio to water 25/85 °C) | 5.3 m$^3$ (2.7) | 5 m$^3$ (2.9) | 23 m$^3$ (0.62) | 17 m$^3$ (∼1) | 7.7 m$^3$ (1.9) | [b]5.6 m$^3$ (2.5) |

[a] Cost for large quantity of extruded material is unknown and is estimated for zeolite 4A

[b] Estimations are based on experimental storage density of ∼420 kWh/m$^3$ for reaction $MgSO_4 \cdot 6H_2O + \text{heat} \Leftrightarrow MgSO_4.0 \cdot 2H_2O + 5 \cdot 8H_2O$

storage system that operates with a chiller that produces chilled water between 4 to 6 °C can be expected to conserve the energy up to 85 %. The most commonly preferred ice thermal storage systems for meeting out the cooling requirements in buildings are explained below.

### 5.1 External Melt Ice Thermal Storage

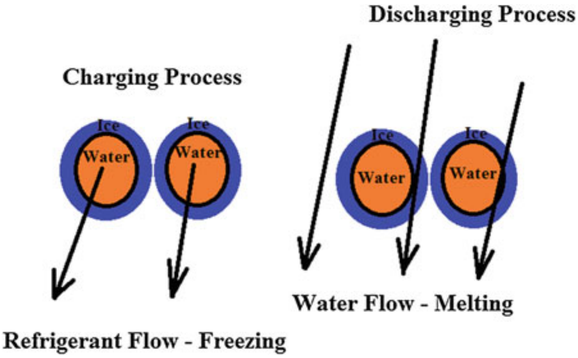
The term external melt basically refers to the extraction of cool thermal energy from the ice that is being melted from the outside of the primary cooling coil circuit (EVAPCO Inc. 2007 and Yau and Rismanchi 2012). The schematic representation and pictorial view of the external melt ice TES system are shown in Fig. 13.

During the charging mode, glycol (or brine) solution at low temperature is pumped through the primary cooling coils by the standard chiller configured with the ice storage tank. By this, the water in the tank starts freezing, thereby forming a thick ice layer over the primary cooling coil circuit. The storage tank is designed in such a way that at complete freezing of water to become ice, the ratio of ice build to water would be 70–30 %.

This aspect ratio would facilitate for better circulation of warm chilled water inside the storage tank in order to retrieve the heat energy from the ice layers. The merits of external ice melt system include the following:

- the energy extraction rate can be modulated based on the cooling load demand persisting in the conditioned spaces,
- the melting of ice with warm water can be done in single stretch, or on timely basis depending on the fluctuating thermal load conditions, and
- the overall cooling system efficiency is appreciable in terms of reduced energy consumption in the secondary chiller and the associated chilled water pumps, as they may be turned off at on-peak conditions.
- As the secondary cooling loop and the storage tank utilize water, appreciable heat transfer mechanism can be expected during charging and discharging cycles.

**Fig. 13** The charging and discharging procedures of an external melt ice storage system



## 5.2 Internal-Melt Ice Thermal Storage

The basic difference between an internal melt and an external melt systems is that glycol (or brine) solution is used for charging and discharging of storage tank, which is not the case for an external ice melt concept (EVAPCO Inc. 2007 and Yau and Rismanchi 2012). The schematic representations of the charging and discharging processes in an internal melt ice TES is shown in Fig. 14.

Typically, during the charging process (at off-peak conditions), the cooled glycol from chiller while flowing in the primary circuit transfers the cold energy to the surrounding water filled inside the tank. This in turn enables the water in the tank to freeze into ice, which builds up to the predetermined quantity. On the other hand, during the discharging process (on-peak conditions), the warm glycol solution entering from the building side (secondary loop) transfers the heat energy to the chilled water (or ice).

By this, the built-in ice gets melted, and subsequently, the glycol solution is cooled to the required temperature. Here, the chilled water present in the storage tank remains static, and the heat transfer mechanism involved in ice storage processes are largely due to the flow of glycol through the primary cooling coil loop. The merits of internal ice melt system include the following:

- the benefits of having a closed-loop arrangement,
- effective control of glycol solution temperatures in both primary and secondary sides,
- COP of primary chiller plant is better than that experienced with an external melt system,
- energy redistribution in buildings is possible with time-dependent charging and discharging modes of operation, and
- water in the storage tank only changes its phase in the due course of operation, which helps to reduce the pumping energy consumption.

Limitations of the ice storage systems include the following:

- thermal losses occur during energy storage and energy redistribution processes,

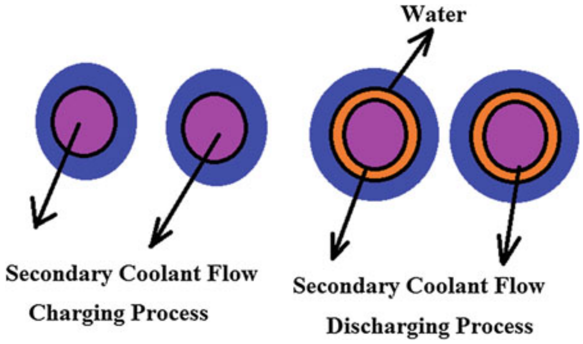


**Fig. 14** Charging and discharging procedure of an internal ice-on-coil storage system

- lower fluid temperature results in the decrease in the overall cooling performance of the system,
- inherent pressure drop in the pumping systems influences the flow rates of fluid, thereby the net heat transfer rate is limited, and
- operational and maintenance costs of such system are normally justified only above several hundred tons of cooling capacity.

## *5.3 Ice Storage Using Harvesting Technique*

This is very similar to the external and internal ice melt techniques, but the cooling coil (evaporator) contains a refrigerant in place of the glycol solution. The refrigerant coils embedded inside the storage tank extract the heat content from the flowing water. The chilled water, at a particular instant of time, changes its phase into ice, which eventually gets deposited over the surface of the cooling coil. The built-up ice is then removed by passing a stream of hot gas through the cooling coil at equal intervals of time (usually 25 or 30 min).

The thermal energy stored in the flakes of ice together with the chilled water is utilized to cater the cooling load demand during on-peak conditions in building. The schematic representation of the ice storage using harvesting technique is shown in Fig. 15 (Yau and Rismanchi 2012).

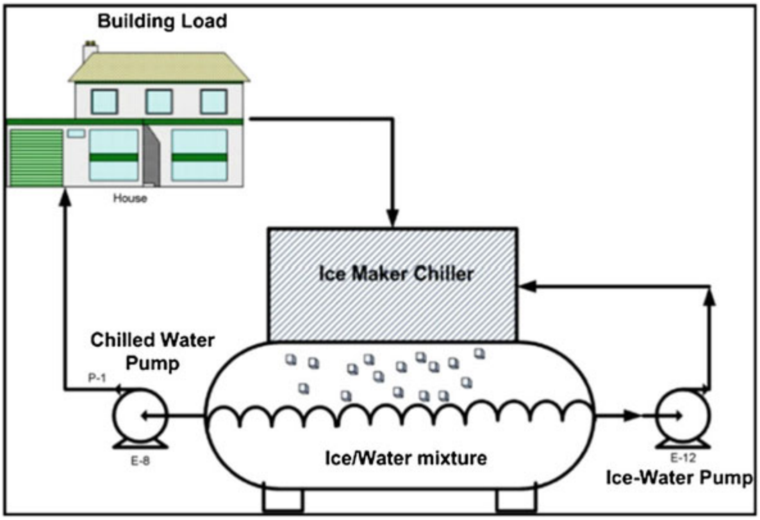


**Fig. 15** Schematic diagram of a typical ice harvesting ITS system (Yau and Rismanchi 2012)

## 5.4 Ice Slurry Storage System

Thermal energy is stored in this system by making use of both the sensible and latent heat characteristics of heat transfer fluid and water contained in the storage tank, respectively. Ice slurry storage usually comprises of a cooling system and a secondary heat exchanger coupled to the building space conditioning unit.

In practice, the storage tank is filled with a designed proportion of a heat transfer fluid and water. The refrigerating loop of the cooling plant enables the heat transfer fluid to be maintained at very low temperature.

Through the direct-contact heat exchange mechanism exhibited between the cooled heat transfer fluid and the water, small ice-like structures are formed and float over the top of the tank in the form of ice slurries. The ice slurries are then pumped to the secondary heat exchanger that is in contact with the space conditioning unit in building.

The net heat transfer rate taking place in the heat exchanger decides the cooling effect in indoor environment. The volumetric capacity ratio of water to the heat transfer fluid determines the rate of formation of ice slurries in the storage tank.

The modified form of ice slurry storage system consists of a vertical shell and tube heat exchanger, wherein the shell acts as the evaporator and the tubes serve as the heat transfer surface. Typically, the heat energy from the fluid flowing through the tubes are retrieved by the refrigerant present in the shell, thereby facilitating the formation of thin flakes of ice on the surface of the tubes. The ice flakes or crystals thus formed are then transported to the collector and ice slurry tanks at regular intervals based on the thermal load demand in buildings.

The instantaneous phase change characteristics of the heat transfer fluid plays a vital role in the formation of ice slurries required for providing cooling in buildings with TES. Interestingly, for the designed cooling load, mass flow rate and temperature of the chilled water returning from the building, the outlet temperature of the ice slurry storage almost remains consistent.

## 5.5 Ice Storage with Low Temperature Air Cooling

The air supplied to indoor spaces in buildings is conditioned to meet out the conditions related to thermal comfort to occupants in addition to achieving energy efficiency in cooling systems. In contrast to the conventional chilled water cooling, the supply air is conditioned to attain temperature between 3 and 9 °C using the ice storage facility. The low temperature acquired by the air paves way for maintaining the relative humidity in indoor environment in the range of 40–55 %.

Having the low-temperature air supply in the conditioned zones, the size of air distribution systems and its associated operational and maintenance costs being involved can be collectively reduced by 10–20 %. Furthermore, for the designed cooling capacity, the reduction in air temperature necessitates for having less air quantity to be supplied in conditioned rooms, thereby minimizing the total energy consumption by 15–30 % on the air-handling unit and air distribution fan systems.

## 6 Phase Change Thermal Energy Storage Technologies

In the modern era, the concept of TES for cooling and heating applications in buildings has gaining impetus, by the continuous and value-added technological improvements taking place worldwide. From this perspective, the revelations on the development of advanced materials for confronting the energy challenges and energy security are of great importance, in recent years. In this context, the phase change materials (PCM) serve as an effective platform to bridge the gap present between the energy supply and energy demand in buildings.

The PCM are a class of heat storage materials capable of storing and releasing large amount of heat energy by changing their phase at isothermal conditions. Typically, when the PCM is cooled below its melting temperature, the cold energy is stored through the phase change of the material from liquid to solid state.

Similarly, when the PCM is heated above its melting temperature, the stored cold energy is dissipated from the material by virtue of phase change from solid to liquid state. In reality, there are numerous PCMs available for enabling this technology to be successfully implemented in buildings.

The theoretical LHS process of the phase change material is depicted in Fig. 16. Precisely, in the freezing (charging) process 1–2, the PCM absorbs heat energy from the surrounding heat transfer medium (chilled water or cool air) and gets sensibly cooled to its phase transition temperature. During the process 2–3, with the continuous supply of cold energy, the PCM starts to change its phase, leading to the formation of solid crystals at constant temperature.

In the process 3–4, the PCM gets further cooled through the sensible heat addition and attains the temperature as that of the surrounding heat transfer fluid.

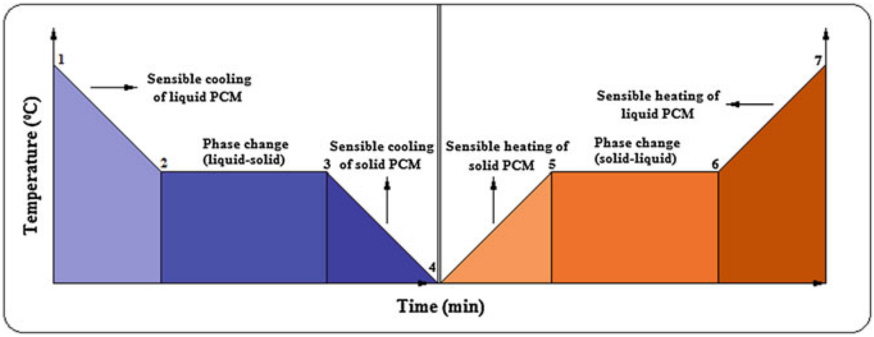


**Fig. 16** Heat storage and release processes of the PCM

In the melting process 4–5, the warm surrounding fluid adds sensible heat to the PCM. This in turn increases the temperature of the PCM. In the process 5–6, with the addition of continuous heat energy, the commencement of melting (phase change) of PCM takes place at constant temperature.

Further heat addition in the process 6–7 leads to the complete melting of the solid phase to liquid phase, and the PCM would acquire the equilibrium temperature condition with that of the surrounding heat transfer medium.

Interestingly, during the processes 2–3 and 5–6, the latent heat phase transformation of the heat storage material is substantial such that higher amount of thermal energy is being stored and released at constant phase change temperature. This is the most essential characteristic of PCMs, which explores their TES capacity highly suitable for building cooling and heating applications.

The PCMs are generally classified into inorganic, organic and eutectic mixtures. The latent functional phase change energy storage materials are meritorious in terms of their rate of charging and discharging characteristics, high latent heat or enthalpy of fusion, energy storage density per unit volume and so on (Dincer and Rosen 2011).

Though the inorganic and organic PCMs exhibit supercooling phenomenon, dissociation of material during phase change, incongruent freezing and melting characteristics, when subjected to the cyclic cooling and heating processes, they are still preferred much for catering the energy redistribution requirements in modern dwellings.

The integration of LTES system with building cooling and heating system indubitably serve to bridge the gap between the energy supply and its usage without losing the energy savings potential in buildings (Parameshwaran et al. 2012).

From this perspective, the LTES systems using a variety of PCMs exhibiting suitable thermal properties being integrated with the building HVAC systems have been extensively discussed in Parameshwaran et al. (2012) and Cabeza et al. (2011).

The selection of an active or a passive TES system mainly depends upon the cooling/heating demand of the occupied zones in building envelope and the phase change characteristics of the heat storage material, including the enthalpy of latent heat, phase transition temperature, thermal conductivity, heat storage and release capacity, thermal stability and thermal reliability. The incorporation and applications of some of the PCM-based passive and active systems in the building envelopes are shown in Fig. 17 (Xin et al. 2009).

In majority of the present latent thermal storage systems being integrated in buildings, the organic PCMs are widely utilized because of their excellent latent heat of fusion, low supercooling, thermal stability, less corrosion, ease availability and moderate cost. Paraffins and their derivatives are widely considered as PCM in the LTES systems for accomplishing effective energy redistribution in buildings.

The limitations of the PCMs as mentioned in the earlier section and in the research works performed by Parameshwaran et al. (2012) and Cabeza et al. (2011) can be considered as challenging factors for their implementation in the LTES systems.

The constraints of using the PCMs in buildings are being investigated by several research groups worldwide, which have resulted in good solutions that are

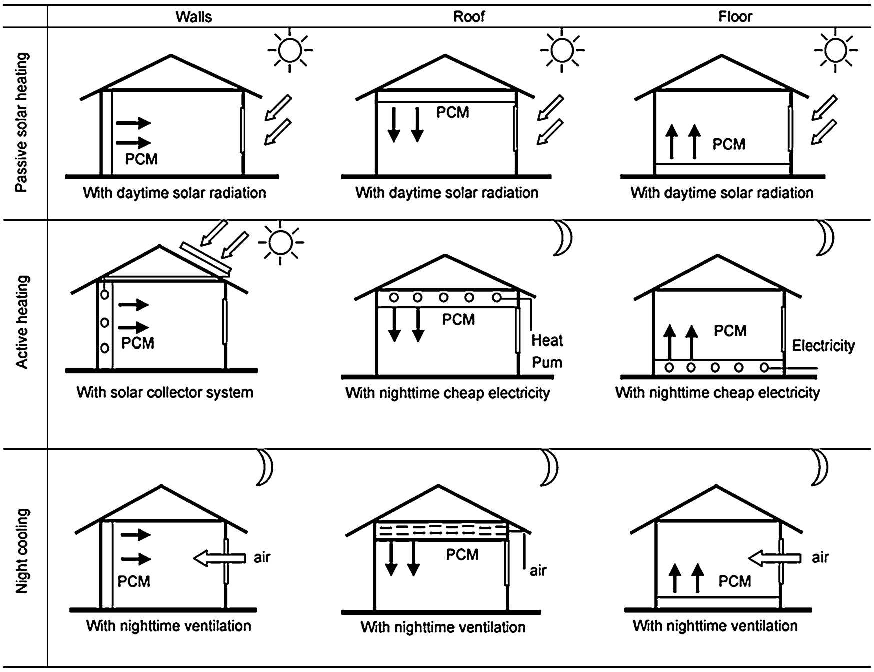


**Fig. 17** Some applications of PCM in building envelopes (Xin et al. 2009)

innovative and appreciably reasonable. But, there is much more to be done for improving the thermophysical properties and energy efficiency of PCMs through performing the basic materials research.

## 7 Chilled Water-Packed Bed Latent Thermal Energy Storage

In the modern energy-efficient building design, the concept of chilled water-based LTES system utilizing the PCM as heat storage material is increasingly popular among the architects and the design engineers worldwide. The full-scale schematic representation of this system being dedicated for the cooling applications in buildings can be referred from Parameshwaran et al. (2010).

Precisely, the operational strategy of this system is divided into two folds: (a) during the charging process (part-load conditions), a portion of the chilled water produced at a temperature of 4–5 °C is pumped to the heat transfer station, and the remaining portion of the chilled water is by-passed to the packed bed LTES system. By this, the chilled water entering the heat transfer station transfers the cold energy to the building-side return warm water flowing at a temperature of 11–12 °C.

Simultaneously, the PCM being encapsulated in the TES tank gets cooled down by the flowing chilled water and is frozen completely with time. The warm water that is cooled at the energy transfer station is pumped into the building air-handling unit, where the supply air is processed and conditioned as per the design cooling load requirements of the indoor environment.

At the same time, the return warm water from the energy transfer station gets mixed with the return water from the LTES tank and is pumped back to the chiller plant for the commencement of the next cyclic process of cooling.

On the other hand, during the discharging process of LTES system (on-peak load conditions), a portion of the warm water from the return loop of the chiller plant is diverted to the LTES tank, where it extracts the cold energy from the PCM encapsulations. The required cooling energy is then transferred to the warm water (coming from the building side) and to the energy transfer station.

The chilled water is then supplied to the building air-handling unit and the discharging process at the LTES system is thus accomplished with complete melting of the PCMs. In this way, the energy storage and heat transfer performance of this system is enhanced without losing the thermal comfort to occupants and energy efficiency in buildings. The specifications of TES tanks, the essential aspects and the key parameters of various TES systems are summarized in Tables 6, 7, 8 and 9.

**Table 6** Specifications of LHES tanks manufactured commercially (Parameshwaran et al. 2012)

| Volume ($m^3$) | External diameter (mm) | Total length (mm) | Outer surface area for insulation ($m^2$) | Inlet/outlet connections (mm) | Cradles required | Weight measured at empty (kg) | Volume of HTF ($m^3$) |
|---|---|---|---|---|---|---|---|
| *Cristopia energy systems* (*Cristopia*) | | | | | | | |
| 2 | 950 | 2,980 | 10 | 40 | 2 | 850 | 0.77 |
| 5 | 1,250 | 4,280 | 18 | 50 | 2 | 1,250 | 1.94 |
| 10 | 1,600 | 5,240 | 29 | 80 | 2 | 1,990 | 3.88 |
| 15 | 1,900 | 5,610 | 37 | 100 | 2 | 2,900 | 5.82 |
| 20 | 1,900 | 7,400 | 47 | 125 | 3 | 3,700 | 7.77 |
| 30 | 2,200 | 8,285 | 61 | 150 | 3 | 4,700 | 11.64 |
| 50 | 2,500 | 10,640 | 89 | 175 | 4 | 6,900 | 19.40 |
| 70 | 3,000 | 10,425 | 106 | 200 | 4 | 7,300 | 27.16 |
| 100 | 3,000 | 14,770 | 147 | 250 | 6 | 12,700 | 38.80 |
| *Environmental process systems limited* (*EPS Ltd.*) | | | | | | | |
| 5 | 1,250 | 3,750 | – | 50 | – | – | – |
| 10 | 1,600 | 4,500 | – | 80 | – | – | – |
| 25 | 2,000 | 8,000 | – | 125 | – | – | – |
| 50 | 2,500 | 10,000 | – | 150 | – | – | – |
| 75 | 3,000 | 10,600 | – | 200 | – | – | – |
| 100 | 3,000 | 11,100 | – | 250 | – | – | – |

**Table 7** Specifications of ice CTES tanks manufactured commercially by CALMAC Manufacturing Corporation (Parameshwaran et al. 2012)

| Volume ($m^3$) | External diameter (mm) | Total length | Floor loading ($kg/m^2$) | Inlet/outlet connections (mm) | Net usable capacity (kWh) | Weight measured at empty (kg) | Volume of HTF (l) | Volume of ice/water (l) |
|---|---|---|---|---|---|---|---|---|
| *Model A storage tank* | | | | | | | | |
| 4.23 | 1,875 | – | 718 | 51 | 144 | 265 | 151 | 1,550 |
| 7.31 | 1,875 | – | 1,382 | 51 | 288 | 465 | 295 | 3,105 |
| 8.84 | 2,260 | – | 1,142 | 51 | 345 | 555 | 341 | 3,710 |
| 9.04 | 1,875 | – | 1,758 | 51 | 369 | 580 | 375 | 3,955 |
| 13.13 | 2,260 | – | 1,894 | 51 | 570 | 885 | 560 | 6,265 |
| *Model C storage tank* | | | | | | | | |
| 7.78 | – | 1,940 | 1,396 | 101 | 288 | 485 | 326 | 3,105 |
| 9.33 | – | 2,340 | 1,157 | 101 | 345 | 580 | 341 | 3,710 |
| 9.42 | – | 1,940 | 1,772 | 101 | 369 | 595 | 375 | 3,955 |
| 13.70 | – | 2,340 | 1,909 | 101 | 570 | 910 | 594 | 6,265 |
| 27.04 | – | 4,620 | 1,909 | 101 | 1,140 | 1,815 | 1,192 | 12,530 |
| 40.45 | – | 6,910 | 1,909 | 101 | 1,710 | 2,720 | 1,787 | 18,795 |

**Table 8** Essential aspects of active cool TES and LTES systems (Parameshwaran et al. 2012)

| | Chilled water storage | Ice storage | Eutectic salt storage | PCM storage |
|---|---|---|---|---|
| Specific heat (kJ/kg K) | 4.19 | 2.04 | – | 2–4.2 |
| Latent heat of fusion (kJ/kg) | – | 333 | 80–250 | 130–386 |
| Heating capacity | Low | High | Medium | Medium |
| Type of chiller | Standard water | Low-temperature secondary coolant | Standard water | Standard water |
| Volume of storage tank ($m^3$/kWh) | 0.089–0.169 | 0.019–0.023 | 0.048 | – |
| Storage charging temperature (°C) | 4–6 | −6 to −3 | 4–6 | −10 to 6 |
| Storage discharging temperature (°C) (higher than charging temperature) | 1–4 | 1–3 | 9–10 | 5–8 |
| Ratio of cooling capacity | 20–30 | More than 50 | 15–40 | 20–50 |
| Performance coefficient of chiller | 5.9–5 | 4.1–2.9 | 5.9–5 | 5.9–5 |
| Fluid for discharging storage | Standard water | Secondary coolant/brine solution | Standard water | Standard water |
| Tank interface | Open system | Closed system | Open system | Closed system |
| Space requirements | More | Less | Less | Less |
| Flexibility | Existing chiller usage; fire protection duty | Modular tanks suitable for small/large installations | Existing chiller usage | Existing chiller usage |
| Maintenance | High | Medium | Medium | Medium |

**Table 9** Key parameters of various active TES systems (Parameshwaran et al. 2012)

| TES system | Energy storage capacity (kWh/t) | Discharge ability (kW) | Efficiency (%) | Storage period |
|---|---|---|---|---|
| Chilled water storage | 20–80 | 1–10,000 | 50–90 | Day-year |
| Aquifer storage | 5–10 | 500–10,000 | 50–90 | Day-year |
| Borehole storage | 5–30 | 100–5,000 | 50–90 | Day-year |
| Ice storage | 100 | 100–1,000 | 80–90 | Hour-week |
| PCM storage | 50–150 | 1–1,000 | 75–90 | Hour-week |

## 8 Sizing of Thermal Energy Storage System

The design of TES system for cooling and heating applications in buildings can be performed by determining the following:

- Thermal load profile of the building for the design day's operation.
- Type of TES system (full or partial storage).
- Heat storage material considered.
- Active or passive system.

The following examples explain the basic sizing of ice and chilled water cool TES systems dedicated to provide energy redistribution requirements in buildings:

### 8.1 *Ice Thermal Energy Storage System Design*

The simple design of an ice TES system is explained below:

Design inputs:
Cooling energy requirement (on daily basis)—5,000 kWh
Charging time of the ice storage—8 h
Discharging time of the ice storage—10 h
Peak cooling load observed in building—700 kW
Rotary screw chiller is considered
Calculation of ice storage capacity:
Assuming the energy storage efficiency factor to be 0.94 with a storage capacity of 50 %, the per day energy generation requirement can be obtained by
$5{,}000 \times (50/100) = 2{,}500$ kWh
Applying the storage efficiency factor, the energy generation $= (2{,}500/0.94)$
Otherwise, the total energy storage capacity $\approx 2{,}660$ kWh
Charging of ice storage for 8 h using the chilled water, which gives out the chiller capacity $= 2{,}660$ kWh/8 h $= 333$ kW
Thus, the cooling duty of the chiller during the design day's operation is determined by: Ice storage discharge time $= 2{,}660$ kWh/10 h $= 266$ kW
Maximum cooling load in the building $= 700$ kW

Therefore, the chiller nominal capacity = 700 − 266 = 434 kW

Hence, the chiller plant selected for catering ice storage at 380 kW is capable of offsetting the thermal load demand and redistributes the energy requirements in building at 50 % higher capacity during its daytime operation, that is, the cooling capacity of the chiller is expressed to be (333 kW × 1.5) ≈ 500 kW.

## 8.2 Chilled Water-Packed Bed Thermal Energy Storage Systems Design

The basic design of the chilled water-packed bed LTES system for the building located in a hot and humid climatic condition is represented in Table 10. The on-peak and part-load conditions existing in the building are highlighted by the orange and blue colours, respectively. The total cooling load requirement of the building was estimated to be 6,186 kW, wherein the nominal cooling capacity of the chiller was determined by

$$\text{Nominal cooling capacity} = \frac{\text{Total cooling load}}{\begin{array}{l}(\text{Total charging hours} \times \text{efficiency factor} \\ +\text{Total discharging hours} \times \text{efficiency factor})\end{array}} \tag{7}$$

Therefore, nominal cooing capacity of the chiller

$$= (6,186/\{(14 \times 0.9) + (10 \times 0.8)\}) = 306\,\text{kW}$$

Here, the efficiency factor for charging and discharging periods is assumed to be 0.9 and 0.8, respectively.

Cooling capacity of chiller during direct cooling (on-peak load conditions)

$$= 306 \times 0.9 = 276\,\text{kW}$$

Cooling capacity of chiller during charging of the TES system (part-load conditions)

$$= 306 \times 0.8 = 245\,\text{kW}$$

Cooling capacity shared by the TES system (energy redistribution) during on-peak condition is determined as follows:

At the start of the part-load condition (typically at 19 h):

$$\begin{aligned}\text{Cooling capacity of TES} = {} & (\text{Cooling capacity of chiller at the specific hour of part load condition} \\ & - \text{Total cooling load at that hour}) + \text{Storage balance at the previous hour}\end{aligned} \tag{8}$$

Thus, the cooling capacity of TES $= (245 - 170) + 0 = 75\,\text{kW}$

**Table 10** Design of the chilled water-packed bed LTES system

| Time (h) | Total cooling energy demand (kWh) | Load satisfied by | | Chiller+TES charging (kW) | TES balance (kW) |
|---|---|---|---|---|---|
| | | Chiller (kW) | TES Tank (kW) | | |
| 0 | 148 | 258 | 148 | 245 | 528 |
| 1 | 148 | 258 | 148 | 245 | 625 |
| 2 | 150 | 258 | 150 | 245 | 720 |
| 3 | 151 | 258 | 151 | 245 | 814 |
| 4 | 154 | 258 | 154 | 245 | 904 |
| 5 | 151 | 258 | 151 | 245 | 998 |
| 6 | 161 | 258 | 161 | 245 | 1082 |
| 7 | 167 | 258 | 167 | 245 | 1160 |
| 8 | 180 | 258 | 180 | 245 | 1225 |
| 9 | 337 | 276 | 61 | 0 | 1164 |
| 10 | 368 | 276 | 92 | 0 | 1072 |
| 11 | 405 | 276 | 129 | 0 | 942 |
| 12 | 450 | 276 | 174 | 0 | 768 |
| 13 | 480 | 276 | 204 | 0 | 564 |
| 14 | 450 | 276 | 174 | 0 | 389 |
| 15 | 405 | 276 | 129 | 0 | 260 |
| 16 | 383 | 276 | 107 | 0 | 153 |
| 17 | 368 | 276 | 92 | 0 | 61 |
| 18 | 337 | 276 | 61 | 0 | 0 |
| 19 | 170 | 258 | 170 | 245 | 75 |
| 20 | 165 | 258 | 165 | 245 | 155 |
| 21 | 158 | 258 | 158 | 245 | 242 |
| 22 | 151 | 258 | 151 | 245 | 336 |
| 23 | 149 | 258 | 149 | 245 | 432 |
| Total | 6186 | 2756 | 3430 | 3430 | |

At the completion of the part-load condition (typically at 8 h):

$$\begin{aligned}\text{Cooling capacity of TES} &= (\text{Total cooling load - }((\text{Nominal cooling capacity of the chiller}\\ &\quad \times \text{peak load operating hours} \times \text{efficiency factor})\\ &\quad + \sum \text{Cooling capacity of chiller during charging at part load conditions}\Big)\Big)\end{aligned} \tag{9}$$

Cooling capacity of TES $= (6,186 - ((306 \times 10 \times 0.9) + \Sigma 245 \times 9)) = 1,225\,\text{kW}$

$$\begin{aligned}\text{Cooling capacity shared by TES } = {} & (\text{Cooling capacity of TES at the completion of part load} \\ & - (\text{Total cooling load} \\ & - \text{Chiller cooling capacity during direct cooling}))\end{aligned} \tag{10}$$

Therefore, the cooling capacity shared by TES during on-peak conditions = (1,225 – (337 – 276)) = 1,164 kW. Hence, by following the aforementioned steps, the cooling energy shared by the TES system at the end of on-peak condition is nil (0 kW), which signifies that the packed bed LTES system has been discharged completely and is ready for the next cycle of charging process.

In the case of underfloor heating systems, the maximum energy output delivered by the system under cooling and heating modes is estimated to be 40 and 100 W/m$^2$, respectively, irrespective of the thermal load demand in the occupied spaces. By modulating the flow rate of the heat transfer fluid flowing in the pipe elements being embedded under the floor surface, the required cooling or heating capacity can be accomplished.

The variation of the floor surface by this scheme can also be done through adjusting the differential temperature between the floor surface and the flowing heat transfer fluid in the range of 5–10 K with respect to the space temperature. If the temperature of the room exceeds by 12 or 13 °C, the issue of condensation may arise. At the same time, while the floor surface temperature exceeds by 28 or 30 °C, it can cause thermal discomfort to occupants.

For the building fabric systems, an increase in the surface area of the slab components, the flow control of heat transfer fluid inside the embedded coil elements as well as the utilization of fan-assisted modules can increase the overall heat transfer rate, charging and discharging characteristics of the thermal storage systems.

The heating storage capacity of solar thermal systems can be increased by increasing the total number of solar thermal collectors as well as using concentrated solar collectors. The limited heat source available during off-sunshine hours can be matched to the greater extent through the integration of the LTES system with the solar collectors.

The source TES system can be sized based on the total cooling/heating demand, availability of the energy source, site location, climatic conditions, thermal conductivity of earth materials, heat pump system integration with the ground source energy loop, cost of erection and installation of large structures beneath the ground level.

## 9 Nanotechnology-Based Thermal Energy Storage

In the context of using LTES systems for redistributing and conserving energy in buildings, the amalgamation of the scientific research performed on the advanced materials with the vision of improving the thermal properties of the PCM is increasingly attractive, in recent years. Nanoscience, the study that deals with the inherent functional properties of the materials or their structures at nanometre level, has substantially implanted numerous identifications on the materials produced at nanoscale.

The advanced nanostructured materials, whose surface-to-volume ratio are very high when compared to the same material at its bulk state plays a vital role in characterizing the thermophysical properties of the base material to which they are embedded.

The active transformation of the scientific innovations on functional materials at nanometre level into the real-time application, as referred to the nanotechnology, has paved way for achieving improved performance of many bulk materials, especially on the heat storage materials.

The penetration of the nanotechnology into the spectrum of TES in buildings from the scheme inception of preparation up to the performance testing of PCMs embedded with nanoparticles are briefly explained in the forthcoming sections.

## *9.1 Preparation of Nanomaterials*

The preparation of the nanomaterials of size ranging from 1 to 100 nm can be performed through two broad techniques, namely top-down and bottom-up methods. In the top-down method, the nanoparticles are produced by subjecting the bulk materials to undergo crushing, grinding or high-energy impact motion for longer period of time.

The final yield obtained can be in the form of wet or dry powder depending on the reactive materials being added during the process. This method is advantageous for producing high thermal conductive materials initially in the form of sheets (e.g. graphene oxide), metallic alloys and nanocomposite structures.

Due to the mechanical stresses and microstuctural deformation observed in the nanomaterials being produced, this method is less pronounced for the preparation of nanoparticles with effective size distribution.

On the other hand, in the bottom-up approach, the nanoparticles are formed by the atomic interaction of two or more chemically reactive materials present in the colloidal state, wherein the size, shape and dispersion of the nanoparticles can be effectively controlled.

This method is widely preferred for the preparation of smaller size nanoparticles in the range of 1–10 nm in colloidal solution, and so this approach is also referred to as the sol–gel method. Numerous nanostructured materials have been prepared using the sol–gel method so far.

Other physical methods are also available to synthesize the nanomaterials, which include physical vapour deposition, chemical vapour deposition, laser ablation, pulsed-vapour method, electric arc method, etc. Each method has its own merits and limitations; however, the size of the nanoparticles can be controlled more efficiently with the wet-chemical sol–gel approach. The elucidation on the detailed preparation methodology of the different types of nanomaterials has been reported in Capek (2004).

## 9.2 Preparation of PCM Embedded with Nanomaterials

The nanomaterials obtained using any of the aforementioned methods have to be doped into the pure (base) PCM in order to realize the thermophysical property changes in the PCM. The nanomaterials are initially characterized for their surface morphology, surface structure, crystallization, thermal stability, etc., using the respective analytical techniques including scanning electron microscope (SEM), transmission electron microscope (TEM), Fourier transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), thermogravimetric–differential thermal analysis (TG-DSC) and so on.

As the first step in doping nanomaterials into the pure PCM, the weight proportions of nanoparticles with respect to the pure PCM are to be determined. In general, the weight proportions of nanomaterials, usually represented in weight percentage (wt%), are represented by the relation given by

$$\text{Weight percentage of nanomaterial} = \frac{\text{Weight of the nanomaterial}}{(\text{Weight of the nanomaterial} + \text{Weight of the PCM})} \tag{11}$$

For instance, the weight of nanoparticles ($W_{np}$, g) that is required for the preparation of 0.1 wt% of 100 g of PCM solution can be calculated using the above relation, as given by

$$\frac{0.1}{100} = \frac{w_{np}}{w_{np} + 99.9} \tag{12}$$

Based on the computation, the required quantity of the nanoparticles is dispersed into the pure PCM using high-frequency ultrasonic vibration technique. The ultrasonication helps the powder nanoparticles to be evenly distributed into the pure PCM solution; thereby the nanoparticles can stay stable without getting settled down in the solution.

In order to keep the nanomaterials stable on a long run, the surfactants or stabilizing agents are added to the PCM solution, which would maintain the nanoparticles from being agglomerated and settle down due to the intermolecular forces of attraction. However, the mixing of surfactant with PCM solution may sometimes affect the thermal properties of the PCM being subjected to several thermal cycles.

## *9.3 Thermal Properties of PCM Doped with Nanomaterials*

The heat transfer performance of the PCM-based LTES system largely depends on the thermal properties of PCM, which includes thermal conductivity, latent heat of fusion, phase transition temperature, degree of supercooling, heat storage and release characteristics, thermal stability and thermal reliability. Interestingly, the thermal properties of pure PCM can be tuned for achieving the improved TES capability using the nanomaterials.

The incorporation of nanomaterials and their effect on the inherent thermal properties of PCM are briefly discussed in the following sections. The thermal conductivity of the PCM in an encapsulated storage plays a significant role in determining its heat transfer ability towards the temperature differential between the PCM and the surrounding heat transfer fluid with respect to the wall thickness.

Generically, the salt hydrate type of PCMs exhibit a higher thermal conductivity than that of the organic PCMs, but the former may get destabilized over periodic thermal processes. Thus, the organic PCMs with low thermal conductivity, but are commercially viable, can be mixed with the proper proportions of nanomaterials. The nanoparticles embedded into the pure PCM may create more thermal conductive interfaces within the PCM matrix layers.

When the PCM is subjected to heat or cold energy, these thermal interfaces can serve as thermal energy carriers to transfer the heat energy effectively throughout the PCM, thereby enabling the PCM to undergo congruent melting and freezing processes. The inherent Brownian motion, diffusion and surface charge effects of the nanoparticles have a direct influence on improving the thermal conductivity of PCM. In recent times, many research works have been performed to improve the thermal conductivity of PCMs using a variety of nanostructured materials (Parameshwaran et al. 2012). The SEM and TEM images of nanomaterials and PCM embedded with nanomaterials are shown in Fig. 18.

The latent heat of fusion and phase change temperature are the most vital parameters of PCM, which decide its applicability for enabling TES facility in buildings. It is well known that water or ice has the maximum latent heat of enthalpy of 330 kJ/kg K when compared to the conventional organic and other salt hydrate PCMs.

But, the phase change characteristics and supercooling of water or ice resist them from utilizing for short-term TES applications in buildings. Precisely, the doping of nanomaterials in PCM at proper weight proportions may lead to the condition of congruent freezing and melting during phase change.

As the size of the nanoparticles are comparatively larger than the PCM molecules, the presence of individual nanoparticles or a cluster of nanoparticles can act as the nucleation sites for the growth of the ice-like crystals in the PCM during freezing process. Similarly, during the melting process, the nanomaterials efficiently transfer the heat energy absorbed within the PCM matrix, enabling the formation of liquid front in the PCM.

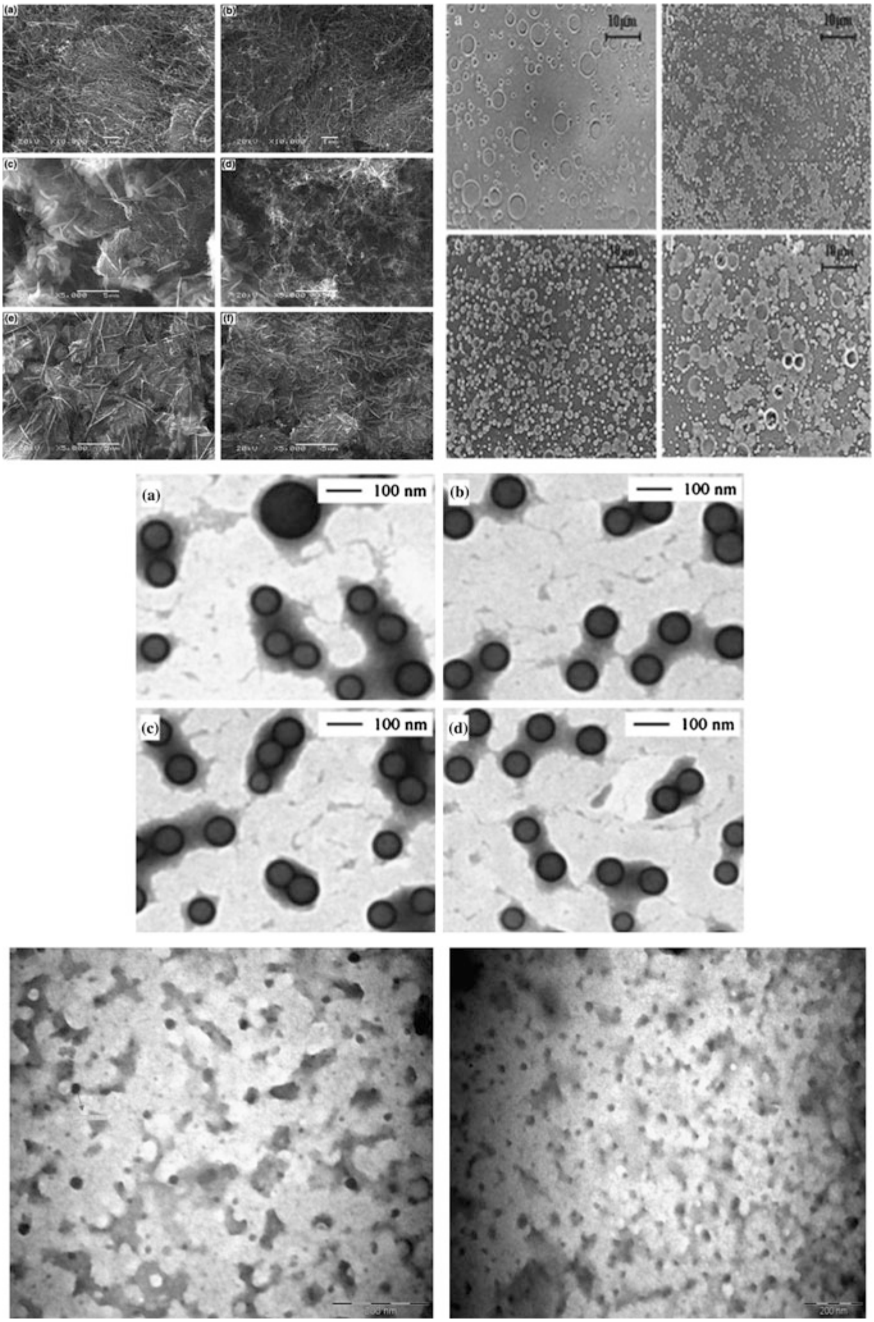


**Fig. 18** SEM and TEM images of nanomaterials and PCM embedded with nanomaterials (Meng et al. 2012; Hu et al. 2013; Chen et al. 2012; Parameshwaran et al. 2013)

The transport of thermal energy inside the PCM can be faster enough with the presence of nanoparticles, by which the rate of heat transfer of PCM is augmented and the energy consumed during charging (freezing) process can be reduced. However, the addition of nanomaterials to the PCM may alter the latent heat of fusion and phase change temperature, but the shift in these parameters has to be kept minimum, which ultimately depends upon the thermophysical aspects of the dispersed nanomaterials.

The term supercooling refers to the temperature drop experienced by the PCM with respect to its phase change temperature during the freezing process. That is, the PCM would still remain in the liquid state even when it is cooled below its freezing point. By supplying the cold energy continuously (activation energy), the PCM would tend to achieve the state of crystallization. The supercooling in PCM would actually lead to the energy consumption, considerably.

In order to reduce the effect of supercooling, various heat enhancement techniques have been proposed widely, in recent years. Of having such methods, the incorporation of nanomaterials has proved to effectually reduce the supercooling in PCMs (Parameshwaran et al. 2013 and Zhang et al. 2012). The fast response exhibited by the nanomaterials towards the change in the heat energy requirements has invariably contributed to the reduced energy consumption with better heat storage and release characteristics of PCMs.

The thermal stability of PCMs is much more important for them to be heat resistant and stable when subjected to elevated temperatures. The thermal stability of PCMs can be increased with the incorporation of nanomaterials that have higher melting temperature. The physical amalgamation of the nanoparticles with the PCM as well as the interbonding linkages of the PCM structure can together contribute to achieving higher temperature of decomposition of PCM.

On the other hand, the nanoparticles can also keep the PCM to be stable enough when tested for several thousand repeated thermal cycles. This may be due to the physical adsorption of nanoparticles with the PCMs or through the capillary action, and the nanoparticles may get into the minute porous structure of the PCMs, thereby giving them a better mechanical strength towards thermal or shock disturbances on the long-term basis.

## 10 Sustainable Aspects of Thermal Energy Storage System

The effective energy redistribution and enhanced energy conservation that can be achievable through the TES systems offer a great potential for gaining the sustainable merits for the new and refurbished buildings. The integration of thermal storage systems with the HVAC systems in buildings can help to shift the on-peak load demand to off-peak conditions as well as minimize the overall primary energy consumption.

The inclusion of the concept of suitable TES technology to satisfy the building energy requirements from the scheme inception to the final construction stages of the building can help to achieve sustainability in every step of the design process.

By combining the renewable energy-based thermal storage systems, the heating or cooling energy demand in buildings can be largely met with, which can serve to maintain the environmental sustainability as well in and around the building envelope and its landscape.

There are several merits that can be realized through the utilization of thermal storage systems, which as prescribed by the Leadership in Energy and Environmental Design (LEED), BREEAM and other internationally recognized organizations, would earn much more ratings for the buildings.

The newly built dwellings or the refurbished constructions that are complete with any of the aforementioned TES system can be designated to be energy efficient based on the credits earned throughout their development process. The points and credits attained by such buildings would help them to reduce the GHG emission per square metre, with an objective of creating a nearly zero-energy building design and sustainable built environment.

## 11 Conclusion

The success in the energy conservation and energy management strongly depends on the ways by which the total energy demand has been matched with the energy supply in buildings. The focus on the value-added technology implementation has a vital role to play at every step of the design and development of building envelopes.

From this perspective, the TES systems offer a wide range of opportunities to bridge the gap between the energy supply and the energy demand in several ways. The TES systems integrated with HVAC system are capable of efficiently shifting, levelling as well as limiting the cooling/heating load demand in buildings.

The acceptable heat storage and release characteristics of the PCMs allow them to be pronounced as potential candidates for the TES systems meant to satisfy the cooling and heating requirements in buildings.

Furthermore, the utilization of efficient and advanced nanomaterials into the latent functional PCMs would pave way for a new venture in meeting out the immediate, intermittent, short-term, long term energy storage and energy security benefits as applied to the newly constructed and the refurbished buildings.

In total, the energy performance of the existing building envelopes can be enhanced with the application of renewable and non-renewable energy-based TES technologies, without losing energy efficiency and environmental sustainability.

## References

Cabeza LF, Castell A, Barreneche C, Gracia AD, Fernández AI (2011) Materials used as PCM in thermal energy storage in buildings: a review. Renew Sustain Energy Rev 15:1675–1695

Caliskan H, Dincer I, Hepbasli A (2012) Energy and exergy analyses of combined thermochemical and sensible thermal energy storage systems for building heating applications. Energy Buildings 48:103–111

Capek I (2004) Preparation of metal nanoparticles in water-in-oil (w/o) microemulsions. Adv Colloid Interface Sci 110:49–74

Chen C, Chen Z, Zeng X, Fang X, Zhang Z (2012) Fabrication and characterization of nanocapsules containing n-dodecanol by miniemulsion polymerization using interfacial redox initiation. Colloid Polym Sci 290:307–314

Dincer I, Rosen MA (2011) Thermal energy storage systems and applications. Wiley, England

Gores JC, Castell A, Cabeza LF (2012) Thermochemical energy storage and conversion: a-state-of-the-art review of the experimental research under practical conditions. Renew Sustain Energy Rev 16:5207–5224

Hu X, Huang Z, Yu X, Li B (2013) Preparation and thermal energy storage of carboxymethyl cellulose-modified nanocapsules. BioEnergy Res. doi:10.1007/s12155-013-9299-2

Jeon J, Lee J-H, Seo J, Jeong S-G, Kim S (2013) Application of PCM thermal energy storage system to reduce building energy consumption. J Therm Anal Calorim 111:279–288

Lemmens B, Desmedt J, Hoes H, Patyn J (2007) Haalbaarheidsstudie naar de toepassing van koude-opslag met recirculatie bij Kaneka te Westerlo, Vlaamse Instelling voor Technologisch Onderzoek, Mol, pp 1–48

Meng X, Zhang H, Sun L, Xu F, Jiao Q, Zhao Z, Zhang J, Zhou H, Sawada Y, Liu Y (2012) Preparation and thermal properties of fatty acids/CNTs composite as shape-stabilized phase change materials. J Therm Anal Calorim. doi:10.1007/s10973-012-2349-8

Mette B, Kerskes H, Drück H (2012) Concepts of long-term thermochemical energy storage for solar thermal applications—selected examples. Energy Procedia 30:321–330

N'Tsoukpoe KE, Liu H, Pierre's NL, Luo L (2009) A review on long-term sorption solar energy storage. Renew Sustain Energy Rev 13:2385–2396

Novo AV, Bayon JR, Fresno DC, Hernandez JR (2010) Review of seasonal heat storage in large basins: water tanks and gravel–water pits. Appl Energy 87:390–397

Parameshwaran R, Harikrishnan S, Kalaiselvam S (2010) Energy efficient PCM-based variable air volume air conditioning system for modern buildings. Energy Buildings 42:1353–1360

Parameshwaran R, Jayavel R, Kalaiselvam S (2013) Study on thermal properties of organic ester phase-change material embedded with silver nanoparticles. J Therm Anal Calorim. doi:10.1007/s10973-013-3064-9

Parameshwaran R, Kalaiselvam S, Harikrishnan S, Elayaperumal A (2012) Sustainable thermal energy storage technologies for buildings: a review. Renew Sustain Energy Rev 16:2394–2433

Pinel P, Cruickshank CA, Morrison IB, Wills A (2011) A review of available methods for seasonal storage of solar thermal energy in residential applications. Renew Sustain Energy Rev 15:3341–3359

Schmidt T, Mangold D, Müller-Steinhagen H (2004) Central solar heating plants with seasonal storage in Germany. Sol Energy 76:165–174

Seaman A, Martin A, Sands J (2000) HVAC thermal storage: practical application and performance issues, BSRIA application guide AG 11

Stitou D, Mazet N, Mauran S (2012) Experimental investigation of a solid/gas thermochemical storage process for solar air-conditioning. Energy 41:261–270

Thermal Ice Storage Application and Design Guide (2007) EVAPCO, Inc., pp 3–66

Thermal storage (2012) ASHRAE handbook—HVAC systems and equipment

Xin W, YinPing Z, Wei X, RuoLang Z, QunLi Z, HongFa D (2009) Review on thermal performance of phase change energy storage building envelope. Chin Sci Bull 54:920–928

Yau YH, Rismanchi B (2012) A review on cool thermal storage technologies and operating strategies. Renew Sustain Energy Rev 16:787–797

Yumrutaş R, Ünsal M (2012) Energy analysis and modeling of a solar assisted house heating system with a heat pump and an underground energy storage tank. Sol Energy 86:983–993

Zhang S, Wu J-Y, Tse C-T, Niu J (2012) Effective dispersion of multiwall carbon nano-tubes in hexadecane through physiochemical modification and decrease of supercooling. Sol Energy Mater Sol Cells 96:124–130

# Phase-Change Materials Use in Nearly Zero Energy Building Refurbishment

**Luisa F. Cabeza and A. Inés Fernández**

**Abstract** Phase-change materials have a very big potential as a tool for energy demand reduction in buildings, and therefore, their use in nearly zero energy buildings refurbishment is clearly an option. Nevertheless, there are little examples where PCM have been used for such application. This chapter shows examples where PCM have been used in research for new buildings, highlighting the more appropriate options for refurbishment.

## 1 Basic Concepts of Phase-Change Materials

The use of storage in a building can smooth temperature fluctuation (Cabeza et al. 2011; Mehling and Cabeza 2007). Thermal energy storage in buildings can be implemented by sensible heat (increasing and decreasing the temperature of the building envelopes, for example), or by latent heat (with the inclusion of phase-change materials—PCM—to increase thermal inertia). The main advantage of latent heat storage is the high storage density in small temperature intervals. Latent storage can be used for heating and for cooling of buildings, and it can be incorporated as a passive system or also in active systems.

Upon melting, while heat is transferred to the storage material, the material still keeps its temperature constant at the melting temperature, also called phase-

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change temperature (Cabeza 2012). Usually, the solid/liquid phase change is studied. The amount of heat stored can be calculated by:

$$Q = m * \Delta h \tag{1}$$

where $\Delta h$ is the phase-change enthalpy, also called melting enthalpy or heat of fusion, and $m$ is the mass of storage material.

# 2 Materials

## 2.1 Phase-Change Materials

Phase-change materials must have a large latent heat and high thermal conductivity, but the most important selection parameter is that the melting temperature of the materials lies in the practical range of operation. Other parameters are congruent melting, minimum subcooling, chemical stability, low in cost, non-toxicity and non-corrosivity. Materials that have been studied are paraffin waxes, fatty acids, and eutectics of organic and non-organic compounds (Farid et al. 2004; Sharma et al. 2009). Tables 1 and 2 show a comparison between organic and inorganic PCM (Mehling and Cabeza 2008; Rathod and Banerjee 2013; Zalba et al. 2003).

According to Kenisarin and Mahkamov (2007), the following phase-change material (PCM) properties to be used for latent heat storage were highlighted as desirable:

- a high value of the heat of fusion and specific heat per unit volume and weight,
- a melting point which matches the application,
- a low vapour pressure (<1 bar) at the operational temperature,
- a chemical stability and non-corrosiveness,
- not to be hazardous, highly inflammable or poisonous,
- a reproducible crystallisation without degradation,
- a small subcooling degree and high rate of crystal growth,

**Table 1** Comparison of organic and inorganic materials for heat storage (Mehling and Cabeza 2008; Zalba et al. 2003)

| | Organic | Inorganic |
|---|---|---|
| Advantages | No corrosives<br>Low or none subcooling<br>Chemical stability | Greater phase-change enthalpy |
| Disadvantages | Lower phase-change enthalpy<br>Low thermal conductivity<br>Flammability | Subcooling<br>Corrosion<br>Phase separation<br>Phase segregation, lack of thermal stability |

**Table 2** Comparison of PCM types (Adapted from Rathod and Banerjee 2013)

| | Organic | | Inorganic | | Eutectics |
|---|---|---|---|---|---|
| | Paraffins | Fatty acids | Salt hydrates | Metals | |
| Formula | $C_nH_{2n+2}$ ($n = 12$–$38$) | $CH_3(CH_2)\cdot COOH$ | $AB\cdot nH_2O$ | – | – |
| Melting point | −12–71 °C | 7.8–187 °C | 11–120 °C | 30–96 °C | 4–93 °C |
| Melting enthalpy | 190–260 kJ/kg | 130–250 kJ/kg | 100–200 kJ/kg | 25–90 kJ/kg | 100–230 kJ/kg |
| Cost | Expensive | 2 to 3 times more expensive than paraffins | Low cost | Costly | Costly |

- a small volume variation during solidification,
- a high thermal conductivity, and
- availability and abundance.

Paraffins are a mixture of pure alkanes that have quite a wide range of the phase-change temperature. These paraffins also have low thermal conductivity compared to inorganic materials, and therefore. the choice of those which can be used for practical solar applications are very limited.

Commercial paraffin waxes are cheap with moderate thermal storage densities (~200 kJ/kg or 150 MJ/$m^3$) and a wide range of melting temperatures. They undergo negligible subcooling and are chemically inert and stable with no phase segregation. However, they have low thermal conductivity (~0.2 W/m °C), which limits their applications.

The main limitation of salt hydrates is their chemical instability when they are heated, as at elevated temperatures they degrade, losing some water content every heating cycle. Furthermore, some salts are chemically aggressive towards structural materials, and they have low heat conductivity. Finally, salt hydrates have a relatively high degree of subcooling.

Salt hydrates are attractive materials for use in thermal energy storage due to their high volumetric storage density (~350 MJ/$m^3$), relatively high thermal conductivity compared to organic materials (~0.5 W/m °C), and moderate costs compared to paraffin waxes, with few exceptions.

According to Cabeza et al. (2011), the PCM to be used in the design of a thermal storage system should have desirable thermophysical, kinetic and chemical properties and desired economics as listed below:

1. Thermophysical properties
   - Melting temperature in the desired operating temperature range: to assure storage and extraction of heat in an application with a fixed temperature range.
   - High latent heat of fusion per unit volume: to achieve high storage density compared to sensible storage.

- High specific heat to provide additional significant sensible heat storage.
- High thermal conductivity of both solid and liquid phases to assist the charging and discharging energy of the storage system.
- Small volume change on phase transformation and small vapour pressure at operating temperature to reduce the containment problem.
- Congruent melting of the phase-change material for a constant storage capacity of the material with each freezing/melting cycle.
- Reproducible phase change: to use the storage material many times (also called cycling stability).

2. Kinetic properties—nucleation and crystal growth
    - High nucleation rate to avoid super cooling of the liquid phase and to assure that melting and solidification proceed at the same temperature.
    - High rate of crystal growth, so that the system can meet demand of heat recovery from the storage system.
3. Chemical properties
    - Complete reversible freeze/melt cycle.
    - No degradation after a large number of freeze/melt cycle.
    - No corrosiveness to the construction materials.
    - Non-toxic, non-flammable and non-explosive material for safety: for environmental and safety reasons.
4. Economics
    - Abundant.
    - Available.
    - Cost effective: to be competitive with other options for heat and cold storage.

For their use, PCM must be encapsulated, either encapsulating the material or encapsulating the building composite, as otherwise the liquid phase would be able to flow away from the location where it is applied.

Encapsulation is carried out either by microencapsulation, where small, spherical or rod-shaped particles are enclosed in a thin, high molecular weight polymer film; or by macroencapsulation, where the PCM is in some form of package such as tubes, pouches, spheres, panels or other receptacle (Cabeza et al. 2011). On the other hand, in shape-stabilised PCM the storage material is included in an unsaturated polyester matrix or integrated with the building materials without encapsulation (Farid et al. 2004; Zhu et al. 2009).

## 2.2 Microencapsulated PCM

Nowadays, microencapsulation technology is the prominent for use of PCM in building materials. With the advent of PCM implemented in gypsum board, plaster, concrete and/or other wall covering materials, thermal storage can be part of the building structure even for light weight buildings (Tyagi et al. 2011;

Zhao and Zhang 2011). Several forms of bulk encapsulated PCMs have been developed for active and passive solar applications in building including direct heat gain. However, the surface area of most encapsulated commercial products has been inadequate to deliver heat to the building after the PCM melted by direct solar radiation. One problem to solve in some PCM applications is the liquid migration, using some kinds of packing.

Microcapsules consist of little containers, which pack a core material with a hard shell. Microencapsulating PCM brings some more important advantages like that microcapsules can handle phase-change materials as core, as far as, they tolerate volume changes.

The microencapsulated phase-change material is defined as composing of phase-change materials (PCMs) core and a polymer or inorganic shell to maintain the shape and prevent PCM from leakage during the phase-change process. Microencapsulated phase-change material overcomes the following problems in comparison with the convectional PCM: corrosive to metal, decomposition, subcooling and leakage.

## *2.3 Phase-Change Slurries*

Recently, a new technique has been proposed to use phase-change materials in thermal storage systems, heat exchangers and thermal control systems. This new technique consists of forming a two-phase fluid, from the mixture of a fluid, such as water, and a phase-change material, such as paraffin, resulting in a latent heat storage fluid (Delgado et al. 2012; Youssef et al. 2013; Chen and Fang 2011; Zhang and Ma 2012; Zhang et al. 2010).

Among the latent thermal fluids, five types of fluids are mentioned:

1. ice slurries;
2. Phase-change material microemulsions, in which the PCM is dispersed in water through an emulsifying agent;
3. microencapsulated PCM slurries, where the PCM is microencapsulated in a polymeric capsule and dispersed in water;
4. clathrate hydrate PCM slurries, where the clathrate hydrates are composed of water molecules (host molecule) forming a weaved structure where the molecules of the other substance (guest molecule) are accommodated, constituting a special molecular structure where the heat associated with the chemical reaction of formation and dissociation of clathrate hydrate is greater than that of ice melting; and
5. shape-stabilised PCM slurries (ssPCM slurries), based on ssPCM, these can consist of paraffin infiltrated in high-density polyethylene, with a melting temperature higher than of the paraffin. In this way, the paraffin is retained inside the structure of high-density polyethylene, avoiding the leak of the PCM. Figure 1 shows a schematic draw of the different types of PCM slurries, although the case of clathrate hydrate PCM slurries does not appear drawn.

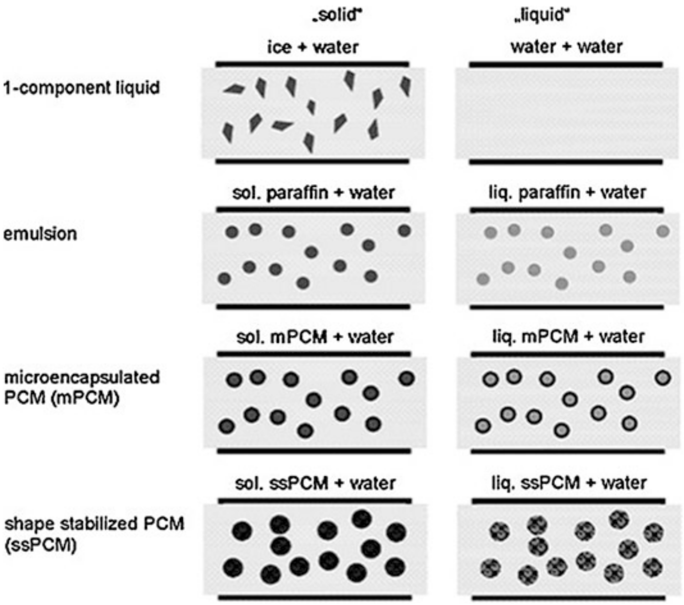

**Fig. 1** Schematic drawing of the different types of slurries (Delgado et al. 2012)

# 3 Use of PCM in Nearly Zero Energy Building Refurbishment

Although there is a tremendous amount of research and publications in the field of phase-change materials in building applications, specific focus on refurbishment cannot be found in the literature. Nevertheless, most of the concepts studied can be used in nearly zero energy building refurbishment. Such approach is assessed here.

Storage concepts have been classified as active or passive systems (Cabeza 2012). An active storage system is mainly characterised by forced convection heat transfer into the storage material. The storage medium itself circulates through a heat exchanger (the heat exchanger can also be a solar receiver or a steam generator). This system uses one or two tanks as storage media. Active systems are subdivided into direct and indirect systems. In a direct system, the HTF serves also as the storage medium, while in an indirect system, a second medium is used for storing the heat. Passive storage systems are generally dual-medium storage systems: the HTF passes through the storage only for charging and discharging a solid material.

## *3.1 Passive Systems*

Passive use of PCM in nearly zero energy buildings would have the objective to decrease the operation energy of the building by decreasing the energy demand of space heating and cooling, basically smoothing the indoor temperature by increasing the energy inertia of the building envelope. When refurbishment, the system considered in passive systems has to be evaluated on its ability to be included in the refurbishment carried out, that is, for example, the use of PCM incorporated in walls would only be possible either if major refurbishment is carried out, where complete walls are substituted, or by the addition of building elements in already existing walls, such as gypsum boards including PCM. On the other hand, it is true that in some refurbishments carried out, the use of PCM could only be the only possibility for drastic energy refurbishment, since the scarcity of space is a real problem in such actions and the energy density of PCM can be an advantage.

One of the oldest options studied and published were PCM wallboards to improve the thermal comfort of lightweight buildings (Sharma et al. 2009), since they are very suitable for the incorporation of PCM (Soares et al. 2013). The efficiency of these elements depends on several factors such as:

1. how the PCM is incorporated in the wallboard;
2. the orientation of the wall;
3. climatic conditions;
4. direct solar gains;
5. internal gains;
6. colour of the surface;
7. ventilation rate;
8. the PCM chosen and its phase-change temperature;
9. the temperature range over which phase change occurs; and
10. the latent heat capacity per unit area of the wall.

The PCM can be added impregnated to the building materials, Schossig et al. (2005) showed that but when added microencapsulated leakage problems are overdue (Fig. 2).

An example of the use of PCM in wallboards was de development of the Dupont product Energain, studied and characterised in several papers (Kuznik et al. 2008a, b, 2011; Kuznik and Virgone 2009). Kuznik et al. (2008a) performed an optimisation process using interior/exterior temperature evolutions within a period of 24 h to optimise the thickness of a PCM wallboard to enhance the thermal behaviour of a lightweight internal partition wall. The PCM wallboard was composed of 60 wt% of microencapsulated paraffin, which has a melting temperature of about 22 °C (Fig. 3). The optimal thickness found was 1 cm. This 1 cm wallboard allows a doubling of the thermal inertia of the building. Kuznik et al. (2008b) carried out an experimental research in a full-scale test cell under controlled thermal and radiative effects, to evaluate the performance of walls, with and without PCMs, during a summer day. The authors used the same PCM composite of Fig. 3 to show that PCM wallboard reduces the air temperature fluctuations in the room and the overheating effect. The authors also concluded that the available storage energy is twice higher with 5 mm of PCM wallboard,

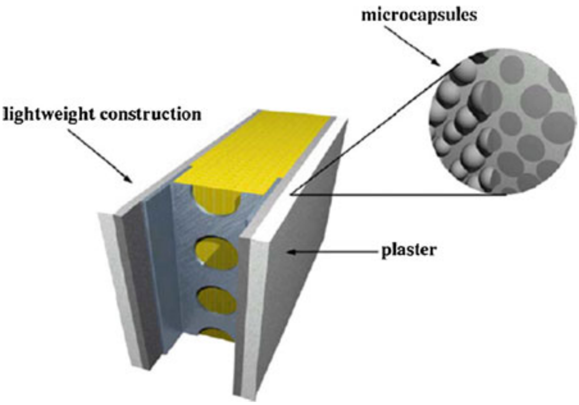

**Fig. 2** Addition of microencapsulated PCM in a lightweight building (Schossig et al. 2005)

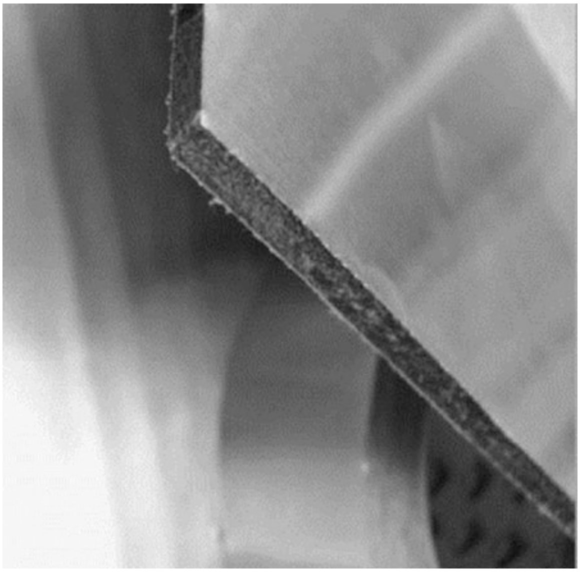

**Fig. 3** Dupont PCM composite wallboard (Kuznik et al. 2008a)

which corresponds to an equivalent concrete layer of about 8 cm. Kuznik and Virgone (2009) carried out a comparative study, using cubical test cells, with and without PCM composite, to provide experimental data that can be used for validation of numerical modelling and then, studying some features related to the use of the PCM wallboard. The effect of hysteresis phenomenon was clearly exhibited with the experimental data, and the authors concluded that the hysteresis phenomenon must be taken into account correctly in numerical modelling, in order to predict the real thermal behaviour of the construction element. In order to really assess the potential of a PCM wallboard constituted of 60 wt% of microencapsulated paraffin within a copolymer (the melting and freezing temperatures are

13.6–23.5 °C, respectively), a renovated office building in Lyon was monitored during one year by Kuznik et al. (2011). A room was equipped with PCM wallboards in the lateral walls and in the ceiling, and another room, identical to the first one, was not equipped but also monitored. The results showed that the PCM wallboards enhance the thermal comfort of occupants due to air temperature and radiative effects of the walls.

Mandilaras et al. (2013) present one of the first attempts to investigate the thermal performance of a purposely built full-scale lightweight demo house constructed in Greece which includes PCM gypsum boards in all external walls as well as in internal partitions of the building (Figs. 4 and 5). Experimental results show that the indoor air temperatures in all thermal zones examined (LVR, MBDR, BDR) do not significantly vary during a 24-h day/night cycle and this can be attributed to the house's enhanced thermal mass associated with the insulation, as well as with the absence of a typical occupant behaviour.

The use of PCM in building envelopes has been demonstrated in a long-term experimental study at the University of Lleida (Spain). Here, different forms of PCM have been tested in a pilot plant (Fig. 6) in several identically shaped cubicles with internal dimensions of 2.4 m × 2.4 m × 2.4 m. The cubicles were built using different typical constructive solutions so concrete cubicles (Cabeza et al. 2007), brick cubicles and alveolar brick cubicles (Castell et al. 2010) can be found.

Two different experiments were performed in the experimental set-up:

- Free-floating temperature, where no cooling system is used. The temperature conditions inside the cubicles are compared. The ones with PCM are expected to have a better behaviour.
- Controlled temperature, where a heat pump or an electric oil radiator is used to set a constant ambient temperature inside the cubicle. The energy consumption of the cubicles is compared. The cubicles using PCM are expected to have lower energy consumptions.

**Fig. 4** External view of a demo house including PCM wallboards (Mandilaras et al. 2013)

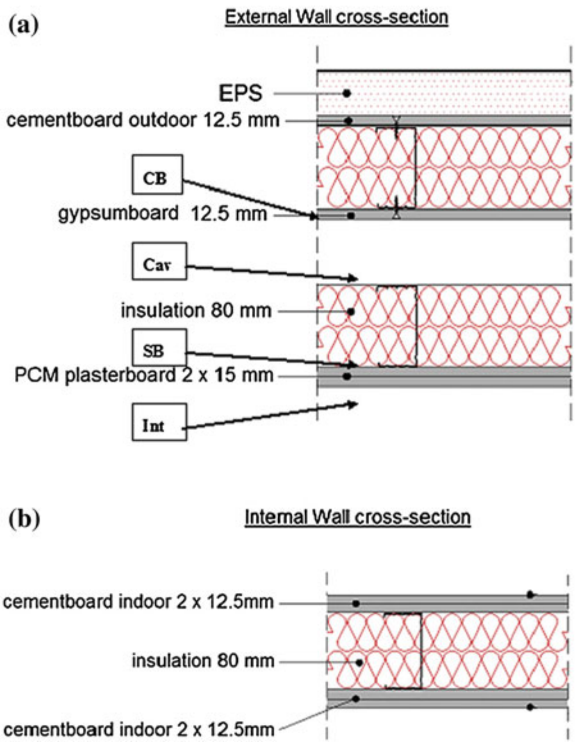

**Fig. 5** Cross section of: **a** The external wall (‘CB’, ‘Cav’, ‘SB’, ‘Int’ correspond to temperature sensors placed in the LVR east wall). **b** The partition wall with cement boards (Mandilaras et al. 2013)

Castellón et al. (2009) show different results of this experimental set-up. As an example results from the brick cubicles are shown here. Figure 7 present the results for free-floating experiments in the brick cubicles, comparing the Reference, PU and RT27+PU cubicles during a week in August 2008, when the PCM is working within the phase-change range. As expected, the Reference cubicle always presents higher temperature oscillations and it is also more sensitive to the ambient temperature changes than the PU and RT27+PU cubicles.

When comparing the PU and the RT27+PU cubicles, the temperature control achieved by the use of PCM is observed. The temperature of the RT27+PU cubicle remains closer to the phase-change range. The RT27+PU cubicle remains cooler (about 0.4 °C) during most part of the week, when the weather is warmer. At the end of the week (when the weather is cooler), the tendency is reversed, with the PU cubicle being cooler than the RT27+PU cubicle. This behaviour can be explained due to the higher thermal mass of the PCM cubicle, which slows down the general cooling tendency that occurs in the last days of the week. The effect of the PCM is also visible in the reduction in the daily oscillations of the inside temperature in the RT27+PU cubicle. It is also observed that the effect of the PCM is only partially used, as there is no single 24-h period in which full melting and solidification are achieved.

**Fig. 6** Experimental set-up located in Puigverd de Lleida, Spain (Castell et al. 2010)

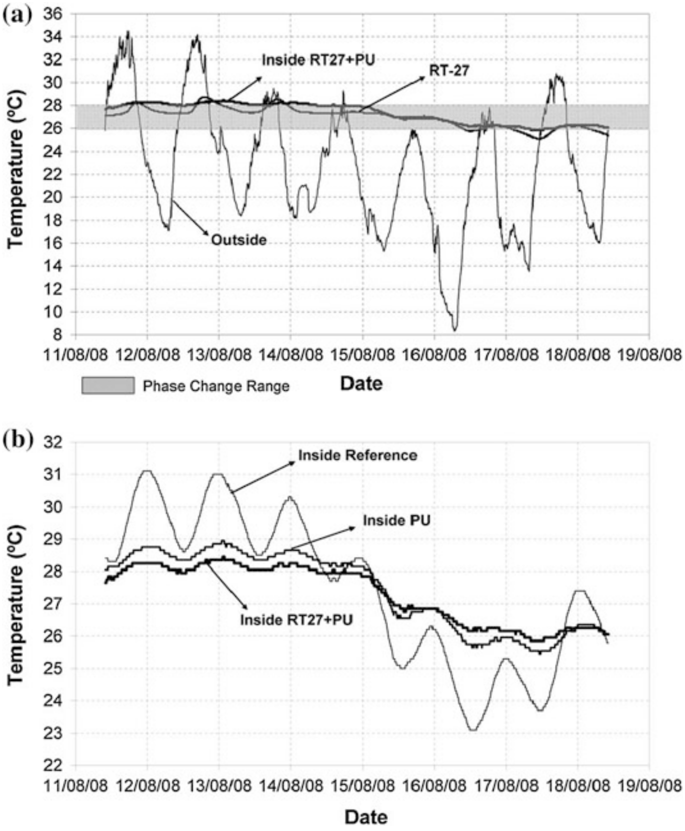

**Fig. 7** Brick cubicles free-floating experimentation: **a** Weather conditions and PCM operating temperature, **b** Indoors ambient temperature for reference, PU, and RT27+PU cubicles (Castellón et al. 2009)

Figure 8 presents the results for free-floating experiments in the Alveolar and SP25+Alveolar cubicles during a week in August of 2007 when the PCM is working within the phase-change range.

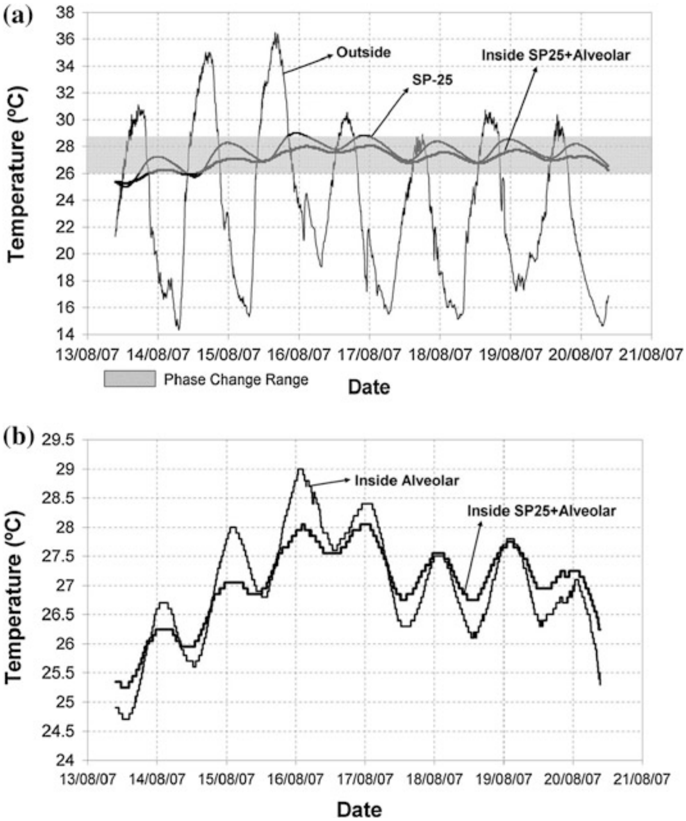

**Fig. 8** Alveolar cubicles free-floating experimentation: **a** Weather conditions and PCM operating temperature. **b** Indoors ambient temperature for Alveolar and SP25+Alveolar cubicles (Castellón et al. 2009)

The effect of the PCM is clearly visible, resulting in lower temperature variations in the SP25+Alveolar cubicle than in the Alveolar one. The maximum and minimum temperature peaks inside the cubicle are reduced, especially at the beginning of the week. The melting of the PCM during the day results in less thermal energy entering the cubicle, since it is stored in the walls. When the PCM is working at the phase-change temperature, even with significant fluctuations in its temperature (due to the complete melting), the inside temperature of the SP25+Alveolar cubicle remains more constant than that of the Alveolar.

Again, it is observed that the regeneration of the PCM during the night is only partially accomplished, as PCM temperature never goes below the 26 °C limit. To improve the results in a real building, some kind of ventilation, either natural or mechanical, should be used to favour the cool down of the PCM during the night. Unfortunately, this test of night cooling could not be done as these cubicles had no windows. The absence of windows was decided to make the cubicles as similar as possible, and to reduce the risk of different thermal behaviours in each cubicle due to slight variations in the thermal bridges, infiltrations, etc., that are inevitable in the manual process of mounting a window.

Figure 9 and Table 3 present the results of the controlled temperature experiments using a set point of 24 °C for a week in August of 2008. The accumulated energy consumption of the Reference cubicle is by large higher than all the other cubicles, with about twice the consumption of the other cubicles. The RT27+PU cubicle is the one with the lowest energy consumption while the SP25+Alveolar cubicle is the second one, consuming even less energy than the PU cubicle. Finally, the Alveolar cubicle is the one that consumes more energy after the Reference cubicle.

Both PCM cubicles reduced the energy consumption compared with the same cubicle without PCM. The RT27+PU cubicle achieved a reduction of 14.75 % compared with the PU cubicle, while the SP25+Alveolar cubicle reached 17.12 % of energy savings compared with the Alveolar cubicle (Table 3). These are considerable energy consumption reductions, which show the synergistic effect of combining thermal insulation with increased thermal inertia due to the PCM inclusion. Furthermore, these savings may be higher, as several aspects of the PCM benefits are not optimised. On the one hand, for optimal PCM behaviour, the set point should be equal to the PCM phase-change temperature and, in this case, should be between 2 and 4 °C lower (or said in other words, the selected PCM has a rather high melting point for the desired comfort conditions in the summer period). On the other hand, a complete recharging of the PCM during the night is needed so it can absorb the maximum heat at day hours, and this is only partially the case in most of the days, as explained before.

One option is to add PCM in Trombe walls; several authors have proposed the inclusion of PCM in walls (Sharma at al. 2009). The most recent development in this topic is the use of PCM in ventilated façades presented by de Gracia et al. (2013a, b and c). These authors studied experimentally (Fig. 10) and by simulation the thermal performance of a ventilated facade double skin facade (DSF) with PCM in its air channel. The studies in the heating season (winter) showed that this concept reduces significantly the electrical energy consumptions of the installed HVAC systems, but these savings depend strongly on the mode of operation and the weather conditions.

## *3.2 Active Systems*

Active systems using PCM in nearly zero energy buildings would have the aim to decrease the operational energy of the building by decreasing the use of fossil fuels in heating, cooling and domestic hot-water production. Again, some systems can only be included in refurbishment if major works are carried out.

In solar water heating systems, the use of PCM can be an advantage since the volume of the necessary water storage tank can be decreased (Cabeza et al. 2006).

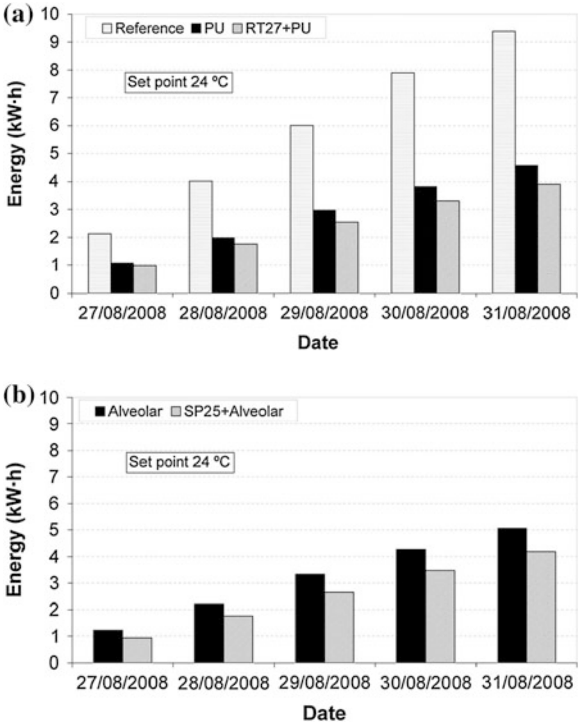

**Fig. 9** Energy consumption of the heat pumps in cooling mode for 5 days in August 2008: **a** Reference, PU, and RT27+PU. **b** Alveolar and SP25+Alveolar cubicles (Castellón et al. 2009)

**Table 3** Accumulated energy consumption and energy savings for the different cubicles

| | Energy consumption (Wh)[a] | Energy savings (Wh)[b] | Energy savings (%)[b] | Improvement (%)[c] |
|---|---|---|---|---|
| Reference | 9,376 | 0 | 0 | – |
| PU | 4,583 | 4,793 | 51.1 | 0 |
| RT27+PU | 3,907 | 5,469 | 58.3 | 14.8 |
| Alveolar | 5,053 | 4,323 | 46.1 | 0 |
| SP25+Alveolar | 4,188 | 5,188 | 55.3 | 17.1 |

*Notes* [a] Set point of 24 °C for 5 days
[b] Refer to the reference cubicle
[c] Refer to the cubicle with analogue constructive solution and w/o PCM

The PCM module geometry adopted in this study was to use several cylinders at the top of the water tank. A granular PCM–graphite compound of about 90 vol.% of sodium acetate trihydrate and 10 vol.% graphite was chosen as the PCM for the experiments presented here. The experiments presented in this paper showed that the inclusion of a PCM module in water tanks for domestic hot-water supply is a very promising technology. It would allow having hot-water for longer periods of time even without exterior energy supply, or to use smaller tanks for the same purpose.

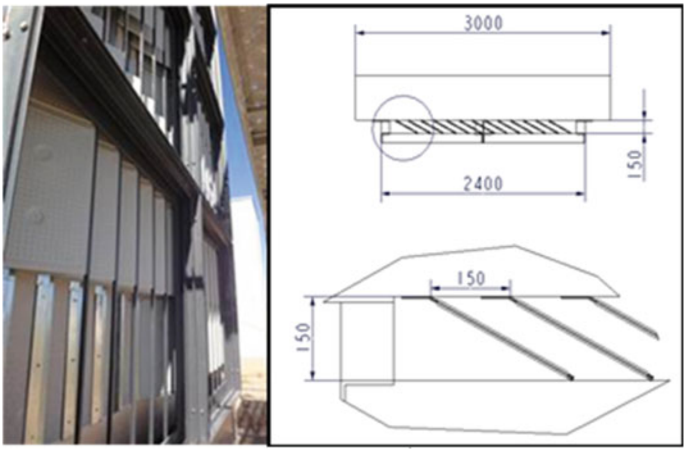

**Fig. 10** PCM distribution inside the air chamber (de Gracia et al. 2013a)

Athienities and Chen (2000) showed the possibility of using PCM in underfloor heating systems. The idea is the use of a radiant heating system but with increased performance due to the inclusion of PCM. The costs have been shown to be reduced if the PCM is used with electrically heated underfloor systems due to the reduction of peak loads and to the use of cheaper night electricity. Similarly, Nagano et al. (2000) presented a floor air conditioning system with latent heat storage in buildings. Floor size of the experimental cell was 0.5 m$^2$. Granulated

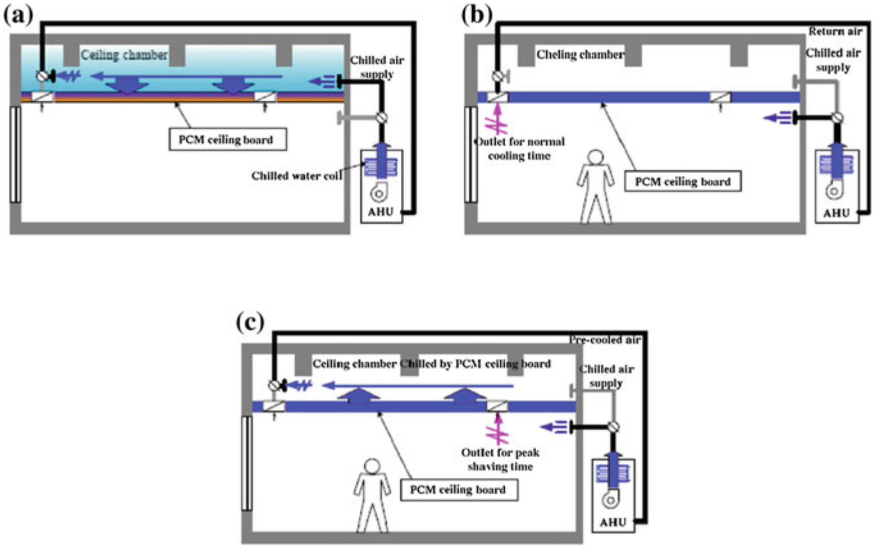

**Fig. 11** Ceiling board with PCM for cooling peak shaving (Kodo and Ibamoto 2002). **a** Overnight thermal storage time. **b** Normal cooling time. **c** Peak shaving control time

phase-change material was made of foamed waste glass beads and mixture of paraffin. The PCM packed bed of 3 cm thickness was installed under the floorboard with multiple small holes. The change in room temperature and the amount of stored heat were measured, and results showed the possibilities of cooling load shifting by using packed granulated PCM.

Also ceiling boards can incorporate PCM for heating and cooling of buildings. An example is that developed by Kodo and Ibamoto 2002, where PCM is used for peak shaving control of air conditioning systems in an office building (Fig. 11). Authors claim that these systems have some advantages over conventional building thermal storage systems that use concrete floor slabs:

1. More efficient thermal storage is expected, since high-density cool air pools on the PCM ceiling board that forms the floor of the ceiling space.
2. All of the ceiling board can be used for thermal storage, since the cool air can flow through the ceiling chamber without being interrupted by beams.
3. Since the surface temperature of the ceiling board is kept at the PCM melting point for an extended period, the indoor thermal environment, including the radiant field, can be improved.

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## References

Athienities A, Chen Y (2000) The effect of solar radiation on dynamic thermal performance of floor heating systems. Sol Energy 69(3):229–237

Cabeza LF (2012) Thermal energy storage. In: Sayigh A (ed) Comprehensive renewable energy, vol 3. Elsevier, Oxford, pp 211–253

Cabeza LF, Ibáñez M, Solé C, Roca J, Nogués M (2006) Experimentation with a water tank including a PCM module. Sol Energy Mater Sol Cells 90:1273–1282

Cabeza LF, Castellón C, Nogués M, Medrano M, Leppers R, Zubillaga O (2007) Use of microencapsulated PCM in concrete walls for energy savings. Energ Build 39:113–119

Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI (2011) Materials used as PCM in thermal energy storage in buildings: a review. Renew Sustain Energy Rev 15:1675–1695

Castell A, Medrano M, Martorell I, Pérez G, Cabeza LF (2010) Experimental study of using PCM in brick constructive solutions for passive cooling. Energ Build 42:534–540

Castellón C, Castell A, Medrano M, Martorell I, Cabeza LF (2009) Experimental study of PCM inclusion in different buildings envelopes. J Sol Energ Eng, 131:041006-1–041006-6

Chen Z, Fang G (2011) Preparation and heat transfer characteristics of microencapsulated phase change material slurry: a review. Renew Sustain Energ Rev 15:4624–4632

de Gracia A, Navarro L, Castell A, Ruiz-Pardo A, Álvarez S, Cabeza LF (2013a) Experimental study of a ventilated facade with PCM during winter period. Energ Build 58:324–332

de Gracia A, Navarro L, Castell A, Ruiz-Pardo A, Álvarez S, Cabeza LF (2013) Thermal analysis of a ventilated facade with PCM for cooling applications. Energ Build (in press)

de Gracia A, Navarro L, Castell A, Cabeza LF (2013) Numerical analysis of a ventilated facade with PCM. Appl Therm Eng (in press)

Delgado M, Lázaro A, Mazo J, Zalba B (2012) Review on phase change material emulsions and microencapsulated phase change material slurries: materials, heat transfer studies and applications. Renew Sustain Energ Rev 16:253–273

Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S (2004) A review on phase change energy storage: materials and applications. Energy Convers Manage 45:1597–1615

Kenisarin M, Mahkamov K (2007) Solar energy storage using phase change materials. Renew Sustain Energ Rev 11:1913–1965

Kodo T, Ibamoto T (2002) Research on using the PCM for ceiling board, IEA ECES IA, Annex 17, 3rd workshop. Tokyo, Japan, 1–2Oct

Kuznik F, Virgone J (2009) Experimental investigation of wallboard containing phase change material: data for validation of numerical modelling. Energ Build 41:561–570

Kuznik F, Virgone J, Noel J (2008a) Optimization of a phase change material wallboard for building use. Appl Therm Eng 28:1291–1298

Kuznik F, Virgone J, Roux JJ (2008b) Energetic efficiency of room wall containing PCM wallboard: a full-scale experimental investigation. Energ Build 40:148–156

Kuznik F, Virgone J, Johannes K (2011) In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. Renew Energ 36:1458–1462

Mandilaras I, Stamatiadou M, Katsourinis D, Zannis G, Founti M (2013) Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls. Build Environ 61:93–103

Mehling H, Cabeza LF (2007) Phase change materials and their basic properties. In: Paksoy HO (ed) Thermal energy storage for sustainable energy consumption: fundamentals, case studies and design. Kluwer Academic Publishers Group, pp 257–278

Mehling H, Cabeza LF (2008) Heat and cold storage with PCM. An up to date introduction into basics and applications. Springer, USA

Nagano K, Mochida T, Iwata K, Hiroyoshi H, Domanski R, Rebow M (2000) Development of new PCM for TES of the cooling system, Terrastock. In: Benner M, Hahne EWP (eds) 8th international conference on thermal energy storage, pp 345–50

Rathod MK, Banerjee J (2013) Thermal stability of phase change materials used in latent heat energy storage systems: a review. Renew Sustain Energy Rev 18:246–258

Schossig P, Henning H-M, Gschwander S, Haussmann T (2005) Micro-encapsulated phase-change materials integrated into construction materials. Sol Energ Mater Sol Cells 89:297–306

Sharma A, Tyagi VV, Chen CR, Buddhi D (2009) Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 13:318–345

Soares N, Costa JJ, Gaspar AR, Santos P (2013) Review of passive PCM latent termal energy storage systems towards buildings' energy efficiency. Energ Build 201(59):82–10

Tyagi VV, Kaushik SC, Tyagi SK, Akiyama T (2011) Development of phase change materials based microencapsulated technology for buildings: a review. Renew Sustain Energy Rev 15:1373–1391

Youssef Z, Delahaye A, Huang L, Trinquet F, Fournaison L, Pollerberg C, Doetsch C (2013) State of the art on phase change material slurries. Energy Convers Manage 65:120–132

Zalba B, Marín JM, Cabeza LF, Mehling H (2003) Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Therm Eng 23:251–283

Zhang P, Ma ZW (2012) An overview of fundamental studies and applications of phase change material slurries to secondary loop refrigeration and air conditioning systems. Renew Sustain Energy Rev 16:5021–5058

Zhang P, Ma ZW, Wang RZ (2010) An overview of phase change material slurries: MPCS and CHS. Renew Sustain Energy Rev 14:598–614

Zhao CY, Zhang GH (2011) Review on microencapsulated phase change materials (MEPCMs): Fabrication, characterization and applications. Renew Sustain Energy Rev 15:3813–3832

Zhu N, Ma Z, Wang S (2009) Dynamic characteristics and energy performance of buildings using phase change materials: a review. Energy Convers Manage 50:3169–3181

# Nanogel Windows

**Cinzia Buratti and Elisa Moretti**

**Abstract** This chapter deals with the application of highly energy-efficient windows and skylights with silica nanogel as a strategy in the building refurbishment. Aerogel windows seem to have the largest potential for improving the thermal performance and daylight in fenestration industry, because of very low conductivity, density, and a good optical transparency. A state-of-the-art review of nanogel windows in building applications is firstly presented. Then, the proprieties of nanogel glazings in terms of thermal, lighting, and acoustic insulation solutions are discussed. Finally, the potential of the nanogel windows for energy saving in order to achieve a nearly zero-energy building is described, thanks to the results of a case study.

## 1 Introduction

In developed countries, a lot of buildings are constructed before 1970: they demand high energy, due to outdated heat production systems and insufficient insulation of the envelope. Many of these buildings will not be demolished and rebuilt in the near future, so retrofit would be more efficient in terms of energy saving, emissions reduction, and sustainability; moreover, the indoor comfort conditions could be improved.

Glass façades have an important role in buildings, both for daylighting and thermal comfort. In highly glazed buildings, the energy demand is greater than the one for buildings with conventional façades, since the glazing systems have thermal performance lower than opaque walls and are influenced by radiation.

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Buildings dated before 1970 usually do not have very large windows, but their performance in terms of thermal insulation is generally very poor (Peréz-Lombard et al. 2008; Sadinemi et al. 2011). Thermal and solar transmittance, light transmission, and finally size and orientation of windows are very important in the energy use in building (Oral et al. 2004; Hassounehn et al. 2010). In particular, in the refurbishment of buildings, windows should be substituted with innovative glazing systems (AbuBakr Bahaj et al. 2008). Aerogel is one of the more promising materials for use in highly energy-efficient windows: innovative glazing systems with silica aerogel in interspace were investigated as a solution for energy saving (Jelle et al. 2012; Koebel et al. 2012; Ivanov et al. 2010). Aerogel is a highly porous nanostructured and light material, with a very low thermal conductivity (down to 0.010 W/m K). Granular translucent and transparent monolithic silica aerogels were developed as insulation materials for windows: advanced glazing systems with monolithic aerogel in the interspace are not yet used in mass production; nevertheless, many daylighting systems with translucent granular aerogels in interspace, such as polycarbonate panels, structural panels for continuous façades, and insulated glasses, are spreading on the market (Baetens et al. 2011; Rigacci et al. 2004).

The chapter reviews the applications of aerogels in buildings as thermal and acoustic insulation materials: the potential of nanogel windows for refurbishment of buildings and the main future research trends are discussed.

## 2 Silica Aerogels: State of Art

### 2.1 General Overview

Aerogel is a special solid material with nanometre-scale pores and an extremely low density when compared with other solids. The porosity is higher than 90 %, and it can reach 99 % (Riffat and Qiu 2012). Usually, it is described by the term 'frozen smoke' because of its appearance (Fig. 1).

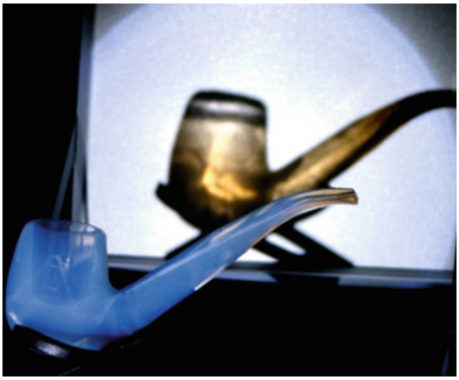


**Fig. 1** 'This is not (the smoke of) a pipe: Silica-aerogel-based sculpture realized by the artist Iannis MICHALOU (di) S (photograph and copyright: MICHALOUS, 1/2008)

Aerogel was discovered by Kistler 80 years ago (Kistler 1931), and it is a dried gel often obtained by means of a very complex synthesis in supercritical drying conditions. The obtained structure (a cross-linked internal structure of silicon dioxide ($SiO_2$) chains and a large number of very small air-filled pores) is extremely light with significant physical, thermal, optical, and acoustic properties, depending on both the silica source and the preparation process. Aerogel has the lowest thermal conductivity among solid materials (down to 0.010 W/m K at room temperature, depending on the pressure).

Aerogels are applied in several fields (Akimov 2003; Baetens et al. 2011; Aegenter et al. 2011; Pierre and Pajonk 2002): microelectronics, electrical engineering, acoustics, oil and gas pipelines insulation, and finally space exploration (aerogel is in fact used as thermal insulation material in US spacecrafts). Moreover, because of the extraordinary properties, nowadays, aerogels are the most promising materials in the market of building insulation. In this field, different types of aerogels were developed (Fig. 2):

1. opaque aerogels, such as aerogel blankets, that could be used to reduce thermal bridges in the building envelope, or additives for high thermal performance coatings. The flexible blankets are obtained by adding fibres in the gel before the drying process (Cabot Corporation, Boston, MA, USA; Aspen Aerogels Inc., Northborough, MA, USA); the thermal conductivity is about 0.013 W/m K, but the cost is about 10 times higher than a conventional material with similar performance (Aspen aerogels 2012);
2. transparent aerogels, such as monolithic aerogels for superinsulating windows. Twenty years ago, several glazing prototypes with monolithic aerogel were involved in a project (HILIT project, in Schultz and Jensen 2008), but at the moment, no commercial products are available because of the synthesis process is very time and cost demanding;
3. translucent granular silica aerogels (often called nanogel), used to realize highly energy-efficient windows and skylights. Different daylighting systems in PMMA are now commercialized: depending on the gas filling and the external and internal panes and properties of granular aerogel in the interpace, U-values can be lower than 0.3 $W/m^2$ K.

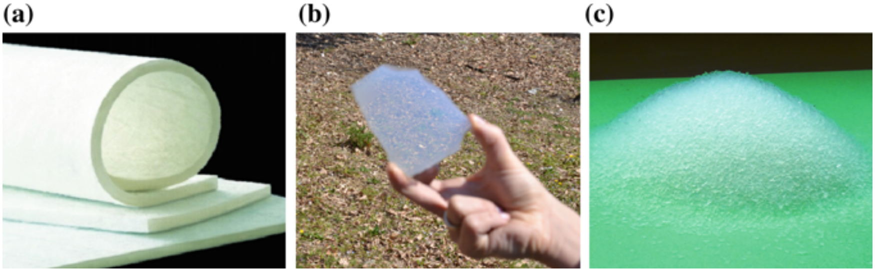


**Fig. 2** Aerogel insulation material for building applications: opaque blankets (**a**), monoliths (**b**), and granular aerogels (**c**)

## *2.2 Silica Aerogels Production and Properties*

Inorganic Silica-Based Aerogels are obtained from a gel by replacing the pore liquids with air and maintaining the network structure as it is in the gel state.

They are manufactured by means of different processes, involving three general steps (Pierre and Pajonk 2002; Soleimani Dorcheh and Abbasi 2008). In the *sol–gel process* (phase 1), silicon alkoxides are dispersed in a liquid, where the solid nanoparticles collide and form a solid three-dimensional network through the liquid (silica sols). Acidic or basic catalysts are usually added in the process. The gels are usually classified according to the dispersion medium used, e.g. hydrogel, alcogel, and aerogel (for water, alcohol, and air, respectively). Then the gels are usually aged before drying (*gel ageing phase*), in order to increase stiffness and strength and to mechanically reinforce the tenuous solid skeleton generated during the sol–gel process. Finally, during the *gel drying phase*, the solid framework of the sol–gel is isolated from liquid; it is the most critical step of the process: the structure can collapse or be fractured, due to the capillary pressure. Two different methods are usually carried out: ambient pressure drying (APD) and supercritical drying (SCD), where the capillary tension can be avoided by removing the liquid above the critical temperature and pressure. A more detailed analysis of the synthesis process and the recent developments could be found in the literature (Soleimani Dorcheh and Abbasi 2008; Aegerter et al. 2011).

The physical, mechanical, optical, and thermal properties of silica aerogels can vary in a wide range and depend on both the starting silica source (such as tetramathoxysilane (TMOS, $Si(OCH_3)_4$ and tetraethoxysilane (TEOS, $Si(OC_2H_5)_4$) and the process methodology, in particular on the used catalyst and solvent (Tajiri and Igarashi 1998; Anderson et al. 2009; Pajonk 2003).

Silica aerogels are extremely light amorphous materials: even if the skeleton density is about 2,200 kg/m$^3$; the bulk density is in the 50–200 kg/m$^3$ range, because of the very high porosity; and the pore size is typically in the 5–100 nm range.

Because of this structure, aerogels are very fragile: the tensile strength is negligible and the compressive strength and the elastic modulus are very low (Beatens et al. 2011; Parmenter and Milstein 1998). In general, the contact with water must be avoided for monolithic aerogels: in commercial applications, aerogel may be used in vacuum conditions, with evident advantages in terms of thermal insulation. Nevertheless, the commercial granular aerogels are hydrophobic.

The optical and thermal properties are widely discussed in the next paragraphs.

Finally, considering safety, the material is not carcinogenic, non-flammable, and non-reactive (Baetens et al. 2011). The main physical properties are summarized in Table 1.

According to the Kistler's procedure, the first commercial aerogels were produced by Monsanto Chemical Corporation (USA) after 1940. Then, the production was stopped between 1960s and 1980s. Nowadays, especially in the last two decades, the production of aerogels is located in the USA, Europe (Sweden, Germany),

**Table 1** Physical properties of silica aerogels (adapted from Riffat and Qiu 2012)

| Properties | Values range |
|---|---|
| Pore diameter (nm) | 5–100 (about 20 in general) |
| Porosity (%) | 85–99.8 (>90 in general) |
| Density (kg/m$^3$) | 50–200 (about 100 in building applications) |
| Surface area (m$^2$/g) | 100–600 |
| Optical behaviour (-) | Opaque (blankets)<br>Translucent (granular)<br>Transparent (monolithic) |
| Thermal conductivity (W/m K) | 0.008–0.020 (depending on temperature, pressure, and production process) |
| Sound speed (m/s) | 40–300 |

**Table 2** Main features of Lumira nanogel® (adapted from Cabot 2012)

| Properties | Values range |
|---|---|
| Particle size (mm) | 0.07–4 |
| Pore diameter (nm) | About 20 |
| Porosity (%) | >90 air |
| Density (kg/m$^3$) | 65–85 (bulk); 120–180 (particle) |
| Surface area (m$^2$/g) | 600–800 |
| Surface chemistry | Fully hydroscopic |
| Optical behaviour | Translucent |

China, Japan, and Russia. Cabot Corporation (USA) seems to be the main manufacturer of granular translucent aerogels. The company developed an innovative manufacturing process and allowed a production on large scale since 2003 in a plant in Frankfurt, Germany; it can produce about 10,000 t per year (Werner and Brand 2010; Aegerter et al. 2011). The translucent aerogels manufactured by Cabot, Lumira™ aerogel, formerly Nanogel® aerogel, are characterized by grain size in the 0.07–4 mm range (Table 2).

# 3 Silica Aerogels Thermal and Lighting Performance

## *3.1 Thermal Properties*

Silica aerogel has the lowest thermal conductivity $\lambda$ among solid materials, despite the silica skeleton structure value being relatively high (in the 1.3–1.4 W/m K range). The overall value is very low: it ranges from 0.018 W/m K for granular silica aerogel to 0.004 W/m K for evacuated monolithic silica aerogel (Koebel et al. 2012; Bouquerela et al. 2012). Table 3 shows the thermal conductivity of silica aerogel, compared to different insulation products: nowadays, only vacuum technology has a thermal conductivity of the same order of aerogel.

**Table 3** Overview of insulation materials: thermal conductivities for conventional and super-insulation materials (adapted from Koebel et al. 2012)

| Insulation material and composition | Ambient thermal conductivity $\lambda$ (W/m K) |
|---|---|
| Mineral wool (inorganic oxides) | 0.034–0.045 |
| Glass wool (silicon dioxide) | 0.031–0.043 |
| Foam glass (silicon dioxide) | 0.038–0.050 |
| Expanded polystyrene (EPS) polymer foam | 0.029–0.055 |
| Extruded polystyrene (XPS) polymer foam | 0.029–0.048 |
| Phenolic resin foam (polymer foam) | 0.021–0.025 |
| Polyurethane foam (polymer foam) | 0.020–0.029 |
| Silica aerogels (SiO2 based aerogel) | 0.012–0.020 |
| Monolithic aerogel | 0.004–0.010 |
| Organic aerogels (aerogels derived from organic compounds) | 0.013–0.020 |
| Vacuum insulation panels (VIP, silica core sealed and evacuated in laminate foil) | 0.003–0.011[a] |
| Vacuum glazing (VG, double-glazing unit with evacuated space and support pillars) | 0.0001–0.0005[b]<br>0.003–0.008[c] |

[a] Vacuum insulation panels age with time. As the pressure inside the evacuated element rises because of envelope permeability, so does the thermal conductivity of the core materials. Equivalent conductivity values of 30-year-aged VIPs depend strongly on the product and materials used and are typically in the order of 0.007–0.012 W/m K

[b] The equivalent thermal conductivity of vacuum glazings $\lambda$ was determined from typical $U$-values in the order of 0.5–0.3 W/m$^2$ K and a thickness of the evacuated gap in the 0.3–1.0 mm range, without taking into account the thickness of the glass pane

[c] $\lambda$-values determined from typical $U$-values of 0.3–0.5 W/m$^2$ K and a total thickness in the 10–16 mm range, considering glass panes

The very low thermal conductivity is due to the pore structure in the porous materials; the total heat transfer depends on the following:

- conduction through the solid material;
- conduction through the pore medium;
- convective transport by the pore medium;
- radiative transport from solid surfaces through the pore fluid; and
- radiative transport from the solid through the solid network or bulk.

In the aerogels, the extremely low thermal conductivity is due to the combination of low density and small pores (Baetens et al. 2011): the small pores limit conductive and convective gas transport, while the solid network offers limited pathways for conduction due to the low density. In particular, convection by the pore fluid (i.e. air) is reduced significantly with micrometre pore sizes, so that only conduction and radiation remain; for these reasons, $\lambda$ can be further reduced by decreasing the maximum pore size, by filling the aerogel with a low-conductive gas or by applying a vacuum: with a pressure of 50 mbar; the thermal conductivity can diminish down to 0.008 W/m K.

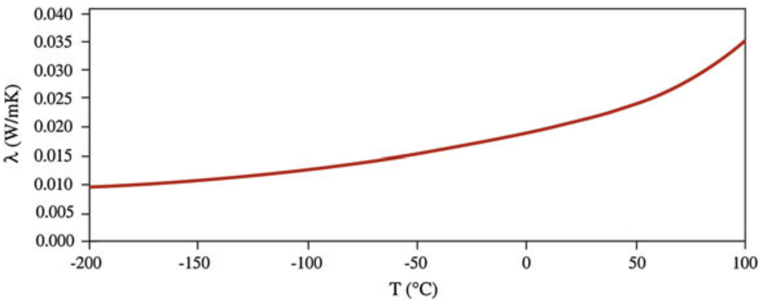


**Fig. 3** Thermal conductivity for granular aerogel Lumira® (adapted from Cabot 2012)

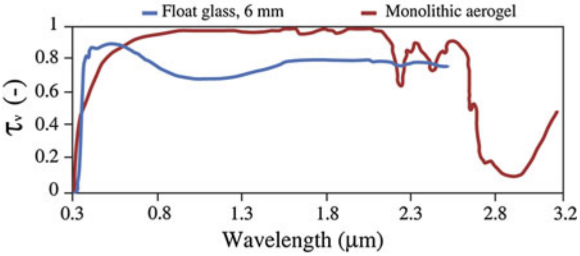
Commercially available aerogels for building purposes (translucent granular aerogels) have a thermal conductivity between 0.013 and 0.018 W/m K at ambient temperature; moreover, the value is nearly constant up to a temperature of 100 °C (Aspen, Cabot 2012, Fig. 3).

## 3.2 *Optical Properties*

The optical transmission and the scattering properties of silica aerogels are widely investigated in the literature (Baetens et al. 2011; Jensen et al. 2004; Reim et al. 2004, 2005; Buratti 2003, 2004; Buratti and Moretti 2011, b, 2012, b). The attitude to diffuse natural light indoors is described by the light transmittance ($\tau_v$), very important since the natural light concurs to save electric energy in daytime and affects general health of human beings.

Monolithic aerogels show very interesting optical properties for building applications: the transmittance in the visible range is high, and it is similar to the one of a 6-mm-thick clear float glass (Fig. 4). Solar transmittance ($\tau_e$) equal to 0.88 was found for an aerogel pane of 10 mm thickness; absorption bands in the NIR transmission spectrum are shown. Furthermore, a part of the radiation is scattered when transmitted through the material, according to the Rayleigh scattering theory. It causes reddening of the transmitted light, the bluish appearance of

**Fig. 4** Transmission properties of monolithic silica aerogels



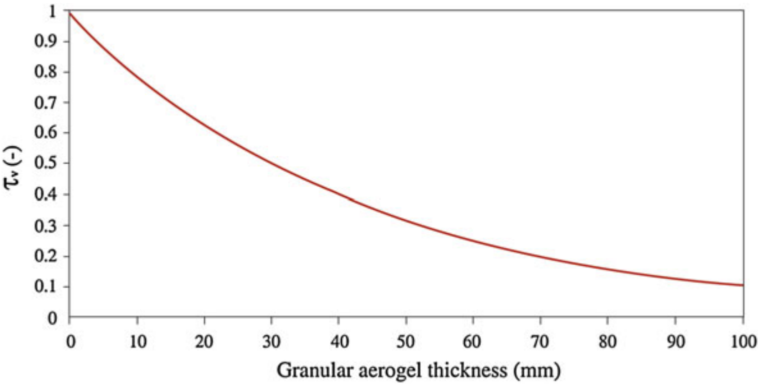


**Fig. 5** Calculated light transmission through granular aerogel (adapted from Cabot 2009)

the reflected light, and a possible blurred deformation of optical images (Duer and Svendsen 1998).

The optical properties are influenced by the production process, i.e. by selecting optimal synthesis parameters (Tajiri and Igarashi 1998), and the transparency has been improved in the last years.

Granular aerogel's light transmission (Cabot, see Fig. 5) is about 80 % with 10 mm thickness, lower than the one of the monolithic samples with the same thickness. It decreases by 20 % each time and its thickness increases by 10 mm: as shown in the Fig. 5, 10 mm of aerogel allows 80 % of light transmission.

The quality of the vision through the material decreases; nevertheless, it could be preferred in some situations, because the light gets very deep in the room, and it can significantly reduce glare problems in façade or skylight. Using aerogel in clear windows can greatly affect the characteristics of the incoming light, which could modify the colour appearance of surfaces and objects, contributing significantly to the comfort and visual satisfaction of human beings. The quality of the transmitted light can be usefully represented by the general colour rendering index $R_a$: it is based on the differences in colour between eight test colours lighted directly by a reference illuminant and by the same illuminant after the transmission through the glazing (EN 410 2011); it is a normalized value in the 0–100 range, representing 100 no difference in colour. A value of 91 was found for 14-mm-thick aerogel panes (Buratti and Moretti 2012, b), which is a good value if compared to the clear glass panes ($R_a$ values of about 98). When considering glazing systems with aerogel in interspace, literature data (Buratti and Moretti 2012, b) showed a very good quality ($R_a > 90$): $R_a$ is lower than the one of windows with air in interspace ($R_a = 98$ with float glasses; $R_a = 94$ with one low-e glass), but it is equal to 93 for float glasses and granular aerogel (14 mm) and equal to 92 with monolithic aerogel. With low-e glasses and granular aerogel, $R_a$ goes down to 90–91.

The transmittance of granular silica aerogels in the infrared spectral range is low, except in the 3.5–5 µm range (see Fig. 6), whereas the reflectance is negligible.

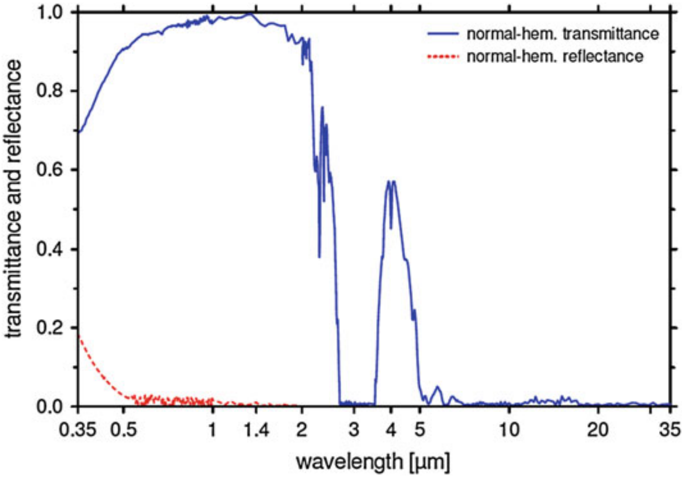


**Fig. 6** Spectral normal–hemispherical transmittance and reflectance in the infrared spectral range of a 10-mm layer of granular aerogel (Cabot Nanogel TDL 302) (Bavarian center for applied energy research 2010)

## *3.3 Acoustic Properties*

The acoustic properties of silica aerogels are very interesting: the sound speed in the material is lower than that in air, down to about 40 m/s through monolithic aerogels and to about 100 m/s through granular ones. The sound propagation depends on different parameters, such as the interstitial gas nature and pressure, the density, and the texture (Forest et al. 1998). In order to characterize the acoustic properties of silica aerogels, the acoustic attenuation was measured by means of the two-thickness method (Forest et al. 2001), and it showed that the large granules of aerogels (mean granules size 3 mm) have an attenuation (about 1 dB/cm) lower than the one of a conventional insulating material, such as glass wool; nevertheless, in the small granules (mean granules size about 80 µm), the attenuation values are in the 0–12 dB/cm range, depending on the frequency range: above 500 Hz, the values are higher than the glass wool ones (about 3 dB/cm).

The efficiency of granular silica aerogels as sound insulators in the 100–2,500 Hz frequency range was also demonstrated, when used in multilayer (a fist layer (1 cm) made of large granules and the second one (3 cm) made of small granules): in the 30–1,700 Hz range, the sound transmitted through the aerogel is 15 dB lower than the one transmitted through glass wool of the same thickness.

For these reasons, translucent insulting material, when used in interspace of glazings, can improve sound insulation of the building envelope, if compared to systems with air. In Buratti and Moretti (2012b), a prototype of window was realized and tested: it was composed of an aluminium frame with two float glasses (4 mm thickness) and granular aerogel in 15-mm interspace. The benefits of aerogels in sound insulation were evaluated by means of the sound reduction index

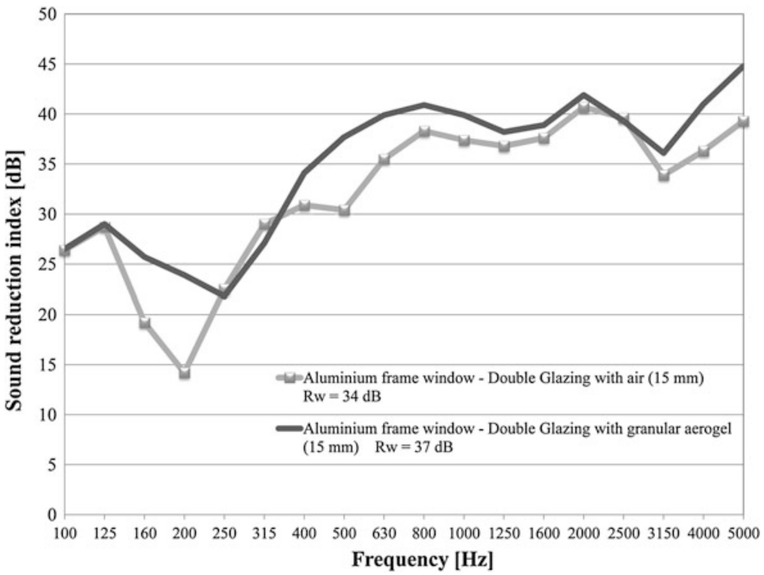


**Fig. 7** Sound reduction index (*R*) values versus frequency for aluminium frame window with conventional glazing (15-mm air) and with glazing prototype with aerogel in interspace (15 mm)

(R, EN ISO 20140-2 2010), which affects the noise transmitted through the windows; high values are required in order to guarantee an adequate acoustic comfort in buildings. The presence of granular aerogel increases the sound reduction index values in all the frequency range (100–500 Hz), especially in the central range (500–2,000 Hz). Moreover, a weighted sound insulation index $R_w$ (EN ISO 717-1 2007) equal to 37 dB was obtained for the innovative prototype, 3 dB higher than the one of the conventional window with air in interspace ($R_w = 34$ dB), confirming good acoustic insulation properties (Fig. 7).

# 4 Aerogel Windows

## *4.1 Glazing Systems*

Many innovative glazing technologies were developed in order to satisfy the growing demand for energy-efficient buildings (Jelle et al. 2012; Ebrahimpour and Maerefat 2011; Wong et al. 2007); in this context, the current focus is to develop super-insulating windows, with *U*-values below 1 W/m$^2$ K, high light transmission, and not too high *g*-value (solar heat gain coefficient). Silica aerogels, both in monolithic and granular form, can be used in high-insulated nanogel windows, thanks to their interesting optical properties and excellent thermal insulation characteristics. Transparent monolithic panes were developed in 1980–1990s

(Airglass A.B) in Sweden, but advanced glazing systems with monolithic aerogel have still not penetrated the market (Duer and Svendsen 1998; Jensen et al. 2004; Schultz and Jensen 2008). At the same time, granular translucent aerogels were manufactured, and, starting from 2005, many daylighting systems (polycarbonate panels, structural panels for continuous façades, insulated glasses) with translucent granular aerogel in interspace are available on the market (Rigacci et al. 2004).

They are the most promising solutions, despite the high cost; nowadays, a reference market price for a cubic metre of granular silica aerogel is in the order of 4,000 US$ (2008), but it could drop below 1,500 US$ by the year 2020, due of the expected increasing of commercialization. It means that a 15-mm-thick interspace filled with granular aerogels could now have a cost of 60 US$/m$^2$, that could become 22.5 US$/m$^2$ in 2020.

The first daylighting system with granular aerogel in interspace consisted of a double-skin sheet of polymethyl methacrylate (PMMA) (Reim et al. 2002). Two types of granular aerogel were used in prototype windows: semi-transparent, consisting of rather regular spheres, and high translucent granulates, consisting of irregularly fractured pieces spheres. The optical properties measured with an integrating sphere (400–2,000 nm wavelength range) showed a decrease in transmission with a decrease in wavelength below 600 nm; the investigated fractured aerogel samples showed a higher transmittance than the regular ones, both in the visible and solar range. A prototype of the new glazing with high translucent granular aerogel was for the first time integrated into the façade of the ZAE building (Bayerisches Zentrum für Angewandte Energieforschung, Fig. 8) in Wurzburg, Germany (2000).

Moreover, in order to optimize the thermal insulation, the sheet was mounted between two low-e coated glass panes (emissivity equal to 0.03 or 0.08), and argon or krypton were used as filling gases. Depending on the filling, the low-e coating emissivity and granular aerogel kind, a *U*-value in the 0.37–0.56 W/m$^2$ K range, and a total solar energy transmittance (solar factor, g) in the 17–45 % range were obtained (Reim et al. 2005).

Also the company Scobalit AG (Switzerland) was a pioneer in aerogel-filled composite panels for translucent daylighting applications. The developed system

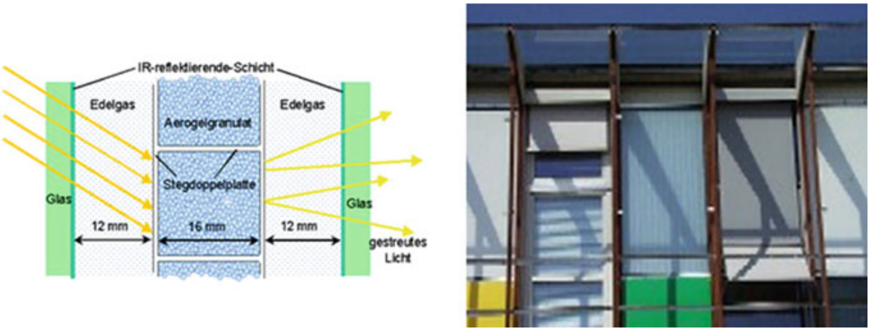


**Fig. 8** The façade of the ZAE (Bayerisches Zentrum für Angewandte Energieforschung): the first example of the use of PMMA systems with granular aerogels (2000)

**Fig. 9** The school Buchwiesen in Zurich: example of the use of granular-aerogel-filled Scobatherm glass fibre composite panels in the form of a transparent daylighting roof (2003)

called *Scobatherm* consists of an aerogel-granulate-filled glass-fibre-reinforced polyester resin composite profile (Scobalit AG 2012). One of its first uses in a building for daylighting is the roof construction of the school ‘‘Buchwiesen’’ in Zurich in 2003 (Fig. 9).

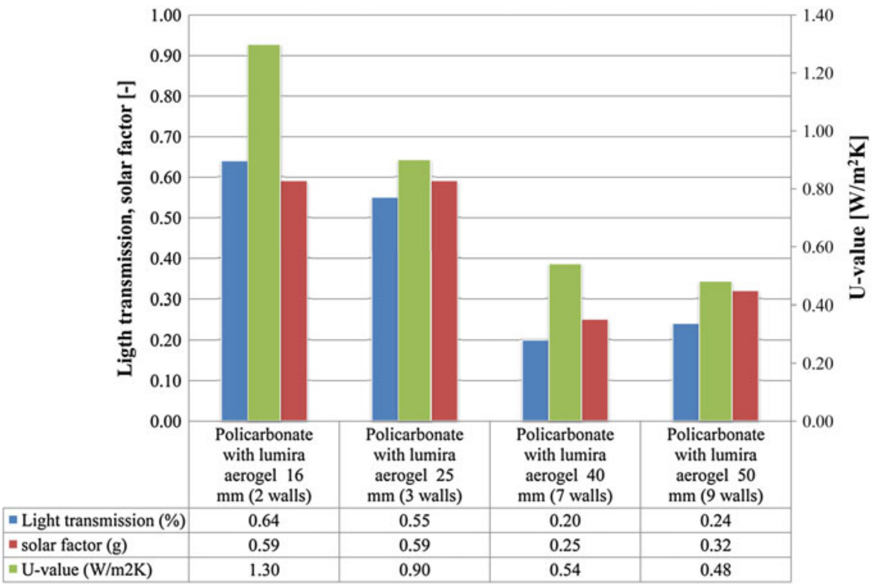
Aerogel glazings, vacuum glazings, new spacer materials and solutions, and electrochromic windows currently seem to have the largest potential in fenestration products (Jelle et al. 2012). At the moment, different commercial systems with granular translucent aerogels are available on the market, offering excellent thermal performance, a good solar heat gain, and a good sound insulation:

1. structural composite panels for skylights and façades;
2. polycarbonate systems for skylights and façades;
3. *U*-channel glass (self-supporting systems of glass channels with an extruded metal perimeter frame);
4. insulated glass units; and
5. tensile structures and roofing.

In Europe, EMB Products AG, Germany (Roda 2012), developed multiwall polycarbonate systems filled with Lumira™ aerogel for use in façades, separation walls, curtain walls, and roofs; the *U*-values vary in the 0.48–1.30 W/m$^2$ K range (Fig. 10), depending on the thickness of the system (16–50 mm).

Other structural polycarbonate systems are proposed by Alcaud Sa and Skydome (France); Xtralite for roof solutions (UK) in Europe; and Wasco, Solar innovations, Duo-Gard, Crystallite, and Aerolenz (skylights) in the USA (Xtralight Rooflight 2012).

Structural composite panels are manufactured by Stoakes systems (UK) (Stoakes Systems 2013), Scobatherm (Switzerland), and Kallwall (USA) (Kalwall Corporation 2013) (Fig. 11a).



| | Policarbonate with lumira aerogel 16 mm (2 walls) | Policarbonate with lumira aerogel 25 mm (3 walls) | Policarbonate with lumira aerogel 40 mm (7 walls) | Policarbonate with lumira aerogel 50 mm (9 walls) |
|---|---|---|---|---|
| 🟦 Light transmission (%) | 0.64 | 0.55 | 0.20 | 0.24 |
| 🟥 solar factor (g) | 0.59 | 0.59 | 0.25 | 0.32 |
| 🟩 U-value (W/m2K) | 1.30 | 0.90 | 0.54 | 0.48 |

**Fig. 10** Thermal, lighting, and solar performances of multiwall polycarbonate systems filled with Lumira$^{TM}$ aerogel (data from EMB Products AG RODA 2013)

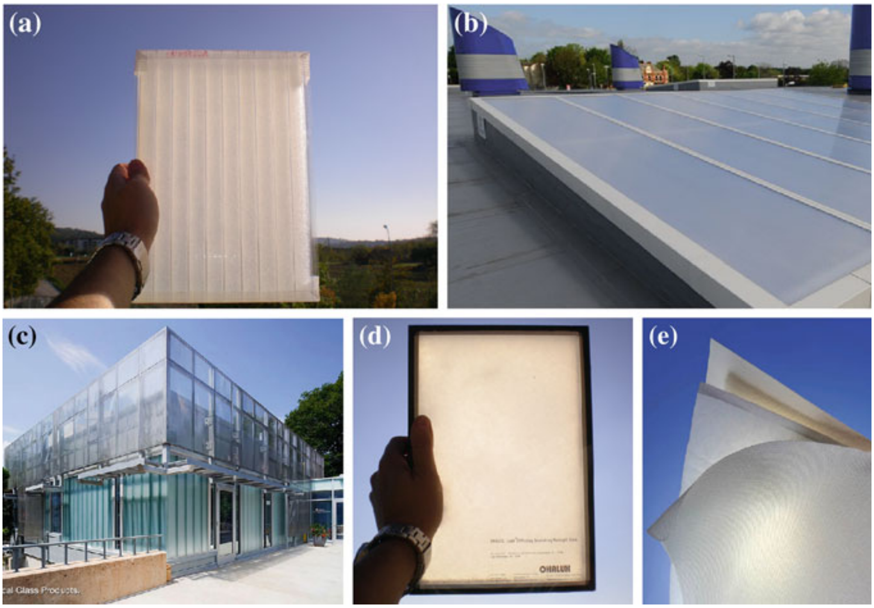


**Fig. 11** Daylighting systems with granular aerogel: structural composite panels for skylights and façades (Emb Products AG, **a**); polycarbonate systems for skylights and façades (**b**); *U*-channel glass (TGP America, **c**); insulated glass units (Okalux, **d**); and tensile structures (Birdair, **e**)

Translucent linear-channel glass systems, Pilkington Profilit $^{TM}$, filled with Lumira$^{TM}$ aerogel were also developed (Pilkington in Europe and TGP America in the USA) (Technical Glass Products 2012) with very interesting thermal performance: $U = 0.19$ (low-e with 16 mm Lumira$^{TM}$)—0.21 W/m$^2$ K (low-e with 25 mm Lumira$^{TM}$) (Fig. 11c).

The system Okagel® was developed by Okalux (Germany) (Okalux GmbH 2012) and consists of two glass layers filled with granular aerogel (Fig. 11d); a hydrostatic stress is applied to the material, in order to avoid its settling during the service life. The $U$-value can decrease down to 0.3 W/m$^2$ K, and the most famous application is the British Haley VI Research Station in the Antarctic. In America, insulated translucent glass units with nanogel® are manufactured from Advanced Glazings Ltd (Canada): the system called Solera® + nanogel® has a $U$-value equal to 0.31 W/m$^2$ K (76.1 mm configuration) (Advanced Glazings Ltd. 2012).

High-performance tensile structures could be obtained by incorporating granular aerogel between two layers of traditional PTFE membranes (Teflon®) (Fig. 11e), allowing an increased thermal efficiency without adding significant weight or creating a barrier to natural light (Birdair 2012).

Finally, in China, Nano High-tech Co. Ltd developed daylighting panels (TP) with aerogel particles (Nano High-Tech Co. 2012). With a thermal conductivity equal to 0.025 W/m K, they could be used in large buildings as theatres, airport terminals, exhibition centres, etc. They are hydrophobic, and the light transmission is in the 40–70 % range, depending on the panel thickness (10–30 mm).

## *4.2 Windows Prototypes*

Double windows with monolithic aerogel (also partially evacuated) in interspace were considered for decades as alternative to gas-filled conventional systems, instead of vacuum glazings. The development of monoliths for windows application began during the 1980s, thanks to efforts of the Airglass A.B. (Sweden) (Airglass 2012). Also thanks to two research projects founded by the European Commission (HILIT—Highly insulating and light-transmitting aerogel glazing for window, 1998–2001, and HILIT+ , 2002–2005); transparent insulating silica aerogel tiles (thickness of about 15 ± 1 mm, 55 × 55 cm$^2$) were manufactured at a pilot scale since 2004. Then, aerogel glazing prototypes were made under vacuum conditions; a rim seal assured a barrier against atmospheric air and water vapour, and low thermal bridge effects were obtained. The solar and light transmittances were optimized by means of low-iron glass covers and antireflection coating. The optical quality had a minimal disturbance in the view through, except if exposed to direct non-perpendicular radiation, when the diffusion of the light becomes significant (Fig. 12). The centre $U$-value, measured by means of a hot-plate apparatus, was equal to 0.66 W/m$^2$ K, with an estimated thermal conductivity of 0.010 W/m K for the aerogel pane (average thickness 14.8 mm). Moreover, the solar transmittance is high for windows with monolithic translucent aerogels:

**Fig. 12** The prototype of super-insulating aerogel glazing (report HILIT)

the measured value for the monolithic window prototype (15 mm aerogel) was higher than 75 % (Jensen et al. 2004), but, at the same time, the $U$-value was equal to the best triple-layered gas-filled glazing units ($U < 0.6$ W/m$^2$ K).

## 4.3 Application in Buildings

A wide number of applications of granular aerogel glazing systems in buildings were chosen as a reliable alternative to conventional solutions especially in the USA and in Europe: schools, libraries, commercial centres, airports, and industrial factories.

Roof applications are the most usual (Fig. 13), because the $U$-values are not dependent on the inclination to the vertical, such as in the gas-filled glazings (air, argon, or krypton) which have a worse behaviour when used as roofs instead of vertical panels (Fig. 14).

The energy benefits of using granular aerogel glazing are also discussed in the literature (Reim et al. 2002). Referring to the German climate, the net heat flux during 1 month (from October to April) was calculated using a simulation model for three insulating materials (Fig. 15):

- an aerogel glazing ($U = 0.4$ W/m$^2$ K and $g = 0.3$);
- a solar triple glazing ($U = 0.8$ W/(m$^2$ K) and $g = 0.6$); and
- an opaque insulation ($U = 0.2$ W/m$^2$ K).
- Negative values represent thermal losses and positive ones solar gains.

Results showed that granular aerogel glazing could reduce the risk of overheating in summer conditions on southern and east/west façades with respect to triple glazing. On north-facing façades, the balance of aerogel glazing was significantly better than triple glazing, due to lower $U$-value: the maximum heat flux during the heating period is about $-5$ kWh/m$^2$(a), while for the triple glazing is $-10$ kWh/m$^2$ (a).

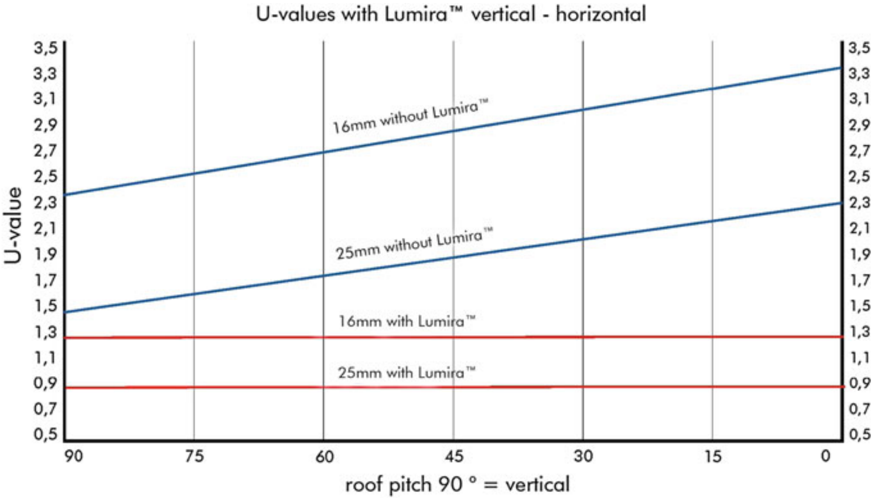


**Fig. 13** Influence of the installation angle on $U$-values of polycarbonate systems with and without nanogel in interspace

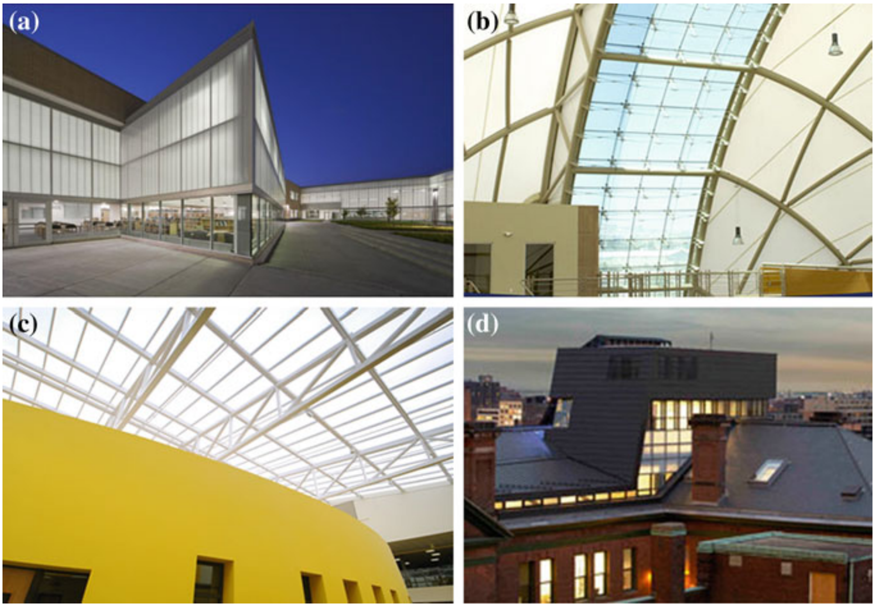


**Fig. 14** Application of daylighting systems with granular aerogels: **a** Metea Valley High School, Aurora, IL (Kalwall); **b** Amber Interactive Center, Tijuana, Baja California, Mexico (Birdair); **c** Application of Lumira$^{\mathrm{TM}}$ aerogel in polycarbonate sheets for roofs (courtesy of Roda, Germany); and **d** University of Toronto Mining Building, Toronto (ON), Okagel systems

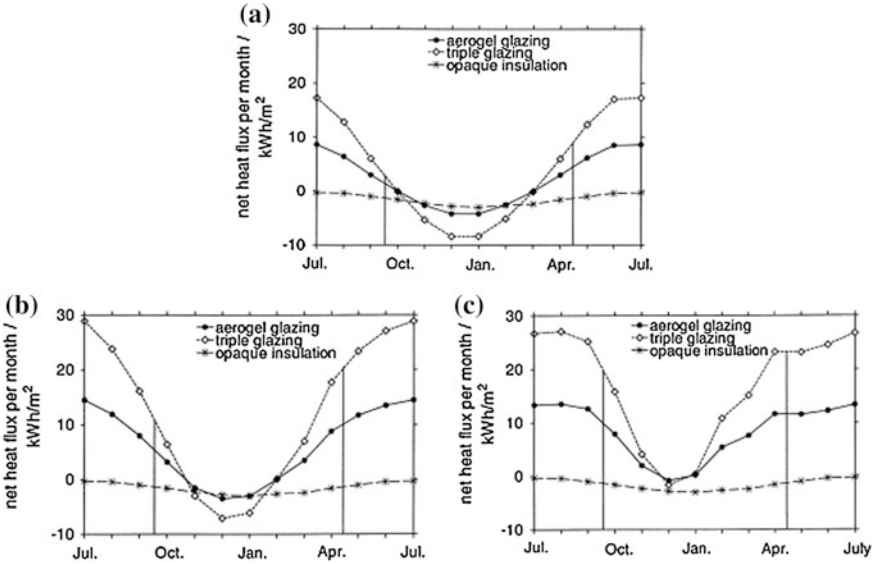


**Fig. 15** Monthly net heat fluxes of an aerogel glazing compared with a solar triple glazing and an opaque insulation calculated in three conditions: a north-oriented wall (**a**), an east- or west-oriented wall (**b**), and a south-oriented wall (**c**) (Reim et al. 2002)

The performance of the aerogel panel in winter is finally similar to the one of the opaque insulation for all the investigated façade orientations.

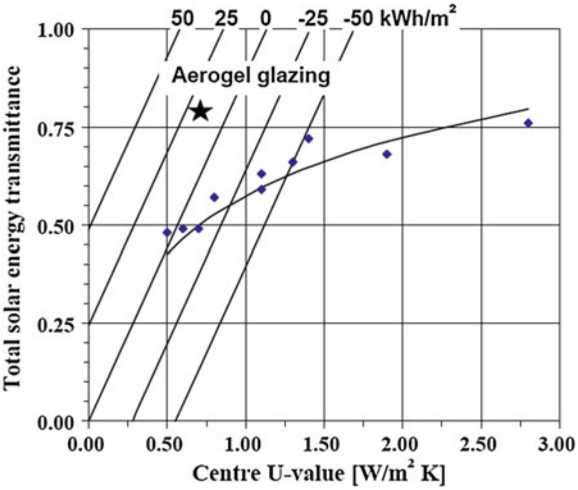
Less applications were realized with monolithic aerogel glazings, due to still rather difficult and expensive production process. An improvement in the optical quality of the aerogel material is also needed, in order to remove the image distortion when looking through an aerogel glazing. These are the most serious restrictions for a spread of aerogel glazings as it substituted the conventional ones.

Recently, Aspen Aerogels engaged in the development of reinforced and highly translucent monolithic aerogel for 'aerogel window' applications, but the technology is currently under study due to the difficulty in producing monoliths of high optical quality (no defects, cracks, and inhomogeneities).

HILIT and HILIT+ projects showed that aerogel windows are the best solutions for cold climates: they have a total solar energy transmittance ($g$-value) higher than conventional double glazings, but at the same time, the $U$-value is equal to the best triple-gas-filled glazing units. As shown in Fig. 16, for the same $U$-value (0.75 $W/m^2$ K), the aerogel glazing has a $g$-value of about 0.75, while the triple glazing has a $g$-value of 0.50. The net heat flux is about +10 $kWh/m^2$ for the aerogel system, while it is $-15$ $kWh/m^2$ for triple glazing.

The influence on the heating energy consumption was also evaluated through simulations of annual energy consumption for a typical single-family house in Denmark (Schultz and Jensen 2008) built according to the present building code. An aerogel glazing with 20 mm aerogel thickness resulting in a centre $U$-value of

**Fig. 16** *G*-value versus *U*-value for different net heat flux during the heating season (approximately October–April) for a single-family house in a Danish climate. The star represents a glazing with 15-mm monolithic aerogel. The dots mark the values for conventional glazing units (Schultz et al. 2005)



0.5 W/m$^2$ K and a *g*-value equal to 0.75 was considered, and the results were compared to a triple-layered argon-filled glazing with two low-e coatings ($U = 0.6$ W/m$^2$ K and $g = 0.46$). The annual energy saving with aerogel glazing was approximately 1200 kWh/year, corresponding to 19 % of the energy for triple glazing (space heating demand equal to 5,040 kWh/year for aerogel, 6220 for triple glazing). In a low-energy house (space heating demand $< 15$ kWh/m$^2$/year), the energy savings was approximately 700 kWh/year, corresponding to 34 % of annual space heating demand (about 2,070 kWh/year).

Nevertheless, in southern climates, the increase in cooling needs, due to the higher solar factor, diminishes the advantage of aerogel glazing, and in some cases, a higher global energy consumption during the year could be obtained (see Sect. 5.2).

Finally, a comparison between the indoor visual comfort with aerogel windows and conventional glazing systems was simulated by means of the calculation code RADIANCE in an office room. Results showed a better diffusion of the direct light for aerogel glazings, with respect to a conventional double heat-reflective glazing (with low-e film), reducing also glare (Fig. 17). The worst situation for aerogels is the one with direct sunlight on the surface (Fig. 17b).

## 5 Building Refurbishment with Nanogel Windows

An experimental application of granular aerogel windows is presented in Sect. 5.1, and the benefits are evaluated in terms of light transmission and energy saving (heat loss reduction).

A multifunctional building was then investigated in Sect. 5.2, and a dynamic thermal model was implemented. The energy demand was estimated for different

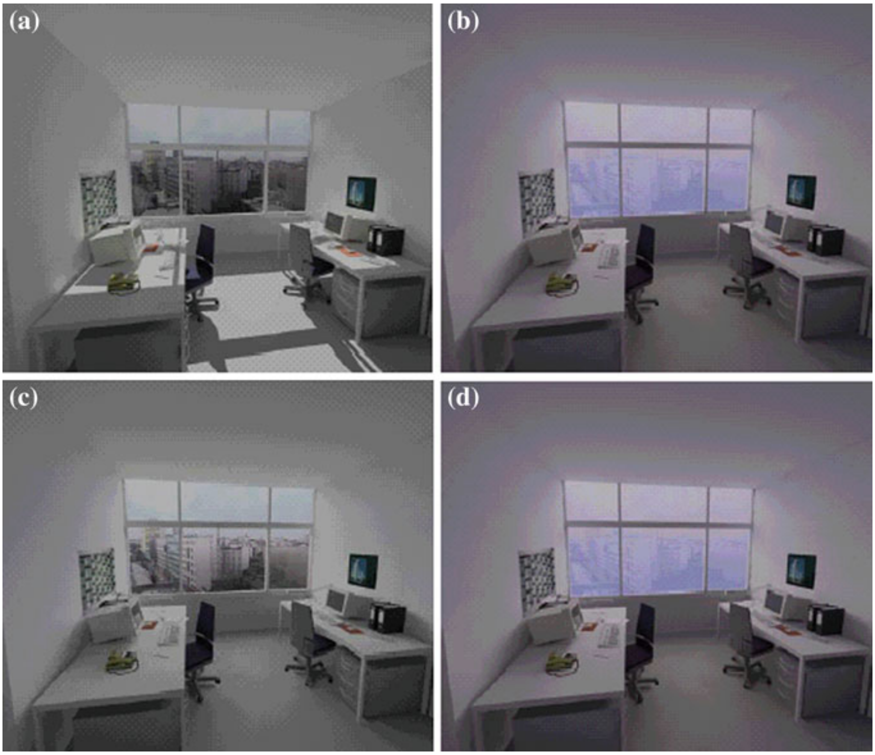


**Fig. 17** Daylighting in an office room with a south façade: conventional double heat-reflective (with low-e film) glazing (**a**, **c**) and aerogel glazings (**b**, **d**) [different sky conditions: direct sunlight (incident angle 45°, **a** and **b**) and diffuse sunlight (**c**, **d**)]

glazing systems (conventional solutions and innovative systems, such as aerogel windows and triple glazings) both for heating and cooling in six world cities with different climate conditions (Rome, London, Moscow, Helsinki, Ottawa, Beijing).

## *5.1 Application of Granular Systems in Existing Buildings: Experimental Data*

Many studies were recently carried out to assess the potential of high-performance translucent granular aerogel insulation to retrofit single glazing reducing heat loss without arresting the useful natural light.

In (Dowson et al. 2011), in situ testing of a 10-mm-thick prototype panel, consisting of a clear twin-wall polycarbonate sheet filled with granular aerogel, are included; the study was validated with steady-state calculations.

Two prototypes of the twin-wall sheet were manually filled with 3-mm-diameter aerogel granules; the first one with a 6 mm aerogel thickness and the second one with 10 mm thickness. Both the prototypes were inserted in a test window, sealed around the edges, and attached to the internal face of the frame using duct tape. A 15-mm air gap was created between the panels and the existing glazing.

In situ *U*-values of the prototypes and the control panel were calculated, by measuring external and internal temperatures by thermocouples, and the heat flux by Peltier modules thermally bonded to the centre of each sample. The light transmission was also measured by lux sensors in the centre of each panel. The average heat flux through the control glass during the test period (from 20 February 2010 to 1 March 2010) was about 18 W/m$^2$, significantly higher than the one through both the prototypes: the 6-mm aerogel panel reduced heat flux by approximately 73 % and the 10 mm aerogel panel by approximately 80 %.

The light transmission in five different test periods was measured. Results show that the proportion of light transmitted does not depend on the period, and the average value through the 6-mm aerogel panel, 10-mm aerogel panel, and the control was, respectively, 58, 51, and 73 %.

A summary of the results of the study is shown in Fig. 18.

Very significant thermal performances were found for aerogels: a 80 % reduction in heat loss with respect to single glazing can be achieved by designing a purpose-built retrofit solution containing aerogel, with an acceptable reduction in light transmission.

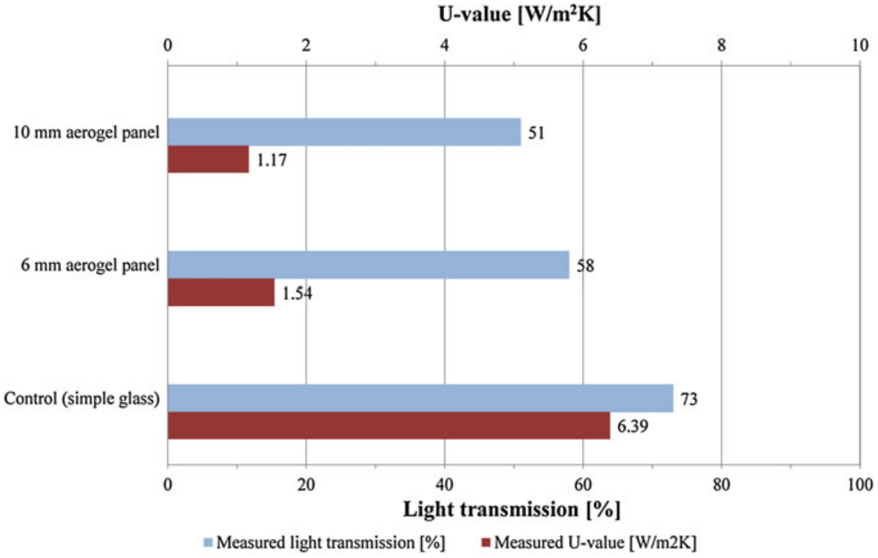


**Fig. 18** Summary of in situ testing results (adapted form Dowson et al. 2011)

## 5.2 *Building Energy Simulations: A Case Study*

### 5.2.1 Simulation Model

The case study is a multifunctional building (Buratti et al. 2013), consisting of one basement and two floors with ten zones each floor. A simplified model consisting of eight zones (4 + 4) was simulated (see the 3D model in Fig. 19). Two room types were considered for the simulations: an office room (*P*) at the first floor and a commercial one (*T*) at the ground floor.

Both ground and first floor zones present a large glass wall in the south façade. The opaque envelope features are reported in Table 4. The building's thermal behaviour was studied in the climatic and solar radiation conditions of Rome, London, Moscow, Helsinki, Ottawa, and Beijing (different climatic zones). Figure 20 shows the monthly mean values of the external temperatures for the chosen cities and the global annual solar radiation. The maximum global solar radiation is related to Rome and Beijing and the minimum value to Helsinki. During the summer period, the maximum external temperature of London is the same as the maximum value of Helsinki, but during winter, the differences exceed more than 10 °C.

The most important simulation hypotheses are summarized in Table 5.

The performance of different kinds of glazing was evaluated (Table 6).

Two standard glazings were considered: a single-pane glazing (6 mm thickness) and a double-glazing system with a total thermal transmittance of 5.7 and 2.7 W/m$^2$ K, respectively. Also a low-e glazing system with argon in interspace was considered (glazing type 3 and total thickness 23 mm).

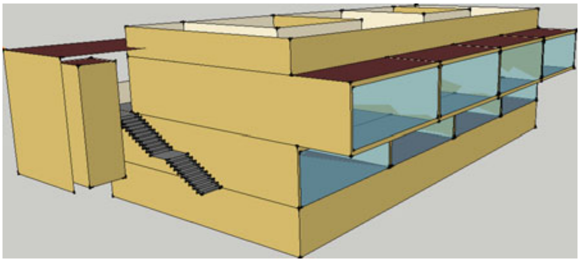
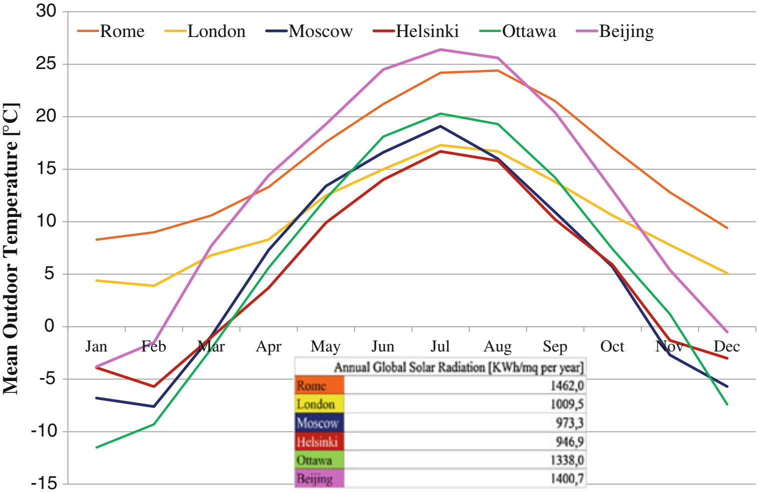


**Fig. 19** 3D model implemented in EnergyPlus

**Table 4** Opaque envelope features

| Building element | Thickness [m] | U—thermal transmittance [W/m$^2$ K] |
|---|---|---|
| External wall—north façade | 0.44 | 0.25 |
| External wall—south façade | 0.56 | 0.22 |
| Internal wall | 0.45 | 0.70 |
| First floor | 0.52 | 0.40 |
| Roof garden | 0.95 | 0.27 |
| Roof | 0.52 | 0.46 |
| Ground floor | 1.32 | 0.46 |



| Annual Global Solar Radiation [KWh/mq per year] | |
|---|---|
| Rome | 1462,0 |
| London | 1009,5 |
| Moscow | 973,3 |
| Helsinki | 946,9 |
| Ottawa | 1338,0 |
| Beijing | 1400,7 |

**Fig. 20** Monthly mean value of external air temperature and global solar radiation for six different cities

**Table 5** EnergyPlus simulation hypotheses

| | | Period | Simulation hypotheses |
|---|---|---|---|
| Occupancy schedule | *T* zone | 8:00 a.m.–7:00 p.m. | Occupants: 10 persons |
| | *P* zone | 8:00 a.m.–5:00 p.m. | Occupants: 5 persons |
| Activity level | | | 108 W/occupant |
| Lighting | | | 1.5 W/m$^2$ |
| HVAC system | Winter period | October 1–April 30 | T set point: 20 °C |
| | Summer period | June 1–September 30 | T set point: 26 °C |
| Zone infiltration | | | 0.22 m$^3$/s |

**Table 6** Glazing system properties

| Glazing | s—total thickness [m] | $\tau_v$—visible transmittance [-] | g—solar factor [-] | U—value [W/m$^2$ K] |
|---|---|---|---|---|
| 1—Standard glazing: single pane 6 mm | 0.006 | 0.89 | 0.84 | 5.70 |
| 2—Standard double glazing: 4 mm–15 mm (air)—6 mm | 0.025 | 0.80 | 0.77 | 2.70 |
| 3—Low-e double glazing: 4 mm–15 mm (argon 90 %)–4 mm low-e | 0.023 | 0.78 | 0.61 | 1.10 |
| 4—PC panels with granular nanogel (25 mm) | 0.025 | 0.55 | 0.53 | 0.91 |
| 5—PC panels with granular nanogel (40 mm) | 0.040 | 0.20 | 0.25 | 0.54 |
| 6—Double glazing with monolithic aerogel: 4 mm–aerogel 20 mm–4 mm | 0.028 | 0.60 | 0.75 | 0.50 |
| 7—Triple glazing: 4 mm low-e–15 mm (argon 90%)–4 mm–15 mm (argon 90%)–4 mm low-e | 0.038 | 0.69 | 0.47 | 0.60 |

Innovative systems with silica aerogel in interspace were also investigated with both monolithic and granular silica aerogels. Granular aerogel with grain size in the 0.5–3 mm range is filled in the interspaces with 25 mm and 40 mm thickness (respectively, glazings 4 and 5), while monolithic pane has 20 mm thickness (type 6).

Finally, a triple-glazing system was simulated: glazing 7 is composed of low-e glasses and argon in both the interspaces.

Four different façade orientations were investigated: South, East, West, and North.

### 5.2.2 Results and Discussion

The energy per conditioned building area (kWh/m$^2$) was estimated both in winter and summer. Significant results were obtained for the south orientation of the glazing. Figures 21 and 22 show the influence of both building location and kind of glazing on the annual energy demand for heating and cooling.

The heating energy demand shows a very wide variation between low values for Rome, Beijing, and London and very high values for Helsinki and Moscow. Rome has in fact the highest external temperatures during the winter period, such as Beijing, especially from March to October. Moreover, Rome and Beijing have a global solar radiation higher than the other cities (1,462 and 1,400 kWh/m$^2$ per year, respectively). More interesting is the influence of the glazing system type: the best solution in winter for all the cities is the monolithic aerogel glazing

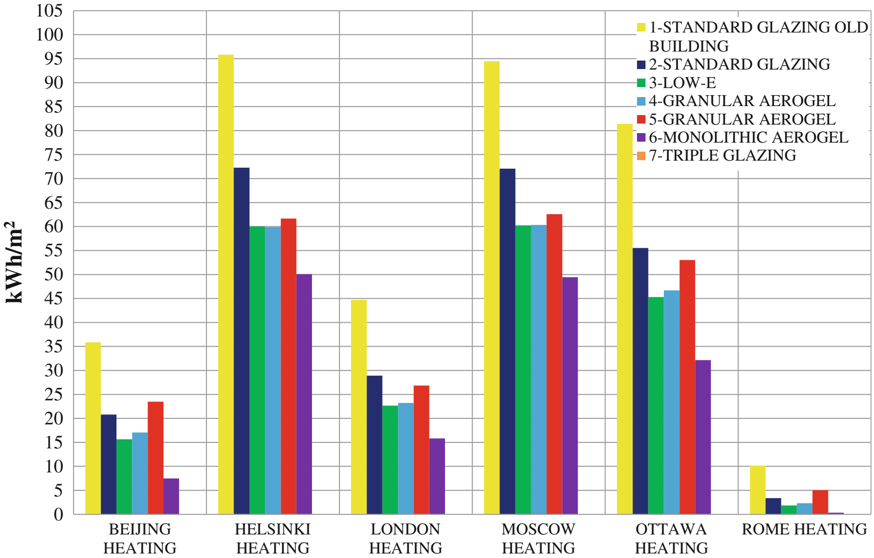


**Fig. 21** South exposure: annual energy demand for heating for the six cities and for seven different kinds of glazing

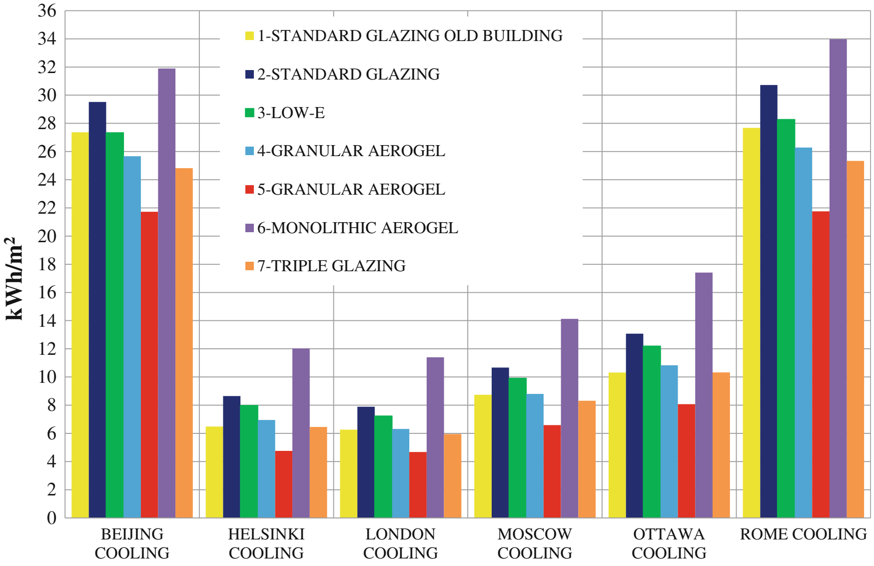


**Fig. 22** South exposure: annual energy demand for cooling for the six cities and for seven different kinds of glazing

(Type 6), which has a low thermal transmittance (0.5 W/m$^2$ K) and a high global solar factor (75 %). Nevertheless, in summer, it has the worst behaviour, because of the high solar factor: in summer nights, the indoor air temperature is higher, due to the low thermal transmittance (0.5 W/m$^2$ K). The energy demand for cooling is minimum for the granular aerogel glazing system (Type 5) of 40 mm thickness due to the low solar factor (0.25). Low thermal transmittance of windows is a good choice since it decreases the heating demand, but low *g*-values have a great impact on the cooling demand. Granular aerogel glazing n.5 saves more energy than the other window solutions: the cooling energy saved is 25 % (7 kWh/m$^2$ per year) for Beijing and 38 % for Ottawa (about 5 kWh/m$^2$ per year) with respect to the standard glazing type 2.

Overall, the monolithic aerogel glazing is the best solution for all the cities except for Rome; this system allows for Ottawa an annual energy demand decrease of about 22–27 % with regard to the standard glazing type 2 (Fig. 23). It is not the best solution for Rome because it does not perform well in summer, and Rome is a mild-climate city in winter.

The annual energy demands per conditioned building area are not very different for low-e glazing system and windows with granular aerogel in interspace, above all for Helsinki and Moscow.

Finally, innovative glazing systems with silica aerogels in interspace are the best solutions in cold climates, especially the monolithic systems. This type of window is a good choice during the winter period, but in summer, it does not

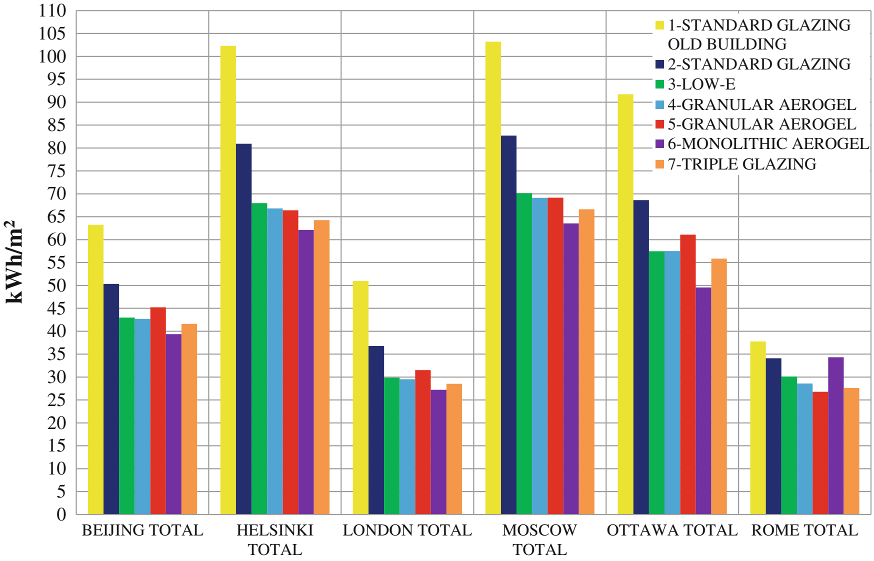


**Fig. 23** South exposure: annual energy demand for conditioned building area for the six cities and for seven different kinds of glazing

perform very well. The best solutions for the annual energy demand reduction are the granular aerogel glazing systems: the annual energy demand reduction varies in 10–20 % range with regard to the standard glazing (type 2).

## 6 General Conclusions and Future Trends

Nowadays, translucent or transparent aerogel glazings have a high potential in fenestration market, due to low *U*-values (down to 0.1 W/m$^2$ K, depending on thickness and technology) together with very interesting properties such as thermal and acoustic insulation, light transmission, and finally lightness. Alternative high-performance solutions, such as vacuum insulation panels (VIP), have technical limits (problem of keeping the glazing gas-tight) and very high costs.

As shown in the case study presented in this chapter, glazings with monolithic aerogel in interspace are the most efficient systems for very cold climates: for instance, in Ottawa the annual energy demand decreases about 22–27 % when compared to the standard glazings. Nevertheless, due to the high solar factor (*g*), the energy demand for cooling increases for monolithic aerogel windows, especially in temperate climates. Therefore, in general, granular aerogel glazing systems could be considered the best solutions in terms of annual energy demand reduction.

In relation to monolithic aerogel systems, in the future, the research should solve some relevant problems: the phenomenon of light scattering, which gives a reduced optical quality of vision through the material and the production process in order to produce very large sheets of monolithic aerogels, without altering performance.

Finally, spread of innovative glazings with granular aerogel could be possible in the near future if the manufacturers put emphasis on cost reduction; then, these solutions could easily replace conventional solutions, especially in very cold climates.

## References

AbuBakr Bahaj S, James PAB, Jentsch MF (2008) Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. Energy Build 5:720–731

Aegerter MA, Leventis N, Koebel MM (2011) Aerogels Handbook. Springer

Akimov YK (2003) Fields of application of aerogels (review). Instrum Exp Tech 3:287–299

Anderson AM, Wattley CW, Carroll MK (2009) Silica aerogels prepared via rapid supercritical extraction: effect of process variables on aerogel properties. J Non-Cryst Solids 2:101–108

Baetens R, Jelle BP, Gustavsen A (2011) Aerogel insulation for building applications: a state-of-the-art review. Energy Build 43:761–769

Bavarian center for applied energy research. Division: functional materials for energy technology ZAE Bayern, Würzburg, Germany (2010) Report ZAE 2—0410—02. Measurement of the transmittance and reflectance of Nanogel samples. Available at http://solarinnovations.com/wp-content/uploads/2012/04/transmittance_reflectance.pdf. (Last access on 23th Jan 2013)

Bouquerela M, Duforestel T, Baillis D, Rusaouen G (2012) Heat transfer modeling in vacuum insulation panels containing nanoporous silicas—a review. Energy Build 54:320–336

Buratti C (2003) Transparent insulating materials: experimental data and buildings energy savings evaluation. In: Proceedings of energy and environment 2003. In: first international conference on sustainable energy, planning and technology in relationship to the environment. Halkidiki, Greece

Buratti C, Moretti E (2011) Transparent insulating materials for buildings energy savings: experimental results and performance evaluation. In: Proceedings of third international conference on applied energy. Perugia, Italy

Buratti C, Moretti E (2011b) Lighting and energetic characteristics of transparent insulating materials: experimental data and calculation. Indoor Built Environ 20(4):400–411

Buratti C, Moretti E (2012) Experimental performance evaluation of aerogel glazing systems. Appl Energy 97:430—437. doi:http://dx.doi.org/10.1016/j.apenergy.2011.12.055

Buratti C, Moretti E (2012b) Glazing systems with silica aerogel for energy savings in buildings. Appl Energy 98:396–403. doi:http://dx.doi.org/10.1016/j.apenergy.2012.03.062

Buratti C, Moretti E, Belloni E, Cotana F (2013) Unsteady simulation of energy performance and thermal comfort in non-residential buildings. Build Environ 59:482–491

Dowson M, Harrison D, Craig S, Gill Z (2011) Improving the thermal performance of single-glazed windows using translucent granular aerogel. Int J Sustain Eng 4(3):266–280

Duer K, Svendsen S (1998) Monolithic silica aerogel in superinsulating glazings. Sol Energy 63:259–267

Ebrahimpour A, Maerefat M (2011) Application of advanced glazing and overhangs in residential buildings. Energy Convers Manage 52:212–219

EN 410 (2011) Glass in building—determination of luminous and solar characteristics of glazing

EN ISO 20140-2 (2010) Acoustics—measurement of sound insulation in buildings and of building elements. Part 2: laboratory measurements of airborne sound insulation of building elements

EN ISO 717-1 (2007) Acoustics—rating of sound insulation in buildings and of building elements. Part 1: airborne sound insulation

Forest L, Gibiat V, Woignier T (1998) Biots theory of acoustic propagation in porous media applied to aerogels and alcogels. J Non-Cryst Solids 225:287–292

Forest L, Gibiat V, Hooley A (2001) Impedance matching and acoustic absorption in granular layers of silica aerogels. J Non-Cryst Solids 285:230–235

Hassouneh K, Alshboul A, Al-Salaymeh A (2010) Influence of windows on the energy balance of apartment buildings in Amman. Energy Convers Manage 51:1583–1591

Ivanov GR, Tomova R, Djambova ST, Nadoliiski M, Dimova–Malinovska D (2010) Functionalized aerogels—new nanomaterials for energy-efficient building. Preliminary AFM, nanoindentation and EIS studies. J Phys: Conf Series 253. doi:10.1088/1742-6596/253/1/012077

Jelle BP, Hynd A, Gustavsen A, Arasteh D, Goudey H, Hart R (2012) Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities. Sol Energy Mater Sol Cells 96:1–28

Jensen KI, Schultz JM, Kristiansen FH (2004) Development of windows based on highly insulating aerogel glazings. J Non-Cryst Solids 350:351–357

Kistler SS (1931) Coherent expanded aerogels and jellies. Nature 127

Koebel M, Rigacci A, Achard P (2012) Aerogel-based thermal superinsulation: an overview. J Sol-Gel Sci Technol 63:315–339. doi:10.1007/s10971-012-2792-9

Oral GK, Yener AK, Bayazit NT (2004) Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions. Build Environ 3:281–287

Pajonk GM (2003) Some applications of silica aerogels. Colloid Polym Sci 281:637–651

Parmenter KE, Milstein F (1998) Mechanical properties of silica aerogels. J Non-Cryst Solids 223(3):179–189

Pérez-Lombard L, Ortiz J, Pout C (2008) A review on buildings energy consumption information. Energy Build 40:394–398

Pierre AC, Pajonk GM (2002) Chemistry of aerogels and their applications. Chem Rev 102:4243–4265

Reim M, Beck A, Körner W, Petricevic R, Glora M, Weth M, Schliermann T, Schmidt CH, Pötter FJ, Fricke J (2002) Highly insulating aerogel glazing for solar energy usage. Solar Energy 1:21–29

Reim M, Reichenauer G, Körner W, Manara J, Arduini-Schuster M, Korder S, Beck A, Fricke J (2004) Silica-aerogel granulate—structural, optical and thermal properties. J Non-Cryst Solids 350:358–363

Reim M, Korner W, Manara J, Korder S, Arduini-Schuster M, Ebert HP, Fricke J (2005) Silica aerogel granulate material for thermal insulation and daylighting. Sol Energy 2:131–139

Rigacci A, Einarsrudb M, Nilsenb E, Pirardc R, Ehrburger-Dolled F, Chevalier B (2004) Improvement of the silica aerogel strengthening process for scaling-up monolithic tile production. J Non-Cryst Solids 350:196–201

Riffat SB, Qiu G (2012) A review of state-of-the-art aerogel applications in buildings. Int J Low-Carbon Technol Adv Access

Sadineni SB, Madala S, Boehm RF (2011) Passive building energy savings: a review of building envelope components. Renew Sustain Energy Rev 15:3617–3631

Schultz JM, Jensen KI, Kristiansen FH (2005) Super insulating aerogel glazing. Sol Energy Mater Sol Cells 89:275–285

Schultz JM, Jensen KI (2008) Evacuated aerogel glazings. Vacuum 82:723–729

Soleimani Dorcheh A, Abbasi MH (2008) Silica aerogel: synthesis, properties and characterization. J Mater Process Technol 199:10–26

Tajiri K, Igarashi K (1998) The effect of the preparation conditions on the optical properties of transparent silica aerogels. Sol Energy Mater Sol Cells 4:189–195

Werner M, Brand L (2010) Focus Report 2010—Aerogels, general sector reports, chemistry and materials, observatory NANO. Available at http://www.observatorynano.eu/project/filesystem/files/WP2_ChemistryMaterials_FocusReport_Aerogels_29_04_2010.pdf. Accessed 22 Jan 2013

Wong IL, Eames PC, Perera RS (2007) A review of transparent insulation systems and the evaluation of payback period for building applications. Sol Energy 81(9):1058–1071

## Company Websites

Advanced Glazings Ltd., Canada. http://www.advancedglazings.com/nanogel. (Last access on 22nd Sept 2012)

Airglass AB, Sweden. http://www.airglass.se/. (Last access on 22nd Sept 2012)

Aspen aerogels, USA. http://www.aerogel.com/

Birdair, USA. http://www.tensothermroofing.com/

Cabot Corporation, USA. USA. http://www.cabot-corp.com/Aerogel/Daylighting. (Last access on 22nd Sept 2012)

Kalwall Corporation. USA. http://www.kalwall.com/aerogel.htm. (Last access on 22nd Sept 2012)

Nano High-Tech Co., Ltd China. http://www.nanuo.cn/english/product-3.htm. (Last access on 22nd Sept 2012)

Okalux GmbH, Germany. http://www.okalux.com. (Last access on 22nd Sept 2012)

Roda E.M.B. Products AG, Germany. http://www.roda.de/download_en_22.html. (Last access on 22nd Sept 2012)

Roofglaze Ltd, Scobalit AG, Switzerland. http://www.scobalit.ch/de/scobatherm.html. (Last access on 22nd September 2012)

Stoakes Systems, UK. http://www.stoakes.co.uk/pages/rooflights/kalwall_nanogel_rooflights.htm . (Last access on 22nd Jan 2013)

Technical Glass Products, USA. http://www.tgpamerica.com/structural-glass/pilkington-profilit/. (Last access on 22nd Sept 2012)

Xtralite Rooflight, UK. http://www.xtralite.co.uk/products/specialist-glazing/lumira-technology/. (last access on 22nd Sept 2012)

# Switchable Glazing Technology: Electrochromic Fenestration for Energy-Efficient Buildings

**Claes G. Granqvist**

**Abstract** Switchable electrochromic glazings employ multilayer devices with a basic resemblance to thin-film electrical batteries and color/bleach upon electrical charging/discharging. The transmittance of visible light and solar energy can be varied reversibly and persistently between widely separated extrema, which makes it possible to regulate solar energy inflow for energy savings as well as visible light level for comfort reasons. This chapter outlines the basics of electrochromic glazing technology and its implementation in buildings. Device designs and component materials are discussed in some detail. Several practical electrochromic glazing designs are introduced with focus on a foil-type construction applicable as a lamination material between glass panes. Electrochromic glazing has been discussed for many years and has many unfulfilled promises; it is argued here that today's developments are likely to change this situation so that electrochromic glazing will be able to take its proper place as an important energy savings and comfort enhancing technology for near-zero-energy building refurbishment as well as for new buildings.

## 1 Introduction

Switchable glazings based on electrochromics allow the transmittance of visible light and solar energy to be changed reversibly and persistently by the use of an electrical signal (Granqvist 1995), thereby creating energy efficiency as well as human comfort in buildings wherein this glazing is employed. Electrochromic glazings have been discussed for many years and have largely been viewed as interesting for niche markets rather than as commodity products

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(Granqvist 2006, 2012a). However, a number of recent market analyses indicate that the time may now be ready for electrochromic glazings to fulfill their long-term promises and take their proper place as a key technology for near-zero-energy building refurbishment.

First of all, one should note that the market for flat glass is huge by any standards: The annual production is about six billion square meters per year and is predicted to have an annual growth rate of roughly 6 % (Freedoniagroup 2011). Most of this is high-quality glass produced by the float process and intended for use in windows in buildings of different kinds. This glass is also suitable as a substrate for surface coatings.

Electrochromics is one of the "green nanotechnologies" (Smith and Granqvist 2010), which enjoy intense interest today. Section 1, discusses why this is so and also looks at the electromagnetic radiation in our natural surroundings in order to define a basis for treating energy-efficient fenestration. Section 2 outlines a standard oxide-based "battery-type" electrochromic device and treats the materials of its components; the discussion includes electrochromic oxides and their nanofeatures and optical absorption mechanisms, transparent and electrically conducting contacts, and electrolytes and their functionalization. Some parts of this section go rather deeply into material science and can be omitted by readers who want to get a general view of electrochromic glazings. Section 3 then covers electrochromic devices with foci on important challenges and on constructions of particular interest for practical implementation of electrochromic glazing. Some alternatives to the "battery-type" device are touched upon. Concluding remarks are given in Sect. 4. Parts of the presentations below are adaptations and updates of earlier, recent book chapters by Granqvist (2013a, b).

## *1.1 "Natural" Radiation and Why Switchable Glazing is Needed*

Windows and glass facades are important for near-zero-energy building refurbishment. The fundamental reason why this is so is that they are weak links in the buildings' energy system and frequently let in or let out too much energy, which then must be balanced by energy-guzzling cooling or heating. And the solution to this conundrum is not that the windows must be made small, because we need windows for visual indoors–outdoors contact and for daylighting, which have been identified as essential factors for human well-being and for good task performance in work by Heshong et al. (2002a, b) and others.

Energy-efficient windows must function in harmony with nature and make good use of the light and energy that nature offers; therefore, we now turn to the electromagnetic radiation in our natural surroundings (Granqvist 1981; Smith and Granqvist 2010). Thermal radiation is given by a blackbody spectrum multiplied by a material-dependent emittance and serves as a suitable starting point. Figure 1 shows that blackbody radiation lies in the $3 < \lambda < 50$ µm wavelength range for

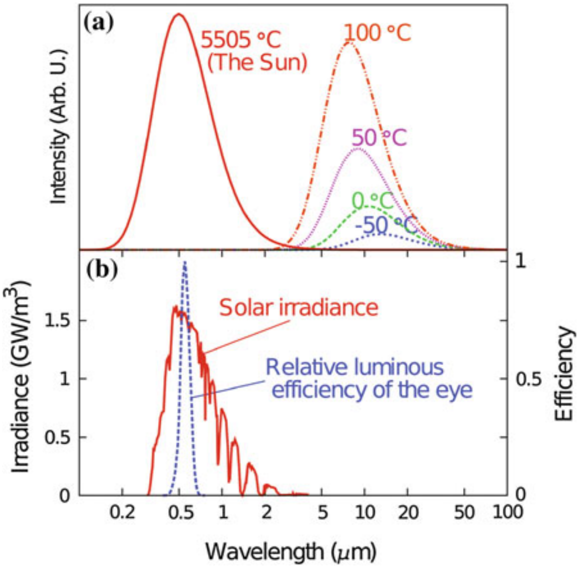


**Fig. 1** *Upper panel* shows blackbody spectra for several temperatures, including that of the sun's surface. *Lower panel* illustrates a typical solar irradiance spectrum at ground level and during clear weather, and the sensitivity of the light-adapted human eye

the temperatures of interest, those between −50 and +100 °C. Solar radiation, on the other hand and also shown in the figure, comes at $0.3 < \lambda < 3$ μm, i.e., at wavelengths that are shorter and almost non-overlapping with those for thermal radiation. Solar irradiation at the earth's ground level almost corresponds to the blackbody spectrum for the sun's surface temperature multiplied by the spectral transmittance through the earth's atmosphere. The human eye, which is considered next, only responds to part of the solar spectrum and has a bell-shaped sensitivity curve at $0.4 < \lambda < 0.7$ μm with a peak at 0.55 μm, as again illustrated in Fig. 1.

Quantitative measures of luminous and solar transmittance of a surface, denoted $T_{\mathrm{lum}}$ and $T_{\mathrm{sol}}$, can be obtained by averaging according to

$$T_{\mathrm{lum,sol}} = \int d\lambda \varphi_{\mathrm{lum,sol}}(\lambda) T(\lambda) \,/\, \int d\lambda \varphi_{\mathrm{lum,sol}}(\lambda)\,, \tag{1}$$

where $T(\lambda)$ is spectral transmittance, $\varphi_{\mathrm{lum}}$ is the eye's sensitivity (Wyszecki and Stiles 2000), and $\varphi_{\mathrm{sol}}$ is solar irradiance for air mass 1.5 (with the sun at 37° above the horizon) (ASTM 2008).

The data in Fig. 1 indicate that the "natural" radiation is *spectrally selective*, and it follows that surfaces devised to make the most of this radiation should be spectrally selective too. For example, it may be desirable to have completely different optical properties for solar and thermal radiation, and one can also create surfaces which are very different for visible light and near-infrared solar irradiation in the $0.7 < \lambda < 3$ μm range (Granqvist 1981, 2007; Smith and Granqvist 2010). Solar radiation can also be dominated by incidence from a specific direction, while visual indoors–outdoors contact is largely along horizontal lines of sight, so *angular selective* optical properties may be interesting. Finally, everyone knows that the "natural" radiation is *time variable* and usually different during different times of the day and during different seasons. To benefit from, or compensate for, this time variability, one would like to have materials whose properties can be changed, reversibly and persistently, via some external stimulus. Materials which permit this kind of variability are known as "chromogenic" (Granqvist 1990; Lampert and Granqvist 1990).

There are several kinds of chromogenic materials (Granqvist 1990; Lampert and Granqvist 1990; Smith and Granqvist 2010). The *photochromic* ones may be the most well known; their optical transmittance drops when subjected to ultraviolet light, and they return to their original properties in the absence of such irradiation. Photochromic glass and plastic are widely used in sunglasses. *Thermochromic* materials have different optical properties depending on their temperature. *Electrochromic* materials, which form the basis for the electrochromic glazings that this chapter is about, change their properties when subjected to an applied electrical current or voltage. There are also *gasochromic* materials with optical properties depending on their gaseous ambience.

## 1.2 Energy Efficiency and Other Benefits of Electrochromic Glazing

Energy efficiency in the built environment is a difficult topic. It is closely tied to user aspects such as thermal comfort (Fanger 1970), which is perceived differently among different persons. Nevertheless, the energy efficiency of electrochromic glazing has been discussed repeatedly and very positive effects have been documented.

A very simplistic model for the energy efficiency was put forward several years ago by Azens and Granqvist (2003a). It is based on solar irradiation intensity, achievable transmittance modulation, and expected use of buildings and argues that the annual energy *savings* would be ~170 kWh per square meter of (south facing) window area, i.e., the same as good solar cell panels with 17 % efficiency would *generate* if they were oriented in the same way as the windows. There are several other more detailed, supporting estimates based on elaborate assessments of the energy performance of commercial buildings; these assessments also highlight aspects such as downsizing of air-conditioning systems, lighting benefits, and user satisfaction (Clear et al. 2006; Lee et al. 2006, 2012a; Zinzi 2006; Lim et al. 2013). An unpublished study has indicated that a modern commercial building in Middle and Northern Europe could function without active air cooling if it were equipped with electrochromic glazing (Ramezani and Nybom 2009). A recent study by Gillaspie et al. (2010) argued that the introduction of well-insulated electrochromic glazing in commercial and residential buildings in the USA would be able to save as much as ~4.5 % on the national energy expenditure.

The energy savings possible with electrochromic glazings depend critically on their control strategy and orientation (Azens and Granqvist 2003a; Assimakopoulos et al. 2004; Jonsson and Roos 2010) and should account for whether persons are present or not in rooms equipped with such glazing. Under unfavorable conditions, some recent modeling results indicate that electrochromic glazing may even increase the energy consumption (Katanbafnasab and Abu-Hijleh 2013).

## 2 Materials for Electrochromic Glazings

The original discovery of electrochromism was made through studies of vacuum-deposited tungsten oxide films during the 1960s and 1970s (Deb 1973, 1995, 2008; Granqvist 1995, 2000). Display devices were of primary interest in the beginning, but the focus was then shifted to energy-efficient glazings—referred to as "smart windows" by Svensson and Granqvist (1986)—as it gradually became clear that electrochromic technology could be used for energy savings in buildings. However, display applications are presently making a strong comeback for applications in "electronic paper" and, more generally, in transparent electronics. The displays can make good use of organic electrochromic materials (Beaujuge and Reynolds 2010; Jensen et al. 2012). The organics are generally regarded as too fragile under ultraviolet light to be useful in glazings, though, and hence, they are not discussed further below.

Parts of Sect. 2 deal with material science issues, and Sects. 2.2, 2.3, and 2.5 are intended for readers with a special interest in these aspects; they are not necessary to get an overall view on electrochromic glazings.

### 2.1 How Does It Work? Basic Device Design and Typical Materials

Figure 2 shows a typical design of an electrochromic device (Granqvist 1995). Five layers are backed by one transparent substrate or are positioned between two such substrates in a laminate configuration. The substrate is transparent and typically of glass or flexible polyethylene terephthalate (PET) foil. In an idealized case, the centrally positioned layer is a pure ion conductor (electrolyte), either a thin-film or a polymer electrolyte. Its ions should be small in order to be easily mobile, with protons ($H^+$) and $Li^+$ being the most common choices.

The electrolyte joins an electrochromic film—which is a mixed conductor for both ions and electrons—and an ion-storage film which in most cases also has electrochromic properties. This three-layer stack is positioned between two transparent and electrically conducting thin films. Applying a voltage between the transparent conductors leads to ion exchange between the electrochromic and ion-storage films, and charge balance is maintained via a counter-flow of electrons in the external circuit and electron injection and extraction in the electrochromic and ion-storage films via the transparent conductors. Voltage reversal or, provided

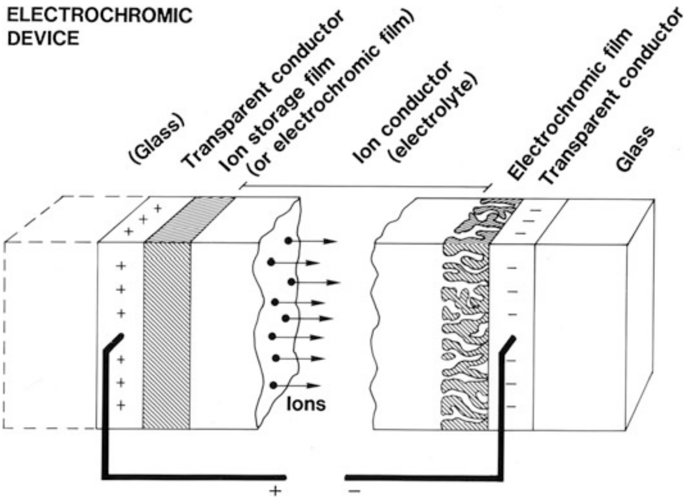


**Fig. 2** Basic design of a "battery-type" electrochromic device. *Arrows* indicate ion transport in an electrical field. From Granqvist (1995)

that suitable materials are used, short-circuiting brings back the original properties. The charging can be interrupted at any intermediate level, implying that the device has open-circuit memory. Hence, electrical power is needed only to change the optical properties, not to maintain them, which is important with regard to energy efficiency. The voltage needed in the electrochromic device is only a few volt DC, which makes solar cell powering convenient (Lampert 2003).

The discussion above makes it clear that the electrochromic device can be described as an electrical battery with a charging state corresponding to a degree of optical absorption. This analog goes a long way, and the two types of devices share numerous properties and idiosyncrasies. One example is that they can be damaged by overcharging or overheating, but that they also exhibit poorly understood "self-healing" features. Another important similarity is that the properties cannot be changed abruptly, and the coloring/bleaching (or charging/discharging) times may amount to seconds for a device that is few square centimeters in size, while it can be minutes or even tens of minutes when the size is of the scale of square meters.

The "battery-type" electrochromic device in Fig. 2 works best if it incorporates two electrochromic films: one coloring under ion insertion and called "cathodic" and another coloring under ion extraction and called "anodic." The most well-known and widely studied cathodic oxides are based on W, Mo, and Nb, whereas the corresponding anodic oxides are based on Ir and Ni (Granqvist 1995). Devices using W oxide together with Ni oxide combine a number of advantageous properties (Avendaño et al. 2006; Niklasson and Granqvist 2007) and are the basis for several practical electrochromic devices, as we return to in Sect. 3. Ir oxide has excellent electrochromic properties, but it is very rare and precious and hence ill-suited for large-scale applications; however, the properties remain rather

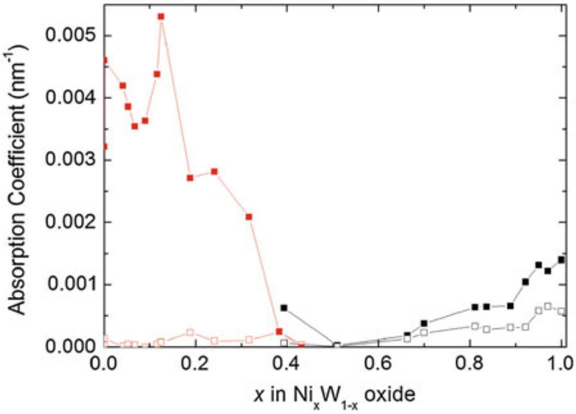


**Fig. 3** Absorption coefficient at $\lambda = 0.55$ μm for electrochromic films in the full range between cathodic W oxide and anodic Ni oxide. *Filled* and *open symbols* refer to colored and bleached states, respectively. Data points are connected by *straight lines*. From Green (2012)

unchanged after dilution with cheaper Sn or Ta (Backholm and Niklasson 2008; Niwa and Takai 2010). Cobalt oxide is less widely investigated than Ni oxide, but the two oxides share many common features (Lee et al. 2012b). V pentoxide is special in its display of anodic and cathodic features in different wavelength ranges (Talledo and Granqvist 1995) but serves mainly as an anodic oxide.

Composite oxides have received relatively scant interest as electrochromic materials, which may seem surprising since mixing can be expected to lead to superior performance. One exception, however, can be found in recent work by Green (2012) on films in the full compositional range from W oxide to Ni oxide. The nanostructure of the mixed material varies strongly with the composition, as investigated by a variety of techniques (Green et al. 2011; Valyukh et al. 2012). Figure 3 shows that the dependence of a key optical property, the absorption coefficient, depends critically on the composition. In the W-rich end, there is a conspicuous peak at ~10 % of Ni for the colored films; in an intermediate range, the electrochromism is almost zero, and at the Ni-rich end, an addition of W plays a minor role. Figure 4 explores the optical properties for W-rich samples in more

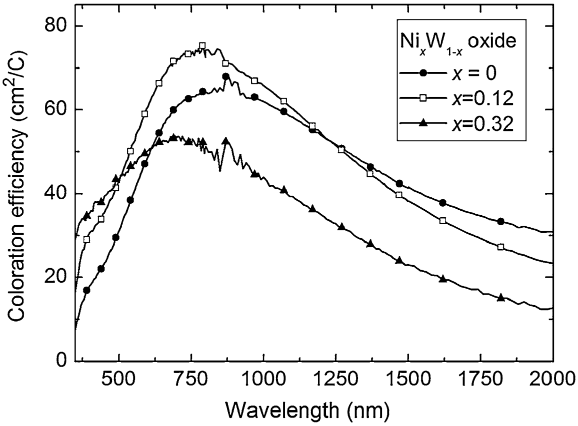


**Fig. 4** Spectral coloration efficiency for electrochromic films with the shown compositions. From Green et al. (2012)

detail and reports data on spectral coloration efficiency (the change in optical density per amount of charge exchange) for a few compositions (Green et al. 2012). The favorable properties of a small Ni addition to W oxide stand out again. Another study showed that the bleached-state transmittance of Ni oxide could be improved by several additives to Ni oxide (Avendaño et al. 2004).

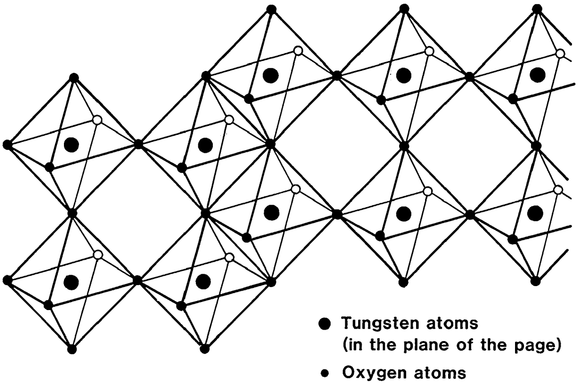
## *2.2 Nanostructures are Crucial for Electrochromic Thin Films*

Nanostructural features are essential for electrochromic devices, as discussed next. The majority of the electrochromic oxides comprise octahedral units in various arrangements (Granqvist 1995), and the spaces between these units are large enough to permit some transport of small ions. Clusters of the octahedra can form disordered and more or less loosely packed aggregates with significant porosity. Hence, nanostructure enters at two or more length scales. The discussion to follow is focused on W oxide, which has been studied in considerable detail. Its generality might be questioned for the anodic electrochromic oxides, though, and film porosity and processes at grain boundaries may then be essential, but the situation is not yet clear.

Figure 5 shows nanostructural features of W oxide and delineates $WO_6$ octahedra comprising six oxygen atoms and a centrally located tungsten atom. Stoichiometry corresponds to a state wherein each octahedron shares corners with neighboring octahedra so that $WO_3$ is formed. Substoichimetry is easily formed in so-called Magnéli phases (Magnéli 1950) with the presence of some edge-sharing octahedra. The three-dimensional structure formed by the octahedra leads to a three-dimensional network of "tunnels," which are wide enough to act as conduits for ion transport.

The crystalline structure above is somewhat simplified, though, since it refers to a cubic structure, and a tetragonal structure is more appropriate for $WO_3$ at normal temperature and pressure. This is, in fact, favorable for ion transport since the

**Fig. 5** Schematic image of corner-sharing and edge-sharing octahedra in slightly substoichiometric crystalline W oxide. From Granqvist (1995)



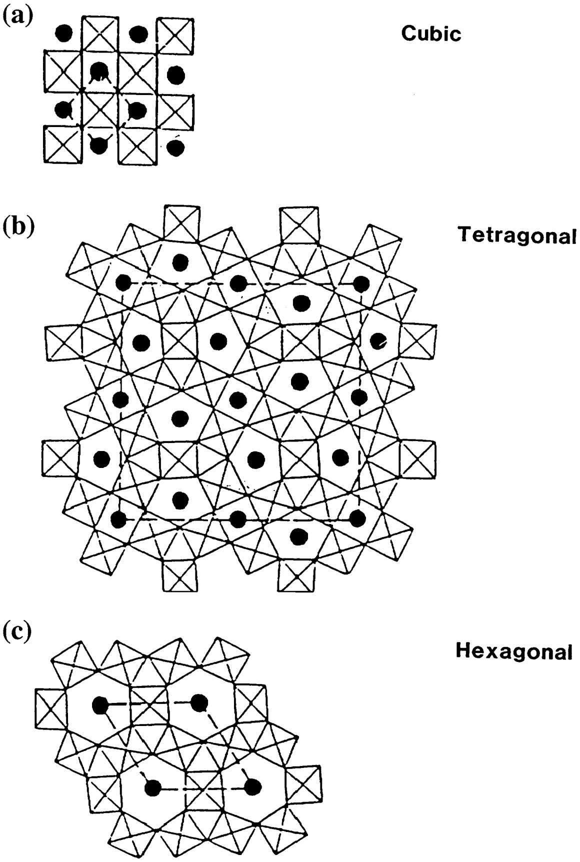


**Fig. 6** Structures representing W oxide with the shown structures. *Dots* indicate sites for ion insertion in open spaces between $WO_6$ octahedra. *Dashed lines* signify extents of the unit cells. From Granqvist (1995)

spaces between the octahedral units are larger than for the cubic structure, as indicated in Fig. 6b. Hexagonal structures, which are delineated in Fig. 6c, seem to be formed easily in thin films (Granqvist 1995), and then, the structure is even better for ion transport.

The actual nanostructures in thin films of W oxide have been studied several times, and Fig. 7 reports data based on modeling of X-ray scattering from samples made by evaporation onto substrates at different temperatures (Nanba and Yasui 1989). A cluster-type structure is apparent with hexagonal-like units that grow and interconnect at sufficiently high substrate temperatures.

The relationship between nanostructure and thin-film deposition parameters can often be well illustrated through “zone diagrams,” which have been reported for different deposition techniques and with different degrees of detail. Figure 8 shows a “Thornton diagram” for the particular case of sputter deposition (Thornton 1974); more elaborate versions can be found elsewhere (Barna and Adamik 1998; Anders 2010). It is evident that low substrate temperatures and high pressures in the discharge plasma for the sputtering lead to nanoporous structures of a kind that

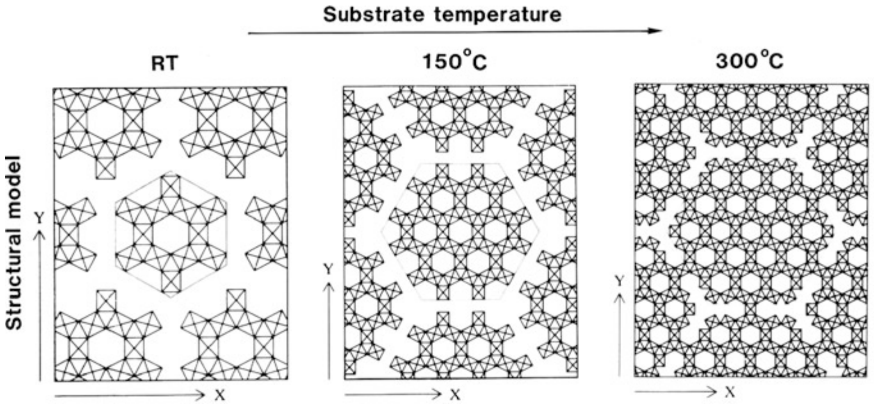
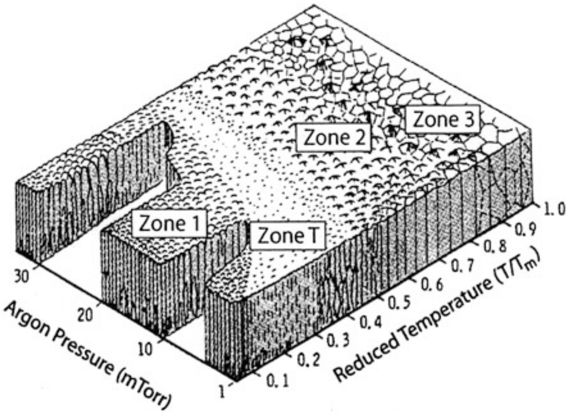


**Fig. 7** Structural models for $WO_6$ octahedra in W oxide films made by evaporation onto substrates at the shown temperatures (*RT* denotes room temperature). *Arrows* in the *x* and *y* directions are 2 nm long. After Nanba and Yasui (1989)

**Fig. 8** Schematic diagram showing thin-film nanostructures for different pressures in the sputter plasma and for different substrate temperatures. The material's melting temperature is denoted $\tau_m$. From Thornton (1974)



is desirable for electrochromic applications. It is of interest to notice in this context that the deposition may involve molecular species, and trimeric $W_3O_9$ molecules are well known to form during evaporation (Maleknia et al. 1991), while a preponderance of $(W_6O_{19})^{2-}$ (known as "Lindqvist anions") may be present in aqueous solutions (Lang et al. 2012) used for liquid-phase thin-film deposition.

## 2.3 Optical Absorption Mechanisms

The reason for the variable optical absorption in electrochromic materials has been discussed extensively and is a complicated issue for several reasons. First of all, the oxides are often poorly defined regarding crystallinity, and they can incorporate different amounts of mobile ions, water molecules, etc. In addition to this complexity, some of the interesting materials—such as NiO—have an electronic structure that has been debated for decades without any clear picture having been established. Here, we discuss the coloration of W oxide and Ni oxide; a more detailed discussion is given elsewhere by Niklasson and Granqvist (2007).

The insertion and extraction of hydrogen ions (protons) and electrons can be written as a simple electrochemical reaction according to

$$(\mathrm{WO_3} + \mathrm{H}^+ + e^-)_{\mathrm{bleached}} \leftrightarrow (\mathrm{HWO_3})_{\mathrm{colored}}, \quad (2)$$

where the $H^+$ ion could be replaced by $Li^+$ and $e^-$ denotes electrons. In order to ensure electrochemical reversibility, the amount of $H^+$ should be limited so that the colored material is $H_xWO_3$ with $x < 0.5$ (Berggren and Niklasson 2006; Berggren et al. 2007). The corresponding reaction for Ni oxide is (Avendano et al. 2005, 2009)

$$(\mathrm{Ni(OH)_2})_{\mathrm{bleached}} \leftrightarrow (\mathrm{NiOOH} + \mathrm{H}^+ + e^-)_{\mathrm{colored}}, \quad (3)$$

where the reaction is supposed to be confined to grain boundaries.

The electronic band structure of oxides comprised of octahedral units forms a good starting point for discussing the optical properties of anodic and cathodic electrochromic oxides. The oxygen 2*p* bands are separated from the metal *d* levels, and the octahedral coordination gives rise to a splitting of the latter band (Goodenough 1971). Inserting and extracting charge leads to a displacement of the Fermi level, which in the cathodic oxides yields a partial filling of the lower part of the *d* band, while for the anodic oxides, this lower part of the *d* band gets completely filled so that the band gap between the two portions of the *d* band produces optical transparency (Granqvist 1994, 1995).

The detailed absorption mechanism can be understood as follows for W oxide: The electrons inserted along with the ions are localized on tungsten sites, which means that some $W^{6+}$ sites are transformed to $W^{5+}$. Photon absorption can provide enough energy to transfer this inserted electron on site $i$ to a neighboring site $j$ by (Schirmer et al. 1977; Granqvist 1995; Ederth et al. 2004)

$$\mathrm{W}_i^{5+} + \mathrm{W}_j^{6+} + \text{photon} \rightarrow \mathrm{W}_i^{6+} + \mathrm{W}_j^{5+}, \quad (4)$$

which is referred to as intervalence transfer or polaron absorption within chemistry and physics, respectively. But the transfer is only possible if it takes place from a site occupied by an electron to an empty site available to receive the electron. This is not always possible, and if the electron and ion insertion is high, there will not only be $W^{5+} \leftrightarrow W^{6+}$ transfer but also $W^{4+} \leftrightarrow W^{6+}$ and $W^{4+} \leftrightarrow W^{5+}$ (Berggren and Niklasson 2006; Berggren et al. 2007). Such “site saturation” effects, first discussed by Denesuk and Uhlmann (1996), may not be so prevalent in a practical situation, though, since the permissible intercalation levels for electrochemical reversibility make $W^{5+} \leftrightarrow W^{6+}$ overwhelmingly common.

## *2.4 Transparent Conducting Thin Films: A Survey*

Transparent electrical conductors are essential for electrochromic devices and may be their most expensive individual components. There are several types of transparent conductors, comprised of different materials and having different properties (Granqvist 2007; Ginley et al. 2010) as discussed below.

Heavily doped wide band-gap oxide semiconductor oxides are often used in electrochromic devices. The most common materials are $In_2O_3$:Sn (indium tin oxide, ITO), ZnO:Al (AZO), ZnO:Ga (GZO), ZnO:In (IZO), and $SnO_2$:F (FTO), and the doping level is a few percent. All these materials can have a resistivity as low as $\sim 1 \times 10^{-4}$ Ωcm, a luminous absorptance of only a few percent in a ~0.3-μm-thick film, and very good durability. The optical properties are well understood (Hamberg and Granqvist 1986; Jin et al. 1988; Stjerna et al. 1994), and hence, modeling of the optical performance can be done reliably. Films of ITO, AZO, GZO, and IZO made by carefully controlled sputter deposition onto glass and PET typically show resistivities of $\sim 2 \times 10^{-4}$ and $\sim 4 \times 10^{-4}$ Ωcm, respectively (Granqvist 2007). High-quality FTO films can be made by spray pyrolysis onto hot glass emerging from the leer during float glass production. All the mentioned oxides have a high value of $T_{sol}$. Concerning $T_{lum}$, antireflection-coated ITO can be more transparent than uncoated glass (Hamberg and Granqvist 1986), as shown in Fig. 9.

ITO films can be more expensive than the Zn-based and Sn-based alternatives as a consequence of the high price of In metal [despite its relative elemental abundance in the earth's crust (Schwarz-Schampera and Herzig 2002)]. Another possibly limiting factor for ITO may be the newly reported danger of thin-film deposition leading to pulmonary disorders (Omae et al. 2011).

Extremely thin continuous metal films—especially of the coinage metals Cu, Ag, and Au—can serve as excellent alternatives to the heavily doped wide band-gap semiconductors (Granqvist 2007; Lansåker et al. 2013). Their electrical

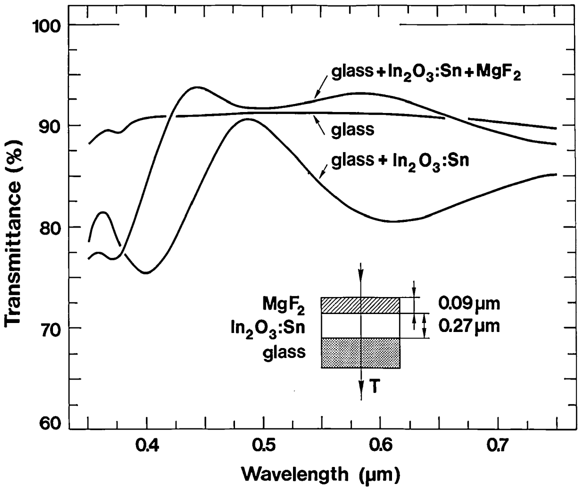


**Fig. 9** Spectral transmittance *T* for an ITO film on glass before and after antireflection treatment with an $MgF_2$ layer having optimized thickness. From Hamberg and Granqvist (1986)

conductivities can be much higher than for ITO and its alternatives, and the metal thickness can be correspondingly smaller in a device. The luminous absorptance, typically, is no larger than some percent. The metal films should be embedded between high-refractive-index coatings in order to benefit from induced transmittance. Multilayer coatings of this kind are used commercially on a very large scale in windows with low thermal emittance ("low-*E*") and hence good thermal insulation, as well as for windows with large near-infrared reflectance ("solar control") and thereby diminished need for space cooling (Gläser 2000). Figure 10 illustrates typical properties of fully developed (commercial) coatings for low-*E* and solar control applications (International Glazing Database 2012). These types of coated glass are of interest also for electrochromic glazings, although it

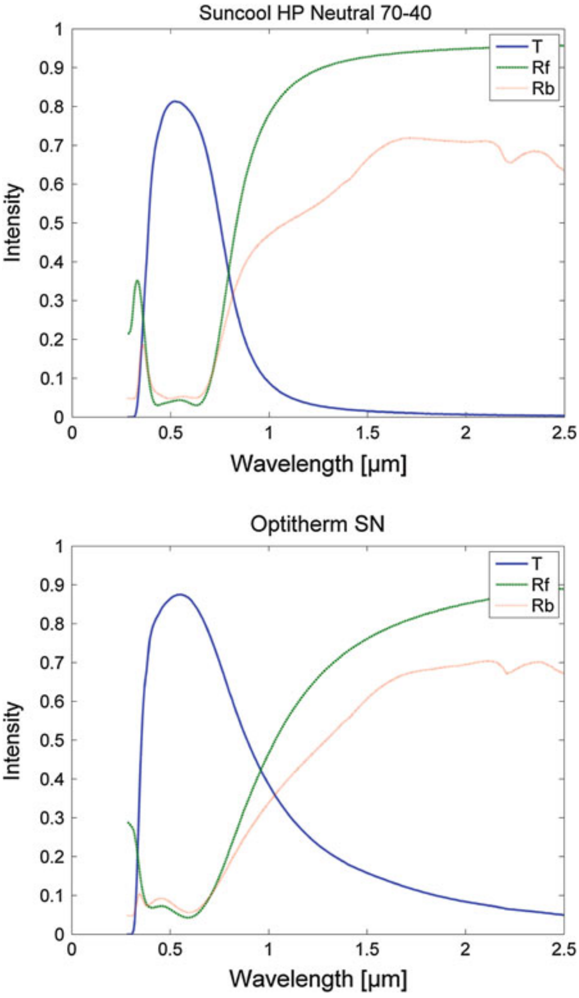


**Fig. 10** Spectral transmittance *T* and reflectance from the front side $R_f$ and back side $R_b$ for glass coated with metal-based films optimized for solar control (*upper panel*) and low thermal emittance (*lower panel*). From the International Glazing Database (2012)

must be assured that the durability is sufficient. The latter requirement may necessitate gold-containing films (Lansåker et al. 2009).

Carbon-based transparent conductors have attracted much interest recently. Meshes of carbon nanotubes can give high values of $T_{\mathrm{lum}}$ and $T_{\mathrm{sol}}$ jointly with good electrical conductivity (Hu et al. 2010a; Niu 2011). An alternative to the nanotubes is graphene, which is subject to intense research and development efforts today (2013); it comprises atomically thin layers of carbon atoms forming a honeycomb lattice (Geim and Novoselov 2007; Eda and Chhowalla 2010). Graphene layers can be made by mechanical or chemical exfoliation of graphite into individual sheets and also by chemical vapor deposition; roll-to-roll preparation of graphene layers has been documented recently by Bae et al. (2010, 2012).

Meshes based on metal nanowires are another possibility, and silver nanowires with diameters below 0.1 μm and lengths exceeding 10 μm can be made in large quantities through cheap reduction of silver nitrate (Hu et al. 2010b, 2011), and suspensions can be used for the deposition of highly stretchable thin films (Xu and Zhu 2012). Such nanowires are shown in Fig. 11. The coatings can have excellent electrical properties but suffer from some haze, which limits their applications for electrochromic glazings. Printable microgrids are an alternative option (Yu et al. 2012).

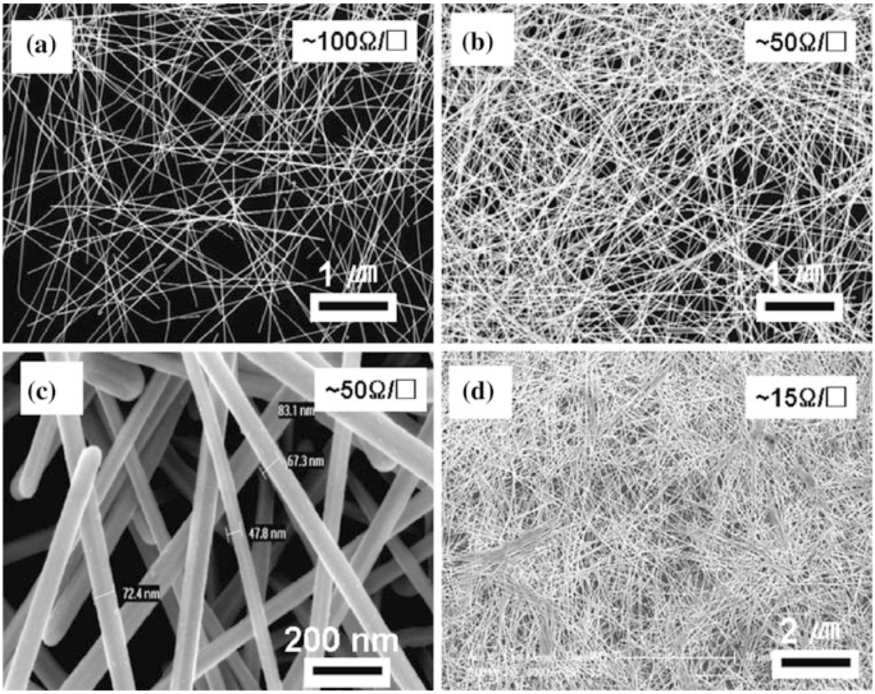


**Fig. 11** Electron micrographs of chemically prepared Ag nanowires at different densities and magnifications, and having the shown resistance per square. From Hu et al. (2010b)

## 2.5 Electrolyte Layers, Especially Functionalized Polymer Electrolytes

The centrally positioned electrolyte is an indispensible part of an electrochromic device. It can be a thin film, and $Ta_2O_5$ (Franke et al. 2000; Ahn et al. 2002, 2003; Subrahmanyam et al. 2007; Abe et al. 2009; Wang et al. 2011; Noguchi et al. 2012) as well as $ZrO_2$ (Larsson and Niklasson 2004) are well-known options. Other alternatives include polymer electrolytes and hybrid materials (Thakur et al. 2012) as well as polymerized ionic liquids (Sydam et al. 2012), which, in principle, allow a superior electrical insulation between the anodic and cathodic parts of the device.

Nanoparticles can be used for functionalization of polymer electrolytes, and recent work has studied these possibilities with regard to a "model electrolyte" consisting of polyethyleneimine–lithium bis(trifluoromethylsulfonyl) imide (PEI: LiTFSI) (Bayrak Pehlivan et al. 2012a, b) as well as to a proprietary electrolyte developed for roll-to-roll manufacturing of electrochromic devices (Bayrak Pehlivan et al. 2013). Figure 12 shows how the ion conductivity—which influences the coloration and bleaching speeds of an electrochromic device—is altered as a result of adding ~7-nm-diameter $SiO_2$ nanoparticles (fumed silica) (Bayrak Pehlivan et al. 2012a). Clearly, the ion conductivity goes up monotonically as the $SiO_2$ content rises. The diffuse optical transmittance remained at ~1 % up to 8 wt % of $SiO_2$, implying that the sample was almost haze free, which is essential for glazing products.

Adding nanoparticles comprised of a transparent conductor instead of $SiO_2$ can produce strong near-infrared absorption, which then invokes a "solar control" function to the electrochromic glazing. Figure 13 reports spectral transmittance for PEI:LiTFSI with ~13-nm-diameter ITO nanoparticles and shows that a strong

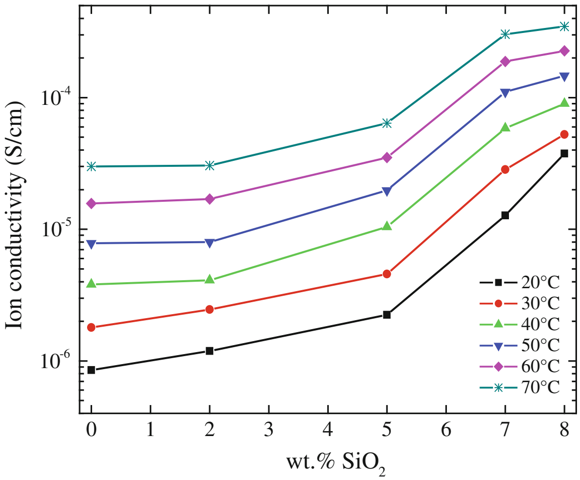
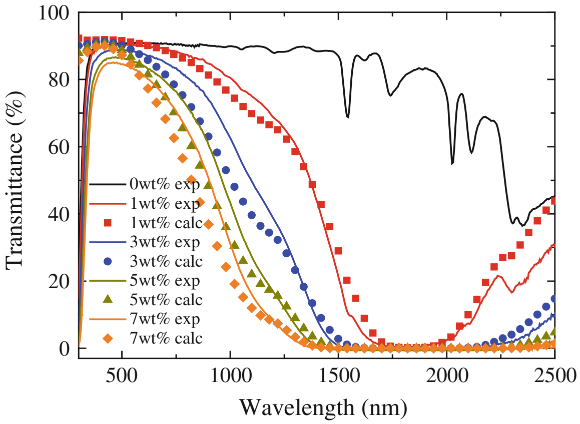


**Fig. 12** Ion conductivity at the shown temperatures for $SiO_2$-containing (PEI-$SiO_2$):(LiTFSI) electrolytes. Data points are connected by straight lines for convenience. From Bayrak Pehlivan et al. (2012a)

**Fig. 13** Spectral transmittance for ITO-containing (PEI-$SiO_2$):(LiTFSI) electrolytes as measured (*curves*) and calculated (*symbols*). From Bayrak Pehlivan et al. (2012b)



transmittance minimum develops in the near infrared when the ITO content is increased, whereas the luminous transmittance is almost unchanged (Bayrak Pehlivan et al. 2012b). For 7 wt % of ITO, one finds $T_{\text{lum}} = 83.3\ \%$ and $T_{\text{sol}} = 56.3\ \%$, while the electrolyte remains practically free from haze. The experimental properties can be understood in considerable detail from calculations, which is a consequence of the accurate theoretical model that exists for heavily doped wide band-gap oxides such as ITO and its Zn- and Sn-based alternatives. We note, in passing, that thermochromic $VO_2$-based nanoparticles would be able to transmit more energy at low temperature than at high temperature (Li et al. 2010, 2011, 2012a), which in principle could lead to additional control of the solar energy throughput of an electrochromic glazing; these possibilities have not yet been explored in detail, though.

# 3 Electrochromic Devices

## *3.1 Several Challenges*

The technology underlying electrochromic glazings involves several steps, and some of these lie outside the mainstream of today's industrial practice. Clearly, all these steps must be mastered for successful devices, and failing on one means failing on the end result. A list of six "critical" procedures has been given by Granqvist (2008a) as follows:

*Firstly*, the electrochromic and counter-electrode films shown in Fig. 2 must be nanoporous and uniform over large surfaces. There are several ways to accomplish this, as touched upon in Sects. 2.1, 2.2 and discussed in more detail elsewhere (Granqvist 2012b, 2013c). Reactive DC magnetron sputtering at pressures higher than those typical for metallization may be a preferred technique (cf. Fig. 8) (Granqvist 2008b).

The *second* point is that the transparent conductors must combine high electrical conductivity, low luminous absorptance, and excellent durability, which is challenging especially for temperature-sensitive substrates such as PET. For the time being (2013), ITO coatings may still be the best option, but metal-based alternatives are very promising.

As a *third* item, one should consider the electrochromic device as an electrical battery, and then, the question of how to introduce the electrical charge, and its balancing between the "anode" and "cathode," stands out as essential processes. Gas treatments have been developed for these purposes (Azens et al. 2003b; Aydogdu et al. 2010), but other means are available too.

*Fourthly*, the electrolyte is critical. If it is a thin film, it must be made under conditions that avoid pinholes and other causes of short-circuiting between the electrochromic film and the counter-electrode; if it is a polymer, it must be stable under ultraviolet irradiation and also serve as a reliable adhesive between the two parts of the electrochromic device. Nanoparticle-based functionalization is a newly introduced asset for the latter type of electrolyte, as discussed above in Sect. 2.5.

The *fifth* challenge concerns long-term cycling and storing durability, which again points at the kinship with electrical batteries. Simple switching between two voltage levels is commonplace in university-based research, but much more elaborate procedures may be required for electrochromic glazings to be used in buildings as discussed by Degerman Engfeldt et al. (2011).

The *sixth* and final item considered here concerns the possibility to accomplish large-scale, low-cost manufacturing. To this end, it is necessary to avoid time-consuming steps such as protracted thin-film deposition, extended post-treatment, separate electrochemical steps for charge insertion and extraction, slow introduction of electrolyte. Roll-to-roll deposition onto web-type substrates (Bishop 2010, 2011) in conjunction with continuous lamination procedures may be favorable techniques for cheap electrochromic glazing, as further elaborated in Sect. 3.3.

## 3.2 Survey Over Some Practical "Battery-Type" Electrochromic Devices

We now consider a number of alternative constructions for "battery-type" electrochromic devices. In fact, there are numerous of these mentioned in the scientific and technical literature published during several decades, but only a few of them can be considered ready for practical applications (Granqvist 2008a, 2012a; Baetens et al. 2010, Jelle et al. 2012).

Five-layer "monolithic" device designs on a single glass pane have been developed by several companies (www.sageglass.com, www.soladigm.com). Their details remain proprietary, but it is apparent that the electrolyte is a thin film. This construction makes it very difficult to avoid some leakage current between the "anode" and "cathode" through structural imperfections or other causes, and repeated electrical "refresh pulses" are demanded to maintain the optical properties during extended periods of time. The "monolithic" approach requires means to protect the electrochromic device from external damage and in practice it must be incorporated in an insulated glass unit (known as "IGU").

A laminated construction embodying two parallel double-layer-coated glass panes is commercially available since few years (www.econtrol-glas.de). The electrolyte is injected as a fluid in a millimeter-wide space between the panes via vacuum filling and is subsequently solidified. The injection procedure is known to be a time-consuming process (Xu et al. 2009).

Another laminated design, described by Kraft and Rottmann (2009), employs an electrolyte based on polyvinyl buteral (PVB)—i.e., a well-known and widely used material for glass lamination—and transparent electrodes of FTO. The ion-storage film comprises ferric hexacyanoferrate ("Prussian blue"), which is easy to deposit by electroplating, whereas, as far as it is known, it cannot be prepared by standard large-scale glass coating such as magnetron sputtering.

Yet another laminated electrochromic device employs web coating and is discussed further in the next section.

### 3.3 *Example: A Foil-Based Device Incorporating W Oxide and Ni Oxide*

W oxide is the most widely studied electrochromic material, and it works well in tandem with Ni oxide in "battery-type" devices (Avendaño et al. 2006; Niklasson and Granqvist 2007). The pertinent elements are abundant in the earth's crust and there are no constraints regarding their availability, which is an essential point for large-scale implementation of electrochromic glazings.

Several studies of electrochromic devices based on W oxide and Ni oxide have been reported for glass-based (Mathew et al. 1997; Larsson and Niklasson 2004; Subrahmanyam et al. 2007; Huang et al. 2011; Wang et al. 2011; Chen and Jheng 2012) and PET-based (Azens et al. 2003c; Niklasson and Granqvist 2007; Granqvist 2012c) constructions. Combinations of Mo oxide and Ni oxide are possible too (Lin et al. 2012). A recent variety of the "battery-type" device utilizes refractive-index modulation in a multilayer structure comprising alternate layers of W oxide and Ni oxide, in what is effectively a Bragg mirror, to accomplish reflectance modulation (Redel et al. 2012).

Figure 14 depicts a specific design of an electrochromic device: One PET foil is coated with ITO and W oxide, another PET foil is coated with ITO and Ni oxide, and an ion-conducting adhesive joins the oxide layers. Electrical charge is inserted and extracted via the ITO films, and then, the mid-luminous transmittance at $\lambda = 0.55$ μm is altered as shown in Fig. 15.

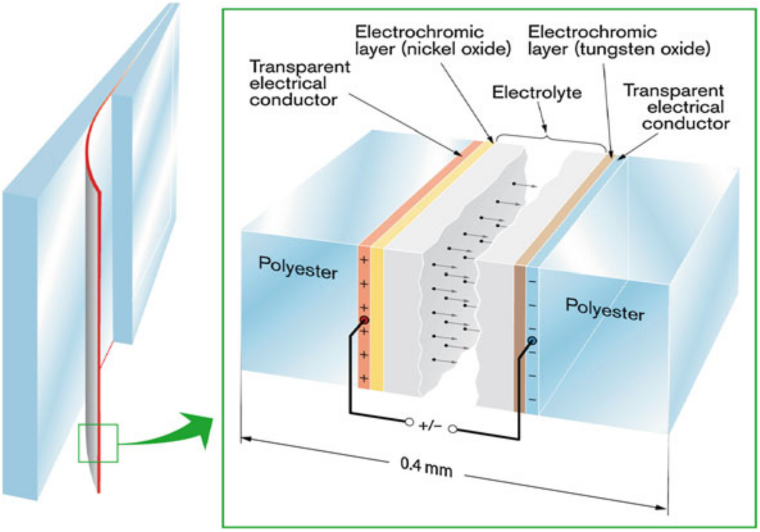


**Fig. 14** Principle construction of an electrochromic foil-based device. The entire foil can be used to laminate glass panes, as indicated in the *left-hand part*

The upper panel refers to the first 1,000 coloration/bleaching cycles driven via an electronic circuit that limits the transmittance at both high and low ends of the transmittance range; the lower setting was deliberately changed after ∼70 cycles. The devices operate well for tens of thousands of cycles without essential loss of performance. The lower panel in Fig. 15 illustrates the coloration dynamics during a single coloration/bleaching cycle, and it is evident that the main part of the optical modulation takes place during a few seconds for a device that is $5 \times 5$ cm$^2$ in size. Larger devices have slower dynamics, and the relevant timescale may be some ten minutes for an electrochromic glazing on the scale of square meters. The latter time is suitable for practical fenestration since it allows the human eye to adapt to varying levels of illumination.

Different optical modulation ranges are of interest depending on the application of the electrochromic device. For energy control of buildings, one may put a premium on a large bleached-state transmittance, and antireflection coatings may then be of interest (Jonsson and Roos 2010; Jonsson et al. 2010). However, if glare control is essential, it is possible to achieve a colored-state transmittance in the one-percent level or lower by putting two or more electrochromic foils on top of each other. Figure 16 illustrates the performance of a double-layer foil (Granqvist 2008a).

Low-cost, large-area manufacturing is a must if electrochromic glazing is going to be used on a large scale. In this context, it is important to note that the foil-type devices described above can be made by roll-to-roll deposition followed by lamination (Granqvist 2012c) and that it is possible to implement a free-form design concept—with post-deposition electrical contacting—to any shape and size consistent with the primary foil manufacturing. This latter option is not easily

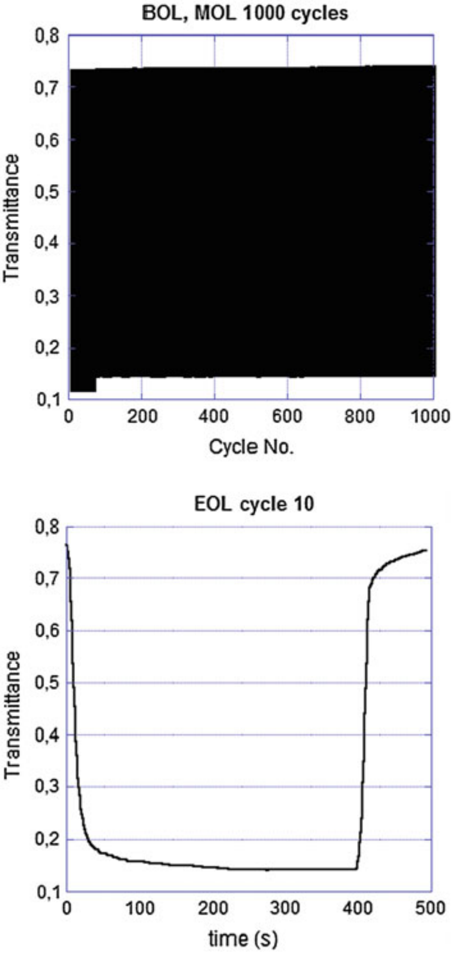


**Fig. 15** Transmittance modulation during 1,000 coloring/bleaching cycles (*upper panel*; the individual transmittance graphs lie so close that the entire swept area looks *black*) and during one cycle (*lower panel*) of a 5 × 5 $cm^2$ device of the type shown in Fig. 14

accomplished for glass-based electrochromic devices. Figure 17 shows a test installation of a multipane skylight equipped with foil-based electrochromic glazing (Gregard 2012). The total glazed area is ~25 $m^2$.

## 3.4 Some Alternative Approaches to Electrochromism: A Brief Sketch

There is a multitude of alternatives to the oxide-based “battery-type” electrochromic device (Mortimer 2013). One well-published option is to use a metal hydride either on its own or in conjunction with an electrochromic film. The hydride can attain a reflecting state under ion insertion, which offers principle

**Fig. 16** Mid-luminous transmittance dynamics for two superimposed electrochromic foils of the type described in Fig. 14. From Granqvist (2008a)

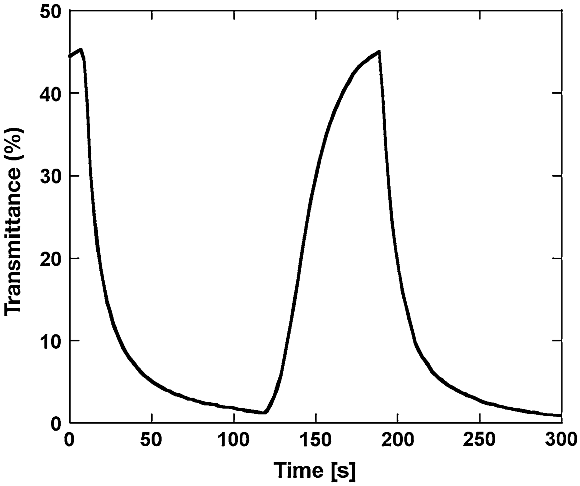


**Fig. 17** Test installation of a foil-based electrochromic glazing on a skylight used in a supermarket in Uppsala, Sweden, during 2012–2013. From Gregard (2012)

advantages. Devices based on Ni–Mg hydride have been investigated in particular detail by Tajima et al. (2010). The results presented so far have shown that the hydride-based devices suffer from limitations in longevity, modulation span, and high-temperature durability (Tajima et al. 2011).

Among the other approaches to electrochromic glazings, it is natural to first consider the suspended particle devices (SPDs) which have a venerable history going back to "light valves" introduced in the 1930s and described in a long series of patent specifications (Marks 1969). The SPD comprises a polymer layer, with a large number of light-absorbing and polarizable particles, between sheets of glass or plastic coated with transparent electrically conducting films facing the polymer layer. The particles should be less than ~100 nm in size in order not to exhibit strong light scattering. They typically consist of polyiodides or, more generally,

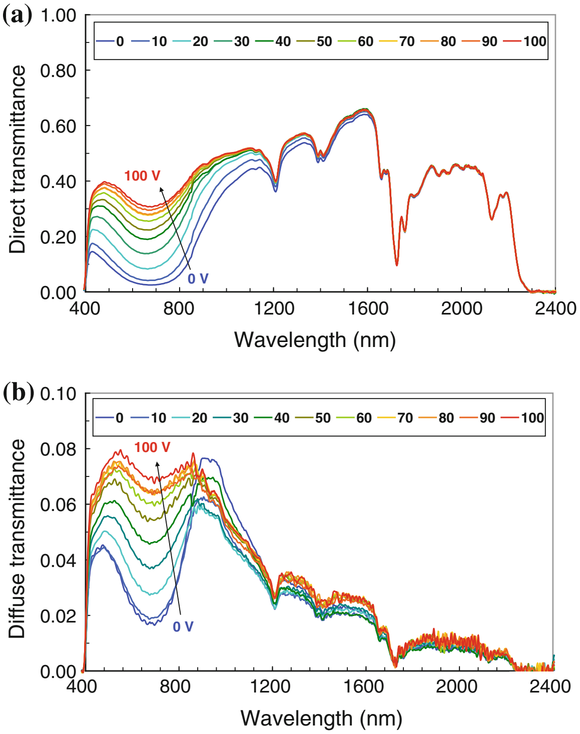


**Fig. 18** Spectral direct **a** and diffuse **b** transmittance of an SPD. The voltage was varied between zero and 100 V ac, as indicated by *arrows*. From Barrios et al. (2013)

polyhalides and have large optical anisotropy. Herapathite (quinine bisulfate polyiodide) is the most well-known compound in this class (Kahr et al. 2009); it was used extensively in early work on polarizers and other optical devices (Knowles 2009). The optical anisotropy was discussed in detail in a recent theoretical study by Liang et al. (2009). Various related compounds have been investigated in later SPDs (Takeuchi et al. 1997; Fanning et al. 2003). When a sufficient AC voltage is applied between the transparent conductors, the particles align and become parallel to the electric field and the overall transmittance goes up. Decreasing the voltage makes the particles more randomly oriented and the device gets darker until it attains a bluish-black color. Figure 18 shows spectral direct and diffuse transmittance for an SPD that was investigated recently by Barrios et al. (2013). It is apparent that $T_{\mathrm{lum}}$ can be varied when the voltage is changed, whereas $T_{\mathrm{sol}}$ is not affected to the same extent. The diffuse scattering lies on the level of several percent, i.e., windows incorporating SPDs are not free of haze.

Liquid crystals are used in other types of electrochromic devices. The most common construction is based on polymer-dispersed liquid crystals (PDLCs) and essentially switches between two states with strongly differing light scattering (Cupelli et al. 2009; Gardiner et al. 2009). Applications are related to privacy rather than to energy control. Another possibility is offered by some organic compounds, which can produce optical absorption when a small electrical current is passed through them. This phenomenon is utilized very successfully in “self-dimming” rear-view mirrors for cars and trucks and is of interest also for other applications mainly in the transport sector. Furthermore, reversible electroplating offers possibilities to achieve a very large modulation of the optical transmittance at all wavelengths. This option has been investigated intensely for many years but has not yet led to practically useful devices (Ziegler 1999; Laik et al. 2001; de Mello et al. 2012). Recent work by Araki et al. (2012) on reversible electroplating has shown that it is possible to transition between transparent, reflecting, and absorbing states.

Finally, very recent work has shown that the electron density of small nanoparticles of wide band-gap oxide semiconductors can be modulated by electrochemical means, and specific results have been demonstrated for nanoparticles comprised of ITO (Garcia et al. 2011) and AZO (Buonsanti et al. 2011). This can lead to “plasmonic” electrochromism, whose theoretical limits were investigated by Li et al. (2012b); results based on this latter work and pertaining to ITO nanoparticles are reported next. Figure 19 shows spectral absorptance for 1 vol. % ITO nanoparticles dispersed in a medium representing typical glass or polymer. The upper panel refers to a 5-μm-thick layer and shows that a strong plasmon resonance shifts toward shorter wavelengths as the electron density goes from $0.1 \times 10^{21}$ to $2 \times 10^{21}$ $\text{cm}^{-3}$, where the upper limit corresponds approximately to the largest electron density that has been documented experimentally (Granqvist 2007). The lower panel reports data for an electron density of $1 \times 10^{21}$ $\text{cm}^{-3}$ and various layer thicknesses up to 100 μm. It appears that the

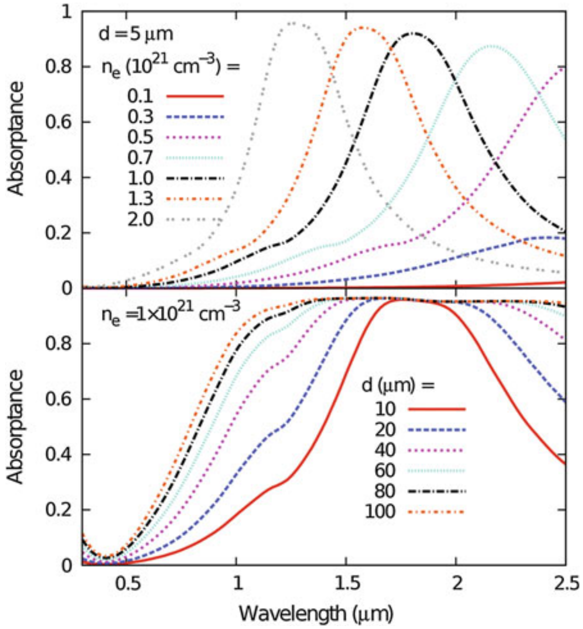


**Fig. 19** Spectral absorptance for a 5-μm-thick layer with electron densities of $0.1 \times 10^{21} \leq n_e \leq 2 \times 10^{21}$ $\text{cm}^{-3}$ (*upper panel*) as well as for layers with thicknesses of $10 \leq d \leq 100$ μm and $n_e = 1 \times 10^{21}$ $\text{cm}^{-3}$ (*lower panel*). The layer contains 1 vol. % of dispersed spherical ITO nanocrystals. From Li et al. (2012b)

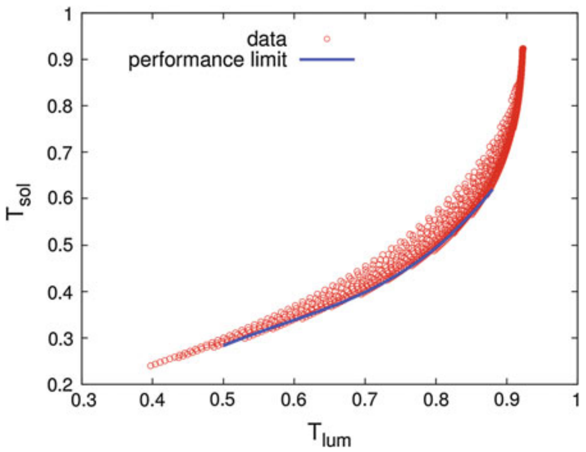


**Fig. 20** Luminous and solar transmittance ($T_{lum}$ and $T_{sol}$, respectively) for a layer containing 1 vol. % of dispersed spherical ITO nanocrystals. The curve delineates an approximate performance limit for plasmonic electrochromism. From Li et al. (2012b)

absorptance can cover the near-infrared wavelength interval, which proves that $T_{sol}$ can be modulated, while $T_{lum}$ remains large. Figure 20 reports $T_{sol}$ as a function of $T_{lum}$ based on a comprehensive set of computations (Li et al. 2012b). It is found that, for example, an optimized sample yields $T_{lum} = 0.60$ together with $T_{sol} \approx 0.34$ in the colored state. However, it remains to be seen whether results as good as these can be accomplished experimentally.

## 4 Concluding Remarks

Electrochromism has been well known for decades in a number of oxides (Deb 1973; Granqvist 1995), and applications have been discussed and investigated ever since the discovery of the phenomenon. The evolution of technology based on electrochromism has been disappointingly slow, however, and reasons for this were mentioned above. Buildings with electrochromic glazings have been considered for many years (Baetens et al. 2010; Jelle et al. 2012) but have not yet made it to the commodity market. It seems that this situation is about to change in the near future, though, and several of the large glass manufacturers are currently (2013) investing in production units for electrochromic glazings, and there is concurrent development in low-cost manufacturing using roll-to-roll coating for electrochromic foil that can be used for laminating glass as well as for building refurbishment by retrofitting existing windows (Granqvist 2012c). Importantly, the roll-to-roll technology also allows new business models since it decouples the electrochromic functionality from glass coating and window manufacturing.

Windows with variable optical properties have been something of a Holy Grail for glass architecture for many years (Wigginton 1996). It should be noted that they lead to a new paradigm for buildings, which are no longer stale entities of concrete, glass, and other building materials but dynamic units capable of regulating flows of light and energy in response to dynamic needs and user preferences.

In the long-term perspective, electrochromic foil technology may be combined with membrane architecture to yield lightweight constructions with little embodied energy (Ishii 1999; Koch 2004). This gives possibilities to control energy flows over large areas and devise zones that bridge indoor conditions with those of a harsher outdoor climate. Membranes of this kind are not unknown but have been put forward by visionaries such as Buckminster Fuller (Gorman 2005) and Frei Otto (Nerdinger 2005). Membrane architecture can also benefit from advances in building materials, such as the emergence of ethylene tetrafluoroethylene (ETFE) (Fernández 2007; LeCuyer 2008) with proven long-term durability.

## References

Abe Y, Itadani N, Kawamura M (2009) Ion conducting properties of hydrogen-containing $Ta_2O_5$ thin films prepared by reactive sputtering. Vacuum 83:528–530

Ahn K-S, Nah Y-C, Park J-Y et al (2003) Bleached state transmittance in charge-unbalanced all-solid state electrochromic devices. Appl Phys Lett 82:3379–3382

Ahn K-S, Nay Y-C, Sung Y-E et al (2002) All-solid-state electrochromic device composed of $WO_3$ and $Ni(OH)_2$ with a $Ta_2O_5$ protective layer. Appl Phys Lett 81:3930–3932

Anders A (2010) A structure zone diagram including plasma-based deposition and ion etching. Thin Solid Films 518:4087–4090

Araki S, Nakamura K, Kobayashi K et al (2012) Electrochemical optical-modulation device with reversible transformation between transparent, mirror, and black. Adv Mater 24:OP122–OP126

Assimakopoulos MN, Tsangrassoulis A, Guarracino G et al (2004) Integrated energetic approach for a controllable electrochromic device. Energy Build 36:415–422

ASTM (2008) G173-03 standard tables of reference solar spectral irradiances: Direct normal and hemispherical on a 37° tilted surface, In: Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, vol. 14.04. http://rredc.nrel.gov/solar/spectra/ am1.5 Cited 19 Nov 2012

Avendaño E, Azens A, Niklasson GA et al (2004) Electrochromism in nickel oxide films containing Mg, Al, Si, V, Zr, Nb, Ag, or Ta. Solar Energy Mater Solar Cells 84:337–350

Avendaño E, Azens A, Niklasson GA et al (2005) Proton diffusion and electrochromism in hydrated $NiO_y$ and $Ni_{1-x}V_xO_y$ thin films. J Electrochem Soc 152:F203–F212

Avendaño E, Berggren L, Niklasson GA et al (2006) Electrochromic materials and devices: brief survey and new data on optical absorption in tungsten oxide and nickel oxide films. Thin Solid Films 496:30–36

Avendaño E, Rensmo H, Azens A et al (2009) Coloration mechanism in proton-intercalated electrochromic hydrated $NiO_y$ and $Ni_{1-x}V_xO_y$ thin films. J Electrochem Soc 156:P132–P138

Aydogdu GH, Ruzmetov D, Ramanathan S (2010) Metastable oxygen incorporation into thin film NiO by low temperature active oxidation: Influence on hole conduction. J Appl Phys 108:113702/1–113702/6

Azens A, Granqvist CG (2003a) Electrochromic smart windows: Energy efficiency and device aspects. J Solid State Electrochem 7:64–68

Azens A, Kullman L, Granqvist CG (2003b) Ozone coloration of Ni and Cr oxide films. Solar Enegy Mater Solar Cells 76:147–153

Azens A, Gustavsson G, Karmhag R et al (2003c) Electrochromic devices on polyester foil. Solid State Ionics 165:1–5

Backholm J, Niklasson GA (2008) Optical properties of electrochromic iridium oxide and iridium-tantalum oxide thin films in different coloration states. Solar Energy Mater Solar Cells 92:1388–1392

Bae S, Kim K, Lee Y et al (2010) Roll-to-roll production of 30-inch graphene films for transparent electrodes. Nature Nanotechnol 5:574–578

Bae S, Kim SJ, Shin D et al (2012) Towards industrial applications of graphene electrodes. Phys Scr T146:014024/1–014024/8

Baetens R, Jelle BP, Gustavsen A (2010) Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: a state-of-the-art review. Solar Energy Mater Solar Cells 94:87–105

Barna PB, Adamik M (1998) Fundamental structure forming phenomena of polycrystalline films and structure zone models. Thin Solid Films 317:27–33

Barrios D, Vergaz R, Sanchez-Pena JM et al (2013) Towards a quantitative model for suspended particle devices: optical scattering and absorption coefficients. Solar Energy Mater Solar Cells 111:115–122

Bayrak Pehlivan İ, Granqvist CG, Marsal R et al (2012a) (PEI–$SiO_2$):(LiTFSI) nanocomposite polymer electrolytes: ion conduction and optical properties. Solar Energy Mater Solar Cells 98:465–471

Bayrak Pehlivan İ, Runnerstrom EL, Li S-Y et al (2012b) A polymer electrolyte with high luminous transmittance and low solar throughput: Polyethyleneimine-lithium bis(trifluoromethyl sulfonyl) imide with $In_2O_3$:Sn nanocrystals. Appl Phys Lett 100:241902/1–241902/4

Bayrak Pehlivan İ, Marsal R, Pehlivan E et al (2013) Electrochromic devices with polymer electrolytes functionalized by $SiO_2$ and $In_2O_3$:Sn nanoparticles: rapid coloring/bleaching dynamics and strong near-infrared absorption. Solar Energy Mater Solar Cells (in press)

Beaujuge PM, Reynolds JR (2010) Color control in $\pi$-conjugated organic polymers for use in electrochromic devices. Chem Rev 110:268–320

Berggren L, Niklasson GA (2006) Optical charge transfer absorption in lithium-intercalated tungsten oxide thin films. Appl Phys Lett 88:081906/1–081906/3

Berggren L, Jonsson JC, Niklasson GA (2007) Optical absorption in lithiated tungsten oxide thin films: experiment and theory. J Appl Phys 102:083538/1–083538/7

Bishop CA (2010) Roll-to-roll deposition of barrier coatings. Wiley, Hoboken

Bishop CA (2011) Vacuum deposition onto webs, films, and foils, 2nd edn. William Andrew, Waltham

Buonsanti R, Llordes A, Aloni S et al (2011) Tunable infrared absorptance and visible transparency of colloidal aluminum-doped zinc oxide nanocrystals. Nano Lett 11:4706–4710

Chen CC, Jheng WD (2012) Effect of Ar/$O_2$ ratio on double-sided electrochromic glass performance. Ceram Int 38:4195–4200

Clear RD, Inkarojrit V, Lee ES (2006) Subject responses to electrochromic windows. Energy Build 38:758–779

Cupelli D, Nicoletta FP, Manfredi S et al (2009) Self-adjusting smart windows based on polymer–dispersed liquid crystals. Solar Energy Mater Solar Cells 93:2008–2012

Deb SK (1973) Optical and photoelectric properties and color centers in thin-films of tungsten oxide. Philos Mag 27:801–822

Deb SK (1995) Reminiscences on the discovery of electrochromic phenomena in transition metal oxides. Solar Energy Mater Solar Cells 39:191–201

Deb SK (2008) Opportunities and challenges in science and technology of $WO_3$ for electrochromic and related applications. Solar Energy Mater Solar Cells 92:245–258

Degerman Engfeldt J, Georén P, Lagergren C et al (2011) Methodology for measuring current distribution effects in electrochromic smart windows. Appl Opt 50:5639–5646

de Mello DAA, Oliveira MRS, de Oliveira LCS et al (2012) Solid electrolytes for electrochromic devices based on reversible metal electrodeposition. Solar Energy Mater Solar Cells 103:17–24

Denesuk M, Uhlmann DR (1996) Site-saturation model for the optical efficiency of tungsten oxide based devices. J Electrochem Soc 143:L186–L188

Eda G, Chhowalla M (2010) Chemically derived graphene oxide: large-area thin-film electronics and optoelectronics. Adv Mater 22:2392–2415

Ederth J, Hoel A, Niklasson GA et al (2004) Small polaron formation in porous $WO_{3-x}$ nanoparticle films. J Appl Phys 96:5722–5726

Fanger PO (1970) Thermal comfort: analysis and applications in environmental engineering. Danish Technical Press, Copenhagen

Fanning B, Saxe RL, Slovak SM et al (2003) Polyhalide particles and light valves comprising same. US Patent 6517746

Fernández JE (2007) Materials for aesthetic, energy-efficient, and self-diagnostic buildings. Science 315:1807–1810

Franke EB, Trimble CE, Hale JS et al (2000) Infrared switching electrochromic devices based on tungsten oxide. J Appl Phys 88:5777–5784

Freedoniagroup (2011) World flat glass to 2014: market research, market share, market size, sales, demand forecast, market leaders, company profiles, industry trends. http://freedoniagroup.com/World-Flat-Glass.html Cited 19 Nov 2012

Garcia G, Buonsanti R, Runnerstrom EL (2011) Dynamically modulating the surface plasmon resonance of doped semiconductor nanocrystals. Nano Lett 11:4415–4420

Gardiner DJ, Morris SM, Coles HJ (2009) High-efficiency multistable switchable glazings using smectic A liquid crystals. Solar Energy Mater Solar Cells 93:301–306

Geim AK, Novoselov KS (2007) The rise of graphene. Nature Mater 6:183–191

Gillaspie DT, Tenent RC, Dillon AC (2010) Metal-oxide films for electrochromic applications: present technology and future directions. J Mater Chem 20:9585–9592

Ginley DS, Hosono H, Paine DC (eds) (2010) Handbook of transparent conductors. Springer, New York

Gläser HJ (2000) Large area glass coating. von Ardenne Anlagentechnik GmbH, Dresden

Goodenough JB (1971) Metallic oxides. Prog Solid State Chem 5:145–399

Gorman MJ (2005) Buckminster Fuller: designing for mobility. Skira, Milan

Granqvist CG (1981) Radiative heating and cooling with spectrally selective surfaces. Appl Opt 20:2606–2615

Granqvist CG (1990) Chromogenic materials for transmittance control of large-area windows. Crit Rev Solid State Phys Mater Sci 16:291–308

Granqvist CG (1994) Electrochromic oxides: a unified view. Solid State Ionics 70/71:678–685

Granqvist CG (1995) Handbook of inorganic electrochromic materials. Elsevier, Amsterdam

Granqvist CG (2000) Electrochromic tungsten oxide films: review of progress 1993–2000. Solar Energy Mater Solar Cells 30:201–262

Granqvist CG (2006) Electrochromic materials: out of a niche. Nature Mater 5:89–90

Granqvist CG (2007) Transparent conductors as solar energy materials: a panoramic review. Solar Energy Mater Solar Cells 91:1529–1598

Granqvist CG (2008a) Oxide electrochromics: why, how, and whither. Solar Energy Mater Solar Cells 92:203–209

Granqvist CG (2008b) Oxide-based electrochromic materials and devices prepared by magnetron sputtering. In: Depla D, Mahieu S (eds) Reactive sputter deposition. Springer, Berlin, pp 485–495

Granqvist CG (2012a) Oxide electrochromics: an introduction to devices and materials. Solar Energy Mater Solar Cells 99:1–13

Granqvist CG (2012b) Preparation of thin films and nanostructured coatings for clean tech applications: a primer. Solar Energy Mater Solar Cells 99:166–175

Granqvist CG (2012c) Progress in oxide-based electrochromics: towards roll-to-roll manufacturing. Mater Res Soc Symp Proc 1315:89–100

Granqvist CG (2013a) Electrochromic materials and devices for energy efficient buildings. In: Garcia-Martinez J (ed) Nanotechnology for the energy challenge, 2nd edn. Wiley-VCH, Weinheim, pp 593–617

Granqvist CG (2013b) Switchable glazing technology for eco-efficient construction. In: Pacheco Torgal F, Diamanti MV, Nazari A, Granqvist CG (eds) Nanotechnology in eco-efficient construction. Woodhead, Cambridge, pp 236–269

Granqvist CG (2013c) Thin films and nanostructured coatings for eco-efficient buildings. In: Pacheco Torgal F, Diamanti MV, Nazari A, Granqvist, CG (eds) Nanotechnology in eco-efficient construction. Woodhead, Cambridge, pp 161–187

Gregard G (2012) Personal communication

Green S (2012) Electrochromic nickel–tungsten oxides: optical, electrochemical and structural characterization of sputter-deposited thin films in the whole composition range. Digital comprehensive summaries of Uppsala dissertations from the faculty of science and technology 963

Green SV, Kuzmin A, Purans J et al (2011) Structure and composition of sputter-deposited nickel-tungsten oxide films. Thin Solid Films 519:2062–2066

Green SV, Pehlivan E, Granqvist CG et al (2012) Electrochromism in sputter deposited nickel–containing tungsten oxide films. Solar Energy Mater Solar Cells 99:339–344

Hamberg I, Granqvist CG (1986) Evaporated Sn-doped $In_2O_3$ films: basic optical properties and applications to energy-efficient windows. J Appl Phys 60:R123–R159

Heshong L, Wright RL, Okura S (2002a) Daylighting impacts on retail sales performance. J Illum Eng Soc (Summer):21–25

Heshong L, Wright RL, Okura S (2002b) Daylighting impacts on human performance in school. J Illum Eng Soc (Summer):101–112

Hu L, Hecht DS, Grüner G (2010a) Carbon nanotube thin films: fabrication, properties, and applications. Chem Rev 110:5790–5844

Hu L, Kim HS, Lee J-Y et al (2010b) Scalable coating and properties of transparent, flexible, silver nanowire electrodes. ACS Nano 4:2955–2963

Hu L, Wu H, Cui Y (2011) Metal nanogrids, nanowires and nanofibers for transparent electrodes. MRS Bull 36:760–765

Huang H, Tian J, Zhang WK et al (2011) Electrochromic properties of porous NiO thin films as a counter electrode for NiO/$WO_3$ complementary electrochromic window. Electrochim Acta 56:4281–4286

International Glazing Database (2012) Version 18.2. http://windows.lbl.gov/materials/IGDB/default.htm Cited 3 Dec 2012

Ishii K (ed) (1999) Membrane designs and structures in the world. Shinkenchikusa-sha, Tokyo

Jelle BP, Hynd A, Gustavsen A et al (2012) Fenestration of today and tomorrow: a state-of-the-art review and research opportunities. Solar Energy Mater Solar Cells 96:1–28

Jensen J, Dam HF, Reynolds JR et al (2012) Manufacture and demonstration of organic photovoltaic-powered electrochromic displays using roll coating methods and printable electrolytes. J Polym Sci B: Polym Phys 50:536–545

Jin Z-C, Hamberg I, Granqvist CG (1988) Optical properties of sputter-deposited ZnO:Al thin films. J Appl Phys 64:5117–5131

Jonsson A, Roos A (2010) Visual and energy performance of switchable windows with antireflection coatings. Sol Energy 84:1370–1375

Jonsson A, Roos A, Jonson EK (2010) The effect on transparency and light scattering of dip coated antireflection coatings on window glass and electrochromic foil. Solar Energy Mater Solar Cells 94:992–997

Kahr B, Freudenthal J, Phillips S et al (2009) Herapathite. Science 324:1407

Katanbafnasab M, Abu-Hijleh B (2013) Assessment of the energy impact of using building integrated photovoltaic and electrochromic glazing in office buildings in UAE. Engineering 5:56–61

Koch K-M (ed) (2004) Membrane structures. Prestel, Munich

Knowles KM (2009) Herapathite: the first man-made polarizer. Philos Mag Lett 89:745–755

Kraft A, Rottmann M (2009) Properties, performance and current status of the laminated electrochromic glass of Gesimat. Solar Energy Mater Solar Cells 93:2088–2092

Laik B, Carrière D, Tarascon J-M (2001) Reversible electrochromic system based on aqueous solution containing silver. Electrochim Acta 46:2203–2209

Lampert CM (2003) Large-area smart glass and integrated photovoltaics. Solar Energy Mater Solar Cells 76:489–499

Lampert CM, Granqvist CG (eds) (1990) Large-area chromogenics: materials and devices for transmittance control. SPIE–The international society for optical engineering, Bellingham. SPIE Institutes for Advanced Optical Technologies, vol IS 4

Lang Z-L, Guan W, Yan L-K et al (2012) The self-assembly mechanism of the Lindqvist anion $(W_6O_{19})^{2-}$ in aqueous solution: a density functional theory study. Dalton Trans 41:11361–11368

Lansåker PC, Backholm J, Niklasson GA et al (2009) $TiO_2$/Au/$TiO_2$ multilayer thin films: novel metal-based transparent conductors for electrochromic devices. Thin Solid Films 518:1225–1229

Lansåker PC, Petersson P, Niklasson GA et al (2013) Thin sputter deposited gold films on $In_2O_3$:Sn, $SnO_2$: In, $TiO_2$ and glass: optical, electrical and structural effects. Solar Energy Mater Solar Cells 117:462–470

Larsson A-L, Niklasson GA (2004) Optical properties of electrochromic all-solid-state devices. Solar Energy Mater Solar Cells 84:351–360

LeCuyer A (2008) ETFE: technology and design. Birkhäuser, Basel

Lee ES, Claybaugh ES, LaFrance M (2012a) End user impacts of automated electrochromic windows in a pilot retrofit application. Energy Build 47:267–284

Lee ES, Selkowitz SE, Clear RD et al (2006) Advancement of electrochromic windows. California Energy Commission, PIER, CEC-500-2006-052

Lee KM, Abe Y, Kawamura M et al (2012b) Effects of substrate temperature on electrochromic properties of cobalt oxide and hydroxide thin films prepared by reactive sputtering using $O_2$ and $H_2O$ gases. Jpn J Appl Phys 51:045501/1–045501/4

Li S-Y, Niklasson GA, Granqvist CG (2010) Nanothermochromics: calculations for $VO_2$ nanoparticles in dielectric hosts show much improved luminous transmittance and solar energy transmittance modulation. J Appl Phys 108:063525/1–063525/8

Li S-Y, Niklasson GA, Granqvist CG (2011) Nanothermochromics with $VO_2$-based core-shell structures: calculated luminous and solar optical properties. J Appl Phys 109:113515/1–113515/5

Li S-Y, Niklasson GA, Granqvist CG (2012a) Thermochromic fenestration with $VO_2$-based materials: three challenges and how they can be met. Thin Solid Films 520:3823–3828

Li S-Y, Niklasson GA, Granqvist CG (2012b) Plasmon-induced near-infrared electrochromism based on transparent conducting nanoparticles: approximate performance limits. Appl Phys Lett 101:071903/1–071903/3

Liang L, Rulis P, Kahr B et al (2009) Theoretical study of the large linear dichroism of herapathite. Phys Rev B 80:235132/1-235132/5

Lim SHN, Isidorsson J, Sun L et al (2013) Modeling of optical and energy performance of tungsten-oxide-based electrochromic windows including their intermediate states. Solar Energy Mater Solar Cells 108:129–135

Lin S-Y, Chen Y-C, Wang C-M et al (2012) Study of $MoO_3$–NiO complementary electrochromic devices using a gel polymer electrolyte. Solid State Ionics 212:81–87

Magnéli A (1950) Crystal structure studies on beta-tungsten oxide. Arkiv Kemi 1:513–523

Maleknia S, Brodbelt J, Pope K (1991) Characterization of the reactive and dissociative behavior of transition metal oxide cluster ions in the gas phase. J Am Soc Mass Spectrom 2:212–219

Marks AM (1969) Electrooptical characteristics of dipole suspensions. Appl Opt 8:1397–1412

Mathew JGH, Sapers SP, Cumbo MJ et al (1997) Large area electrochromics for architectural applications. J Non-Cryst Solids 218:342–346

Mortimer RJ (2013) Switching colors with electricity. Am Sci 101:38–45

Nanba T, Yasui I (1989) X-ray diffraction study of microstructure of amorphous tungsten trioxide films prepared be electron beam vacuum evaporation. J Solid State Chem 83:304–315

Nerdinger W (ed) (2005) Frei Otto: complete works. Birkhäuser, Basel

Niklasson GA, Granqvist CG (2007) Electrochromics for smart windows: thin films of tungsten oxide and nickel oxide, and devices based on these. J Mater Chem 17:127–156

Niu C (2011) Carbon nanotube transparent conducting films. MRS Bull 36:766–773

Niwa T, Takai O (2010) All-solid-state reflectance-type electrochromic devices using iridium tin oxide as counter electrode. Thin Solid Films 518:5340–5344

Noguchi D, Taneda H, Higashimaru Y et al (2012) Ion conductivity of $Ta_2O_5$ solid electrolyte thin film prepared by combination sputtering with radio frequency oxygen plasma irradiation. Jpn J Appl Phys 51:025801/1–025801/5

Omae K, Nakano M, Tanaka A et al (2011) Indium lung: case reports and epidemiology. Int Arch Occup Environ Health 84:471–477

Ramezani D, Nybom S (2009) Energiberäkningar för elektrokroma fönster (in Swedish). Unpublished report

Redel E, Mlynarski J, Moir J et al (2012) Electrochromic Bragg mirror: ECBM. Adv Mater 24:OP265–OP269

Schirmer OF, Wittwer V, Baur G et al (1977) Dependence of $WO_3$ electrochromic absorption on crystallinity. J Electrochem Soc 124:749–753

Schwarz-Schampera U, Herzig P (2002) Indium: geology, mineralogy and economics. Springer, Berlin

Smith GB, Granqvist CG (2010) Green nanotechnology: solutions for sustainability and energy in the built environment. CRC Press, Boca Raton

Stjerna B, Olsson E, Granqvist CG (1994) Electrical and optical properties of RF sputtered tin oxide films doped with oxygen vacancies, F, Sb, or Mo. J Appl Phys 76:3797–3817

Subrahmanyam A, Kumar CS, Karuppasamy KM (2007) A note on fast protonic state electrochromic devices: $NiO_x/Ta_2O_5/WO_{3-x}$. Solar Energy Mater Solar Cells 91:62–66

Svensson JSEM, Granqvist CG (1986) Electrochromic coatings for "smart windows". Solar Energy Mater 12:391–402

Sydam R, Deepa M, Srivastava AK (2012) Electrochromic device response controlled by an in situ polymerized ionic liquid based gel electrolyte. RSC Adv 2:9011–9021

Tajima K, Yamada Y, Bao S et al (2010) Optical switching properties of all-solid-state switchable mirror glass based on magnesium–nickel thin film for environmental temperature. Solar Energy Mater Solar Cells 94:227–231

Tajima K, Yamada Y, Okada M et al (2011) Polyvinyl chloride seal layer for improving the durability of electrochromic mirrors based on Mg–Ni thin film. Thin Solid Films 519:8114–8118

Takeuchi H, Usuki A, Tatsuda N et al (1997) Suspended particle display using novel complexes. Mater Res Soc Symp Proc 424:317–322

Talledo A, Granqvist CG (1995) Electrochromic vanadium-pentoxide-based films: structural, electrochemical, and optical properties. J Appl Phys 77:4655–4666

Thakur VK, Ding G, Ma J et al (2012) Hybrid material and polymer electrolytes for electrochromic device application. Adv Mater 24:4071–4096

Thornton JA (1974) Influence of apparatus geometry and deposition conditions on the structure and topography of thick sputtered coatings. J Vac Sci Technol 11:666–670

Valyukh I, Green SV, Granqvist CG et al (2012) Ellipsometrically determined optical properties of nickel-containing tungsten oxide thin films: nanostructure inferred from effective medium theory. J Appl Phys 112:044308/1–044308/6

Wang S-C, Liu K-Y, Huang J-L (2011) Tantalum oxide film prepared by reactive magnetron sputtering deposition for all-solid-state electrochromic device. Thin Solid Films 520:1454–1459

Wigginton M (1996) Glass in architecture. Phaidon, London

www.econtrol-glas.de Cited 30 Dec 2012

www.sageglass.com Cited 30 Dec 2012

www.soladigm.com Cited 30 Dec 2012

Wyszecki G, Stiles WS (2000) Color science: concepts and methods, quantitative data and formulae, 2nd edn. Wiley, New York

Xu C, Ma C, Kong X et al (2009) Vacuum filling process for electrolyte in enhancing electrochromic polymer window assembly. Polym Adv Technol 20:178–182

Xu F, Zhu Y (2012) Highly conductive and stretchable silver nanowire conductors. Adv Mater 24:5117–5122

Yu J-S, Kim I, Kim J-S et al (2012) Silver front electrode grids for ITO-free all printed polymer solar cells with embedded and raised topographies, prepared by thermal imprint, flexographic and inkjet roll-to-roll processes. Nanoscale 4:6032–6040

Ziegler JP (1999) Status of reversible electrodeposition electrochromic devices. Solar Energy Mater Solar Cells 56:477–493

Zinzi M (2006) Office worker preferences of electrochromic windows: a pilot study. Building Environ 42:1262–1273

# Solar Photovoltaic/Thermal Technologies and Their Application in Building Retrofitting

**Xudong Zhao and Xingxing Zhang**

**Abstract** In this chapter, the global market potential of solar thermal, photovoltaic (PV) and combined photovoltaic/thermal (PV/T) technologies on current stage and near future was overviewed. The concept of PV/T technology and the theory behind the PV/T operation were briefly introduced. Evaluation standards for technical, economic and environmental performance of the PV/T systems were individually addressed. A comprehensive introduction of the R&D achievements and practical applications of the PV/T technology was illustrated. The PV/T technologies were critically analysed in terms of type and research methodology. Opportunities for further improvement in PV/T technology were identified. This chapter helps to bring forward the barriers remaining in PV/T field, untangle the practical applications of PV/T technology in building retrofitting, establish the standards of PV/T design/installation, identify new research directions and promote its market penetration throughout the world.

## 1 Introduction

The global energy consumption has been steadily growing over the past 40 years. In 2008, the total annually consumed energy reached 474 exajoules (474 × 1,018 J), of which 80–90 % is from combustion of fossil fuels (BP 2009). Despite the recent energy review (Enerdata 2009) indicated that the world energy consumption was decreased by 1.1 % in 2009 due to the unexpected global economic recession, energy consumption in several primary developing countries,

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particularly the fast-economy-growing Asia countries, still grows. Increased fossil fuel consumption has led to continuous rising of carbon emission to the environment (Wikipedia 2011), which is thought to be the direct reason causing the global warming.

Solar thermal is currently providing only 0.5 % of total primary energy need and solar PV has even lower energy supply ratio of 0.04 % (IEA 2007). Both solar thermal and PV technologies have far high space to grow which would be driven by the continuous technical advances and increased concerns of energy saving and environment protection. This development would certainly contribute to significant reduction in fossil fuel consumption and cut of carbon emission.

Solar thermal is one of the most cost-effective renewable energy technologies and has huge market potential globally. It, representing more than 90 % of the world-installed solar capacity, is utilised for various purposes including domestic hot water generation and space heating, solar-assisted cooling and industrial process heating. The global solar thermal market has been continuously growing since the beginning of the 1990s. In the EU, solar thermal market was tripled from 2002 to 2006 and still in booming. A vision plan issued by European Solar Thermal Technology Platform (ESTTP 2009) indicated that by 2030, up to 50 % of the low- and medium-temperature heat will be delivered by solar thermal. The European Solar Thermal Industry Federation (ESTIF 2007) has predicted that by 2020, the EU will reach a total operational solar thermal capacity of between 91 and 320 giga-Watts (GW), thus leading to saving of equivalent to at least 5,600 tons crude oil. By 2050, the EU will eventually achieve 1,200 GW of solar thermal capacity (ESTIF 2007).

PV is currently a technically and commercially matured technology able to generate and supply short-/mid-term electricity using solar energy. Although current PV installations are still small and provide only 0.1 % of world total electricity generation, a market review indicated that the global PV installations are growing at a 40 % average annual rate (IEA 2010). With continuous technical advance, increased installation volume, reduced price and encouraging legal policies, PV will certainly continue on the fast-growing pace and eventually become an important energy supplier. It is predicted by IEA at its recent Technology Roadmap—Solar Photovoltaic Energy that PV will deliver about 5 % of global power need by 2030 and 11 % by 2050. The accelerated use of PV will result in more than 100 giga-tons (Gt) of $CO_2$ emission reduction during the period of between 2008 and 2050 (IEA 2010).

PV/T is a hybrid technology combining PV and solar thermal components into a single module to enhance the solar conversion efficiency of the module and make economic use of the building space. A PV/T module can simultaneously generate electricity and heat and therefore takes advantages of both PV and solar thermal technologies. The dual functions of the PV/T result in a higher overall solar conversion rate than those of standard PV or solar collector and thus enable a more effective use of solar energy. Its market potential is therefore expected to be higher than individual PV and solar thermal systems. However, since the PV/T is a recently emerging technology, various issues relevant to PV/T, e.g. current technical status, difficulties and problems remaining, market potential and barriers in practical application, still remain unclear. To clear up these matters, an introduction into the current achievements on PV/T technology is most desired. The work will have significant global impacts in terms of several important aspects, namely (1) helping engineers/professionals to understand the basic knowledge of PV/T, identify the technical feature of the PV/T systems and select, design, install and evaluate PV/T system; (2) helping academia/researchers to identify research directions/topics of PV/T technology; (3) helping policy makers and governmental officers to deliver the strategic plans related to PV/T and establish the associated standards and regulations; and (4) helping industry to identify the barriers of PV/T in piratical application, develop the commercially variable PV/T products and establish the associated market exploitation plan to promote wide application of PV/T technology across the world.

## 2 Basic Concept and Theory, Classification and Performance Evaluation Standards of the PV/T Technology

### *2.1 Basic Concept and Theory Behind the PV/T Operation*

PV cells/modules are well-known solar electricity-generating components, and the solar efficiency of the PVs is a parameter associated with the cells' materials and temperature. In general, the PVs' electrical efficiency is in the range 6–18 %, which is a value measured at the nominal operating cell temperature (NOCT) (0.8 kW/m$^2$ of solar radiation, 20 °C of ambient temperature and 1 m/s of wind speed) (Messenger and Ventre 2003). It is well known that the solar electrical efficiency of the PV cells falls with the rise in its operating temperature, as shown in Fig. 1. Increasing the temperature of PV cells by 1 K leads to about 0.4–0.5 % reduction in the electrical efficiency for the crystalline silicon-based cells (Brinkworth et al. 1997; Kranter et al. 1999) and around 0.25 % for the amorphous silicon (a-Si) cells (Kalogirou and Tripanagnostopoulos 2006).

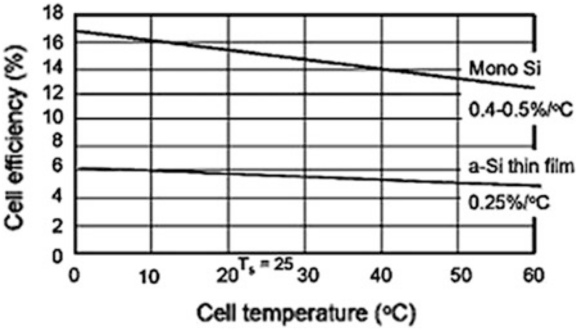


**Fig. 1** Established efficiency-to-temperature relationship (Zhang et al. 2012)

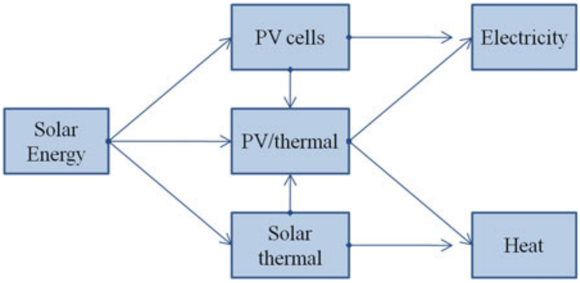
To increase the PV electrical efficiency and make good use of the incident solar radiation, it is most desired to remove the accumulated heat from the concealed PV surface and use this part of heat appropriately. The PV/T is a technology developed for this purpose, which combines the PV cells/modules and heat extraction components into a single module. This allows cooling of the PV cells leading to increased PVs' electrical efficiency and, in the meantime, simultaneously utilizing the extracted heat for heating purpose. By doing so, the PV/T solar collector can obtain the enhanced overall solar efficiency and thus provide a better way utilizing solar energy. The PV/T, merging PVs into the solar thermal module, represents a new direction for renewable heating and power generation. Figure 2 indicates the interrelationship among different solar conversion technologies.

A typical PV/T module is a sandwiched structure comprising several layers, namely from the top to bottom, a flat-plate thermally clear covering as the top layer; a layer of photovoltaic cells or a commercial PV lamination laid beneath the cover with a small air gap; tubes or flowing channels through the absorber and closely adhered to the PV cell layer; a thermally insulated layer located right below the flow channels. All the layers are fixed into a framed module using the adequate clamps and connections. Figure 3 is a schematic of a typical PV/T module structure.

The general concept of PV/T technology was originally addressed by Kern and Russell (1978). For a PV/T module, the solar irradiation with the wavelength from 0.6 to 0.7 μm is absorbed by the PV cells and converted into electricity, while the remaining irradiation is mostly transformed in the form of thermal energy. The PV/T module can collect solar energy at different grades (wavelengths) and consequently lead to an enhanced energy and exergy efficiency. According to Zongdag et al. (1999) and Zhao et al. (2011), the PV/T module could collect and convert higher percentage of solar energy than either an individual PV panel or thermal collector do at the same absorbing area and therefore offers a potential creating a low-cost and highly effective solution for heat and power generation.

A PV/T module is basically derived from the combined functions of a flat-plate solar (thermal) collector and of a photovoltaic panel. The overall efficiency is sum of the collector's thermal efficiency $\eta_{\text{th}}$ and the PVs' electrical efficiency $\eta_e$, which are defined as the ratios of useful system heat gain and electricity gain to the incident solar irradiation striking on the collector's absorbing surface, and is written as follows:

**Fig. 2** Network of different solar conversion technologies (Zhang et al. 2012)



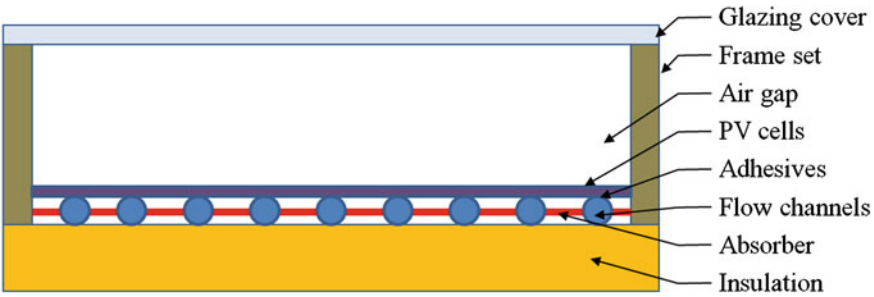


**Fig. 3** A focused cross section of typical PV/T module (Zhang et al. 2012)

$$\eta_o = \eta_{\mathrm{th}} + \eta_e \tag{1}$$

*Thermal Efficiency of the PV/T Collector* ($\eta_{\mathrm{th}}$)

The thermal efficiency ($\eta_{\mathrm{th}}$) of a flat-plate PV/T collector is a ratio of the useful thermal energy, $Q_u$, to the overall incident irradiation, $I$, and can be written as

$$\eta_{\mathrm{th}} = \frac{Q_u}{I} \tag{2}$$

The heat collected by the flat-plate PV/T collector could either be given as the coupling result of average mass flow rate ($m$), heat capacity of flowing medium ($C_p$) and temperature difference of the medium at the collector inlets ($T_{fi}$) and outlets ($T_{fo}$), as below

$$Q_u = mC_p\left(T_{fo} - T_{fi}\right) \tag{3}$$

Or it could be simply expressed by the difference in absorbed solar radiation, heat loss and produced electrical energy

$$Q_u = A_c\left[I(\tau\alpha) - U_L\left(T_{p,m} - T_a\right) - Q_e\right] \tag{4}$$

where $A_c$ is the collector area; $(\tau\alpha)$ is transmittance–absorption effort of glazing cover; $U_L$ is the overall thermal loss efficient; $T_a$ is the average air temperature; and $Q_e$ is the electrical energy generated from the PV. The parameter $T_{p,m}$, representing the mean absorber plate temperature, is difficult to measure or calculate since it is a complex function of different collector designs, incident solar radiation and working medium properties. To allow analysis, the equations for a flat-plate solar collector are modified by the Hottel and Whillier (1958) using the fluid inlet temperature to replace the mean absorber temperature, which has been widely used in the design and evaluation of solar air and liquid collectors. It should be stressed that the equations are correlated with the solar collector configuration as shown in Fig. 4. If the configuration of the collector is changed, some geometrical parameters in the equations may vary correspondingly, while the basic working principle of the collector remains the same.

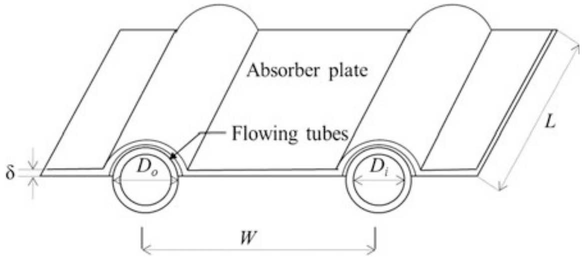


**Fig. 4** Schematic of an absorber plate showing the various dimensions (Zhang et al. 2012)

Hence, the heat collected by the flat-plate PV/T collector could be revised by the fluid inlet temperature

$$Q_u = F_R A_c \left[ I(\tau\alpha) - U_L \left( T_{fi} - T_a \right) - Q_e \right] \tag{5}$$

where $F_R$ is the heat-removal factor which is connected with the efficiency factor ($F'$) using the following equation:

$$\frac{F_R}{F'} = \frac{IC_p}{U_L F'} \left[ 1 - \exp\left( -\frac{U_L F'}{IC_p} \right) \right] \tag{6}$$

where $F'$ varies with different types of working mediums (e.g. water or air)

$$F' = \frac{1/U_L}{W\left[\frac{1}{U_L[D_o + (W - D_o)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{wm}}\right]} \quad \text{for water} \tag{7}$$

$$F' = \frac{1}{1 + \left[ U_L / \Big( h_{wm} A/A_c + \frac{1}{(1/h_r + 1/h_{wm})} \right]} \quad \text{for air} \tag{8}$$

where $W$ is the distance between tubes; $D_o$ and $D_i$ are the outside and inside diameter of flow tubes; $C_b$ is the conductance of the bond between the fin and tube; $h_{wm}$ is the heat transfer coefficient of working medium; $A/A_c$ is the ratio of heat transfer area to collector aperture area; $h_r$ is the equivalent radiation coefficient; $F$ is the fin efficiency, which could be given by

$$F = \frac{\tanh\left[ \sqrt{(U_L/k\delta)} \left( \frac{W - D_o}{2} \right) \right]}{\sqrt{(U_L/k\delta)} \left( \frac{W - D_o}{2} \right)} \tag{9}$$

where $k$ is the thermal conductivity of the fin and $\delta$ is the fin thickness.

*Electrical Efficiency of the PV Modules ($\eta_e$)*

It is known that the electrical efficiency of the PV module decreases with the increase in the cells' working temperature and this dependence can usually be written as (Duffle and Beckman 1991)

$$\eta_e = \eta_{rc}[1 - \beta_{PV}(T_{PV} - T_{rc})] \tag{10}$$

where $\eta_{rc}$ is the initial electrical efficiency at reference temperature; $\beta_{PV}$ is the cell efficiency temperature coefficient; $T_{pv}$ and $T_{rc}$ are, respectively, the PV cell temperature and its reference temperature.

Alternatively, in practice, the electrical efficiency ($\eta_e$) of a PV module can be regarded as the ratio of measured output power ($P_o$) to the overall incident solar radiation.

$$\eta_e = \frac{P_o}{IA_c} \tag{11}$$

The generated electrical energy can be therefore calculated by

$$Q_e = P_o = \eta_e IA_c \tag{12}$$

## 2.2 *Classification of the PV/T Modules*

PV/T modules could be structurally and functionally very different. In terms of coolant used, the modules could be classified as air, water, refrigerant and heat pipe fluid-based types. In terms of the physical structure applied, the modules could be classified as flat-plate, concentrated and building integrated types. In this chapter, the coolant-based classification was adopted and illustrated as follows.

*Air-Based PV/T*

An air-based PV/T module is a solar air heater with an additional PV layer laminated on the top or bottom of the naturally or mechanically ventilated air channels. This PV/T type could be formulated by incorporating an air gap between the PV modules' back surface and the building fabric (facade or tilted roof). Usually, this type of PV/T module is designed for the end-users who have demand in hot air, space heating, agriculture/herb drying or increased ventilation, as well as the electricity generation. For this type of module, air could be delivered from above, below or on both sides of the PV absorber, as shown in Fig. 5.

*Water-based PV/T*

A water-based PV/T module, as previously shown in Fig. 3, has a similar structure as the conventional flat-plate solar collectors. The absorber is attained with numerous PV cells that are series or parallel connected and fixed with a serpentine or a series of parallel tubes underneath. Water is forced to flow across the tubes, and if the water temperature remains lower, the PV cells will be cooled, thus leading to the increased electrical efficiency. In the meantime, the passing water will be heated by absorbing the PV heat and will be delivered to certain heat devices to provide heating. This part of water may be consumed or alternatively cooled in the heating services and flows back to the module to regain heat. Compared to the air-based system, the water-based PV/T systems could achieve

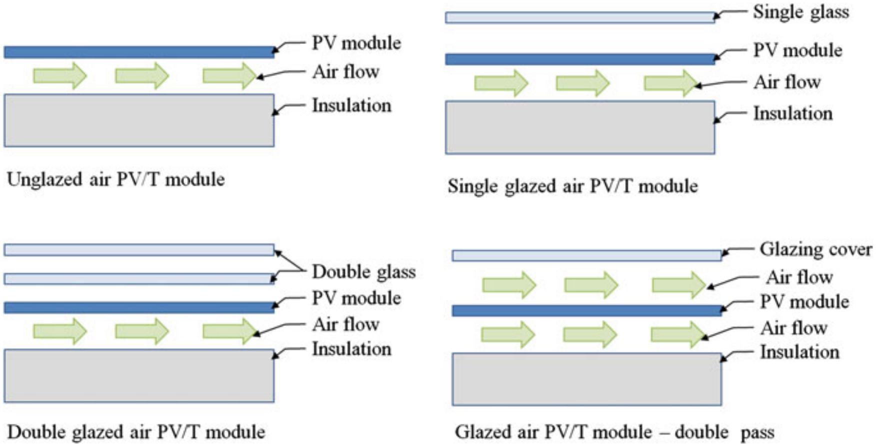


**Fig. 5** Cross sections of air-based PV/T modules (Zhang et al. 2012)

the enhanced cooling effectiveness due to higher thermal mass of water over the air, and therefore, both the thermal and electrical efficiencies of the systems would be higher. Zondag et al. (2003) addressed several water flow patterns in the PV/T, namely sheet-and-tube, channel, free-flow and two-absorber types, which are shown schematically in Fig. 6.

*Refrigerant-Based PV/T*

In recent years, refrigerant-based PV/T heat pump systems have been studied. Kern and Russell (1978) initially proposed a simple PV/T collectors connected with heat pump systems and studied their energy-saving and economic benefits. Recent study suggested a novel concept of PV/T module for heat pump application. This module lays the direct expansion evaporation coils underneath the PV

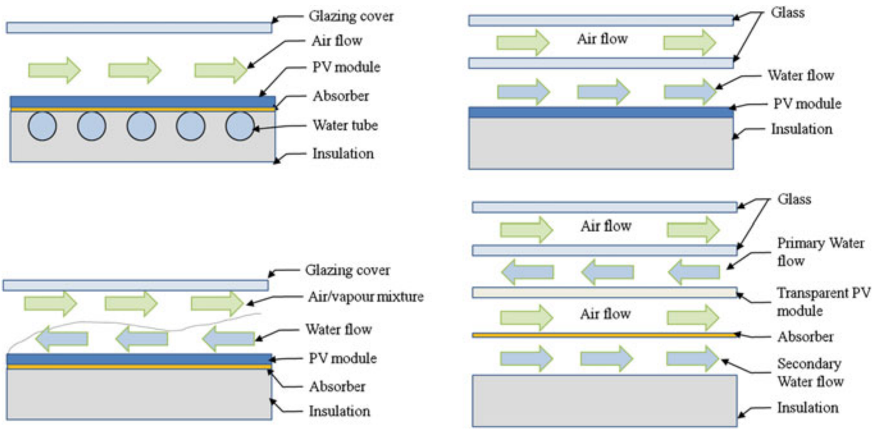


**Fig. 6** Types of water PV/T collectors (Zhang et al. 2012)

modules which allow a refrigerant to be evaporated when passing through the modules. In this way, the coils would act as the evaporation sector of the heat pump, which would allow the refrigerant to evaporate at a very low temperature, e.g. 0–20 °C. As a result, the PV cells would be cooled to a similar low temperature, which would result in significant increase in the panels' heat and electrical efficiencies. The compressor in the heat pump would increase the pressure of the vapour generated from the panels and deliver it to the condenser to provide heating. In operation, the compressor would be driven by the PV-generated electricity, thus creating a solar-powered heat pump independent of fossil fuel energy. Figure 7 gives a cross-sectional view of a glazed PV evaporator roof panel, and Fig. 8 is the schematic of the PV/T-based heat pump system (Zhao et al. 2011).

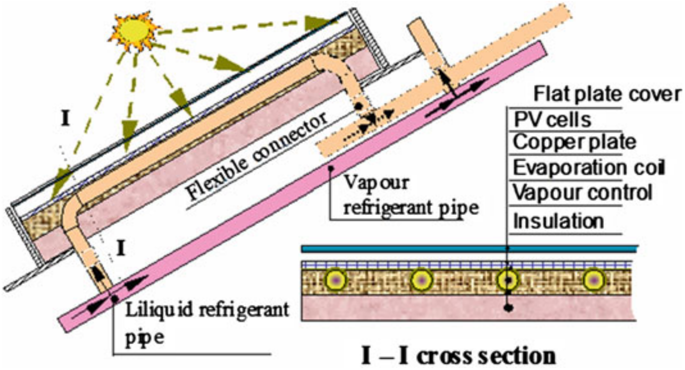


**Fig. 7** Cross-sectional view of the PV evaporator roof panel (Zhao et al. 2011)

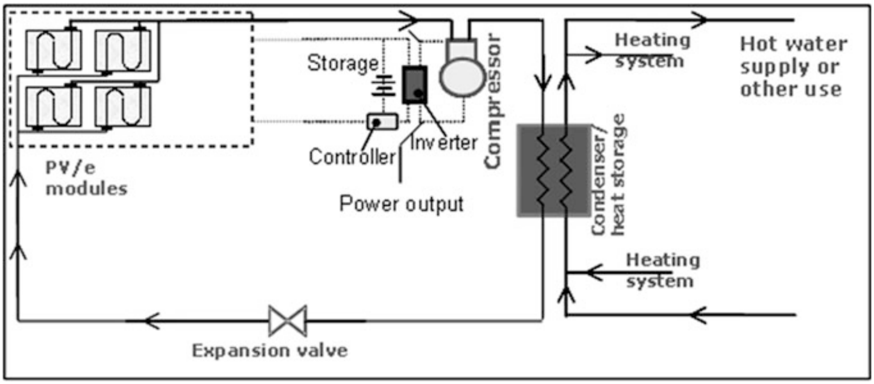


**Fig. 8** PV/e roof-module-based heat pump and micro-generation system (Zhao et al. 2011)

### *Heat-Pipe-Based PV/T*

Heat pipes are considered efficient heat transfer mechanisms that combine the principles of both thermal conductivity and phase transition. A typical heat pipe, as indicated in Fig. 9, consists of three sections, including evaporated section (evaporator), adiabatic section and condensed section (condenser), and provides an ideal solution for heat removal and transmission.

PV/heat pipe combination has been recently studied. Zhao et al. (2008, 2009, 2010) proposed a PV/flat-plate heat pipes array for co-generation of electricity and hot air/water. This prototype module comprises a photovoltaic layer and a flat-plate heat pipe containing numerous micro-channel arrays acting as the evaporation section of the heat pipes. The other end of the heat pipe is the condensation section which releases heat to the passing fluid, and the fluid within the section is condensed owing to the heat discharge. He claimed that the flat-plate geometry is more efficient due to the excellent thermal contact between the PV cells and heat extraction devices, which results in a smaller thermal resistance and higher overall solar conversion efficiency. In this way, the PV efficiency could increase by 15–30 % compared to the sole PVs, if its surface temperature is controlled to around 40–50 °C. The overall solar conversion efficiency of the module was around 40 %. Figures 10 and 11 show schematically three types of PV/heat pipe modules acting as the thermal and power co-generation units.

Qian et al. (2008, 2010) brought forward a new concept for building integrated PV/T system (IPVTS) utilizing oscillating heat pipe. This system is designed as the façade-assembled components to transport heat from the concealed PV cells (OHP-BIPV/T), as shown in Fig. 12. The system consists of the oscillating heat pipes, headers, finned tube, graphite conductive layer, metal frame, PV laminate module and insulations. When in operation, the working fluid within the metal heat pipes will absorb heat from the PV cells and be evaporated into vapour fluid. The vapour will flow up into the finned tube where it is condensed by releasing heat to the passing fluid and returns back to the absorber by effect of gravity and capillary forces.

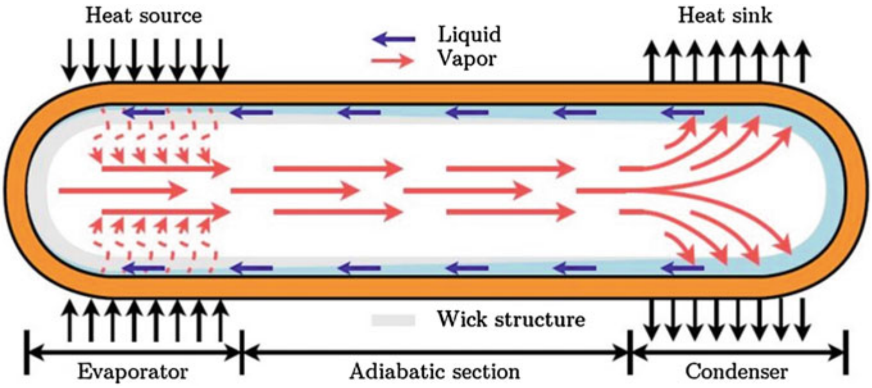


**Fig. 9** Schematic of a conventional heat pipe (Zhang et al. 2012)

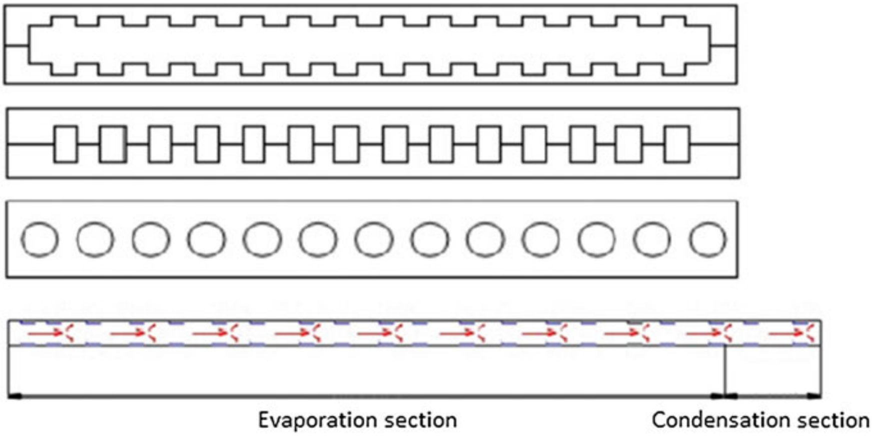


**Fig. 10** Three types of flat-plate heat pipes with micro-channel array (Zhang et al. 2012)

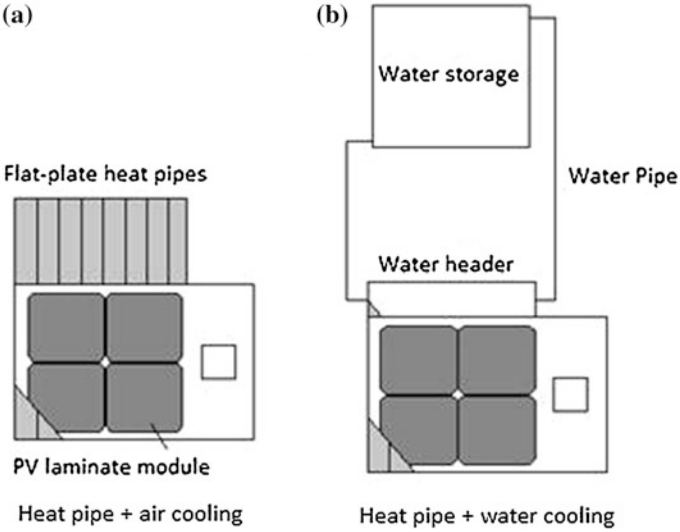


**Fig. 11** PV/flat-plate heat pipe: **a** air cooling and **b** water cooling (Zhang et al. 2012)

*General Comparison of the Currently Available PV/T Types and Their Technical Characteristics.*

A general comparison of the four currently available PV/T types was made in terms of their technical characteristics, as indicated in Table 1. The overall module efficiencies for different PV/T types were calculated on the basis of the same external solar/weather conditions (i.e. typical weather condition on 22 December

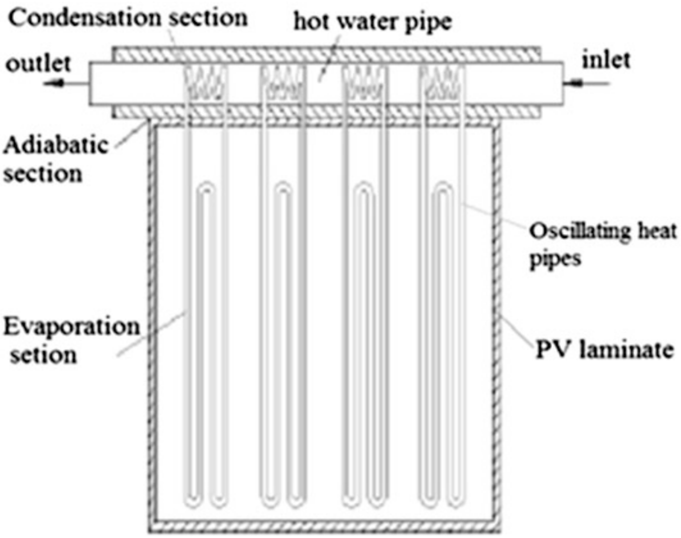


**Fig. 12** The schematics of OHP-BIPV/T module (Zhang et al. 2012)

in mid-east area of UK) and operational conditions (i.e. 0.01 kg/m$^2$ s of mass flow rate, 10 % of initial PV efficiency). The calculation models used are (1) indoor simulator (IS) model for air-based PV/T (Solanki et al. 2009); (2) IPVTS model for water-based PV/T (Huang et al. 2001); (3) PV solar-assisted heat pump (PV-SAHP) model for refrigerant-based PV/T (Ji et al. 2008); and (4) PV/flat-plate heat pipe (PV/FPHP) model for heat-pipe-based PV/T (Zhao et al. 2010). It is seen that the air- and water-based PV/Ts are riskless and lower cost and therefore considered to be more practical systems for application. The refrigerant-based PV/T has the advantage of low/steady working temperature, which could significantly improve the system's solar conversion efficiency, whereas the heat-pipe-based PV/T can extract heat from PV cells instantly, and if the operating temperature of the heat pipe fluid can be adequately controlled, the solar efficiency of the system could be significantly improved. However, these four systems have also found their own disadvantages that are addressed in the Table 1. To summarise: (1) air type has poor heat-removal performance due to its low thermal mass and less organised air flow; (2) water type remains increasingly growth of water temperature over the operational period which results in poor heat-removal effectiveness and low solar efficiency; (3) refrigerant type is difficult to handle in operation as pressurisation and depressurisation are required in different parts of the system, and risks of leakage and unbalanced refrigerant distribution remain high during the whole process; (4) heat-pipe type retains the cost problem that may affect its wide deployment in practical projects.

**Table 1** Characteristics comparison of different heat extraction methods (Zhang et al. 2012)

| PV/T models | Efficiency (%) | Advantage | Disadvantages |
|---|---|---|---|
| 'IS' model for air-based PV/T type (Solanki et al. 2009) | 24–47 | -low cost<br>-simple structure | -low thermal mass<br>-large air volume<br>-poor thermal effectiveness<br>-high heat loss |
| 'IPVTS' model for water-based PV/T type (Huang et al. 2001) | 33–59 | -low cost<br>-direct contribution<br>-high thermal mass<br>-low flow volume | -still-high PV temperature<br>-unstable heat effectiveness<br>-complex structure<br>-possible piping freezing |
| 'PV-SAHP' model for refrigerant-based PV/T type (Ji et al. 2008) | 56–74 | -low PV temperature<br>-stable performance<br>-high efficiency<br>-effective heat removal | -risk of leakage<br>-uneven liquid distribution<br>-high cost<br>-difficult to operate |
| 'PV/FPHP' model for heat pipe-based PV/T type (Zhao et al. 2010) | 42–68 | -low PV temperature<br>-stable performance<br>-high solar efficiency<br>-effective heat removal<br>-reduce power input | -high cost<br>-risk of damage<br>-complex structure |

## 2.3 Performance Evaluation Standards

Several national/regional standards are currently available for evaluating the performance of solely arranged solar thermal and PV devices. For solar thermal, the available standards include EN 12975 (2006a, b), EN 12976 (2006a, b), EN 12977 (2008, 2010a, b, c and d), Solar Keymark (2010), ISO 9806 (1994, 1995a, b), MCS 004 (2008) and other national solar thermal themes; for PV, standards, including IEC 61215 (2005), IEC 61646 (2008), IEC 61730 (2004a, b), UL 1703 (2002), UL 1741(2010) and UL 4703 (2005), IEEE 1262 (1995) and IEEE 929 (2000), Mark (2010) and other national electric codes, are in place. No published legal standards were found to address the performance issues of the PV/T. Instead, the methods for evaluating the PV/T were suggested in several academic papers. To summarise, the technical performance of the PV/T systems is usually evaluated using several indicative parameters including overall energy efficiency, overall exergy efficiency, primary-energy-saving efficiency and solar fraction. The economic performance of the PV/T systems is measured with life cycle cost (LCC) and cost payback time (CPT), and the environmental benefit of the system is justified using the energy payback time (EPBT) and greenhouse gas payback time (GPBT). These parameters are briefed as below.

### 2.3.1 Technical Performance Evaluation Parameters

*Overall Energy Efficiency*

Overall energy efficiency is the ratio of collected electrical and heat energy to incident solar radiation striking on the PV/T absorber. It is yielded from the first law of thermodynamics and indicates the percentage of the energy converted from the solar radiation. In a PV/T module, the electrical efficiency is much lower than the thermal efficiency, and therefore, the overall energy efficiency will largely rely on the thermal energy conversation of the system. It should be pointed out that the overall energy efficiency ignores the difference between heat and electrical energy in terms of the energy grade (quality) and therefore is inadequate to fully justify the energy performance of the PV/T systems.

*Overall Exergy Efficiency*

Overall exergy efficiency takes into account difference in energy grades between heat and electricity and involves a conversion of low-grade thermal energy into the equivalent high-grade electrical energy using the theory of Carnot cycle. The overall exergy ($e_o$) of the PV/T could be written as follows:

$$e_o = e_{\mathrm{th}} + e_e = (\xi_{\mathrm{th}} + \xi_e)I = \xi_o I \tag{13}$$

where $e_{\mathrm{th}}$ *and* $e_e$ are the thermal and electrical exergy, respectively; $\xi_{\mathrm{th}}$ and $\xi_e$ are the thermal and electrical exergy efficiency; $\xi_O$ is the overall exergy efficiency. The thermal exergy could be further written as follows:

$$e_{\text{th}} = \eta_c Q_u = \eta_c \eta_{\text{th}} I = \xi_{\text{th}} I \tag{14}$$

where $\eta_c$ is the ideal Carnot efficiency (Bosanac and Sørensen 2003):

$$\eta_c = \left(1 - \frac{293\,\text{K}}{293\,\text{K} + (T_{wm} - T_a)}\right) \tag{15}$$

where $T_{wm}$ is the final temperature of the work medium.

The electrical exergy is written as follows:

$$e_e = \eta_e I = \xi_e I \tag{16}$$

The overall exergy efficiency could be written as follows:

$$\xi_o = \eta_c \eta_{\text{th}} + \eta_e \tag{17}$$

The exergy efficiency has considered the energy grade difference between heat and electricity and therefore is a more rational index to evaluate performance of the PV/T systems.

*Primary-energy-saving efficiency*

Huang et al. (2001), Huang (1993) proposed another performance evaluation method to recognise the energy grade difference between heat and electricity, namely the primary-energy-saving efficiency ($E_f$), which is given by

$$E_f = \eta_e / \eta_{\text{power}} + \eta_{\text{th}} \tag{18}$$

where $\eta_{\text{power}}$ is the electrical power generation efficiency for a conventional power plant which is considered 0.38. For simplicity, the efficiency of conventional heating systems is considered 100 % which is achievable if a condensing boiler is used. Huang et al. (2001) suggested that primary-energy-saving efficiency of a PV/T system should be higher than 0.50, in order to compete a pure solar hot water system.

*Solar Fraction*

From the primary energy saving point of view, solar fraction ($f$) can also be used to evaluate the performance of PV/T system. It is defined as the fractional ratio of primary energy saving that a PV/T system can obtain to the overall energy demand and could be written as follows:

$$f = \frac{1}{2} \times \left(\frac{Q_{\text{load},t} - Q_{\text{aux},t}}{Q_{\text{load},t}} + \frac{Q_{\text{load},e} - Q_{\text{aux},e}}{Q_{\text{load},e}}\right) \tag{19}$$

where $Q_{\text{load},t}$ and $Q_{\text{aux},t}$ are the overall thermal load and auxiliary heat required; $Q_{\text{load},e}$ and $Q_{\text{aux},e}$ is the total electrical load and auxiliary electricity needed. Kalogirou (2001) indicated that the solar fraction is lower in the winter months and higher in the summer months reaching an annual value of 0.49 for a hot water supply system.

To summarise, the energy and exergy efficiencies are the major performance evaluation indexes for PV/T systems, whereas the primary-energy-saving efficiency and solar fraction are occasionally used to evaluate the fossil fuel-saving capacity of the PV/T systems. In reality, different end-users have different energy demands that would somehow affect the performance of the PV/T systems in use. Choosing an appropriate evaluation method for a specific PV/T installation would need to take both energy supply and demand into consideration.

### 2.3.2 Economical and Environmental Assessments

In terms of economic measures of the PV/T, Tripanagnostopoulos et al. (2005) suggested the LCC assessment method which takes into account the capital cost of system installation and associated operational and maintenance cost over the system's life cycle. The time-related issues such as inflation, tax and/or company discount rates should also be the factors to be considered. A simplified approach for assessing PV/T's economic value is by using CPT (in year), which ignores the time-relevant items and maintenance cost and therefore is inaccurate. Table 2 details the cost breakdown/payback issues related to various types of PV/T installations.

For environmental measures, two payback items, the EPBT and the greenhouse gas payback time, can be applied. EPBT is the ratio of the embodied energy for the PV/T and its annual energy output. Embodied energy refers to the quantity of energy required to produce the PV/T in its production phase. Chow (2010) suggested the mathematic expressions of the EPBT and GPBT for the PV/T system as below:

$$\mathrm{EPBT} = \frac{\Sigma_{\mathrm{pvt}} + \Sigma_{\mathrm{bos}} - \Sigma_{\mathrm{mtl}}}{E_{\mathrm{pv}} + E_{\mathrm{th}} + E_{\mathrm{ac}}} \tag{20}$$

where $\Sigma_{\mathrm{pvt}}, \Sigma_{\mathrm{bos}}\, and\, \Sigma_{\mathrm{mtl}}$ are the embodied energy of the PV/T system, the balance of system and the replacing building materials; $E_{\mathrm{pv}}$ is the annual useful electricity output; $E_{\mathrm{th}}$ is the annual useful heat gain (equivalent); and $E_{\mathrm{ac}}$ is the annual electricity saving of HVAC system due to thermal load reduction.

$$\mathrm{GPBT} = \frac{\Omega_{\mathrm{pvt}} + \Omega_{\mathrm{bos}} - \Omega_{\mathrm{mtl}}}{Z_{\mathrm{pv}} + Z_{\mathrm{th}} + Z_{\mathrm{ac}}} \tag{21}$$

where Ω represents the embodied GHG (or $CO_2$ equivalent) and Z is the reduction in annual GHG emission from the local power plant owing to the PV/T operation. The environmental measures of the selected PV/T installations are given in Table 3 (Tripanagnostopoulos et al. 2005).

**Table 2** Cost breakdown and cost payback time (Tripanagnostopoulos et al. 2005)[a]

| System cost 30 m$^2$ installation cost payback time (CPBT) | Cost of PV + HRU + REF (€) | Cost of electrical + terminal (€) | Installation cost (€) | Total cost (€) | CPBT for electricity saving (in yr) | CPBT for electricity and gas saving (in yr) |
|---|---|---|---|---|---|---|
| PV | 21,000 | 1,500 | 1,500 | 24,000 | 25.8 | 25.8 |
| PV + REF | 22,500 | 1,500 | 1,500 | 25,500 | 22.9 | 24.1 |
| PY-TILT | 21,000 | 1,500 | 900 | 23,400 | 28.2 | 26.9 |
| PVT/TJNGL-25 °C | 24,000 | 4,500 | 1,500 | 30,000 | 11.9 | 18.1 |
| PVT/UNGL-35 °C | ≥ | ≥ | ≥ | ≥ | 18.7 | 23.8 |
| PVT/UNGL-45 °C | ≥ | ≥ | ≥ | ≥ | 28.1 | 29.6 |
| PVT/UNGL + REF-25 °C | 25,500 | 4,500 | 1,500 | 31,500 | 11.1 | 17.2 |
| PV T/UNGL + REF-35 °C | ≥ | ≥ | ≥ | ≥ | 17.0 | 22.3 |
| PVT/UNGL + REF-45 °C | ≥ | ≥ | ≥ | ≥ | 25.5 | 28 1 |
| PVT/GL-25 °C | 27,000 | 4,500 | 1,500 | 33,000 | 10.5 | 17.6 |
| PVT/GL-35 °C | ≥ | ≥ | ≥ | ≥ | 14.5 | 21 9 |
| PVT/GL-45 °C | ≥ | ≥ | ≥ | ≥ | 21.2 | 27.9 |
| PVT/GL + REF-25 °C | 28,500 | 4,500 | 1,500 | 34,500 | 10.3 | 17 2 |
| PVT/GL + REF-35 °C | ≥ | ≥ | ≥ | ≥ | 13.9 | 21 1 |
| PVT/GL + REF-45 °C | ≥ | ≥ | ≥ | ≥ | 19.8 | 26.3 |
| PVT/UNGL-TILT-25 °C | 24,000 | 4,500 | 900 | 29,400 | 11 8 | 18.2 |
| PVT/UNGL-TILT-35 °C | ≥ | ≥ | ≥ | ≥ | 18.5 | 24.2 |
| PVT/UNGL-TILT-45 °C | ≥ | ≥ | ≥ | ≥ | 28.2 | 30.8 |
| PVT/GL-TILT-25 °C | 27,000 | 4,500 | 900 | 32,400 | 10.5 | 17.9 |
| PVT/GL-TILT-35 °C | ≥ | ≥ | ≥ | ≥ | 14.2 | 22 1 |
| PVT/GL-TILT-45 °C | ≥ | ≥ | ≥ | ≥ | 20.7 | 28.2 |

[a] *Note HRU* heat recovery unit; *UNGL* unglazed; *GL* glazed; *REF* stationary flat diffuse reflectors; *TILT* tilted installation

**Table 3** EPBT and $CO_2$ PBT values (Tripanagnostopoulos et al. 2005)

| System EPBT and $CO_2$ PBT results | EPBT for replacing electricity only (yr) | $CO_2$ PBT for replacing electricity only (yr) | EPBT for replacing electricity and gas (yr) | $CO_2$ PBT for replacing electricity and gas (yr) |
|---|---|---|---|---|
| PV | 2.9 | 2.7 | 2.9 | 2.7 |
| PV + REF | 2.7 | 2.5 | 2.7 | 2.5 |
| PV-TILT | 3.2 | 3.1 | 3.2 | 3.1 |
| PVT/UNGL-25 °C | 1.0 | 0.9 | 1.2 | 1.5 |
| PVT/UNGL-35 °C | 1.9 | 1.7 | 2.2 | 2.4 |
| PVT/UNGL-45 °C | 3.6 | 3.3 | 3.8 | 3.7 |
| PVT/UNGL + REF-25 °C | 0.9 | 0.9 | 1.2 | 1.4 |
| PVT/UNGL + REF-35 °C | 1.7 | 1.5 | 2.0 | 2.2 |
| PVT/UNGL + REF-45 °C | 3.1 | 2.9 | 3.4 | 3.4 |
| PVT/GL-25 °C | 0.8 | 0.8 | 1.1 | 1.3 |
| PVT/GL-35 °C | 1.3 | 1.2 | 1.6 | 1.9 |
| PVT/GL-45 °C | 2.2 | 2.0 | 2.6 | 3.0 |
| PVT/GL + REF-25 °C | 0.8 | 0.8 | 1.0 | 1.3 |
| PVT/GL + REF-35 °C | 1.2 | 1.1 | 1.5 | 1.8 |
| PVT/GL + REF-45 °C | 2.0 | 1.9 | 2.4 | 2.7 |
| PVT/UNGL-TILT-25 °C | 1.0 | 1.0 | 1.3 | 1.6 |
| PVT/UNGL-TILT-35 °C | 1.9 | 1.8 | 2.3 | 2.5 |
| PVT/UNGL-TILT-45 °C | 3.8 | 3.5 | 4.1 | 4.1 |
| PVT/GL-TILT-25 °C | 0.8 | 0.8 | 1.1 | 1.4 |
| PVT/GL-TILT-35 °C | 1.3 | 1.2 | 1.6 | 2.0 |
| PVT/GL-TILT-45 °C | 2.2 | 2.0 | 2.7 | 3.1 |

## 3 R&D Progress and Practical Application of the PV/T Technologies

### *3.1 Overview of the R&D Achievements in PV/T Field*

Quantitative researches have been carried out to study the performance of different PV/T configurations, optimise their geometrical sizes and suggest the favourite operational parameters. As a result, many achievements and conclusive remarks have been obtained and these are selectively indicated as follows.

Hendrie (1980) developed a theoretical model for the flat-plate PV/T solar collectors, and by using the model, he carried out the study in the thermal and electrical performance of an air- and a liquid-based PV/T solar collector. He concluded that when the PV modules were not in operation, the air- and liquid-based collectors could achieve the peak thermal efficiencies of 42.5 and 40 %, respectively. However, when the PV modules were in function, the air- and liquid-based units obtained slightly lower thermal efficiencies, which are 40.4 and 32.9 %, respectively. The measured peak electrical efficiency of these units was 6.8 %.

Florschuetz (1979) used the well-known Hottel–Whillier (1958) thermal model for the flat-plate solar collectors to analyse the performance of the combined PV/T collector. By slightly modifying the parameters existing in the original computer program, the model became available for analysing the dynamic performance of the PV/T collector. Assuming that the solar PVs' electrical efficiency is linearly reduced when the cells' temperature increases, the thermal and electrical efficiencies of the combined PV/T collector were obtained and the results are further analysed to established the correlations between the efficiencies and various operational parameters of the collectors.

Raghuraman (1981) developed two one-dimensional analytical models to predict the thermal and electrical performance of both liquid- and air-based flat-plate PV/T collectors. The analysis took into account the difference in temperature of the primary absorber (the PV cells) and secondary absorber (a thermal absorber flat plate), and a number of design notes were recommended to enable maximised energy utilisation of the collectors.

Bergene and Lovvik (1995) developed a dedicated PV/T mathematical model and the associated algorithms enabling quantitative predictions of the performance of the system. The model was established on analysis of energy transfers including conduction, convection and radiation initiated by Duffie and Beckman (1991), and the results of model operation suggested that the overall efficiency of PV/T collectors is in the range 60–80 %.

Sopian et al. (1996) developed the steady-state models to analyse the performance of both single- and double-pass PV/T air collectors. The models yielded the temperature profiles of the glass cover, plates and air stream, while the mean plate temperature could be applied to evaluate the efficiency of the photovoltaic cells. Performance analysis showed that the double-pass photovoltaic thermal solar collector produces better performance than the single-pass module at a normal operational mass flow rate range. In addition, the thermal and combined thermal and electrical efficiencies increased when the packing factor (defined as the ratio of the PV cell area to absorber area) decreased, whereas the electrical efficiency of the PVs decreased slightly.

Sandnes and Rekstad (2002) constructed a PV/T unit by using a polymer solar heat collector combined with single-crystal silicon PV cell. An analytical model derived from the Hottel–Whillier (1958) equations was used to simulate the temperature distribution and the performance of both the thermal and photovoltaic parts. The simulation results were in agreement with the experimental data. They found that pasting solar cells onto the absorbing surface would reduce the solar energy absorbed by the panel (about 10 % of incident energy) due to lower optical absorption in the solar cells compared to the black absorber plate. Further, there is an increased heat transfer resistance at the surface of absorber and within the fluid which reduces the collector's heat-removal factor, $F_R$. Moreover, they concluded that the solar cells' temperature is strongly related to the system (inlet fluid)'s temperature and also to the collectors' heat transport characteristics. The combined PV/T concept should therefore be associated with applications of sufficiently low temperature to give the desired cooling effect.

Tiwari and Sodha (2006) developed a thermal model for an integrated photovoltaic and thermal solar collector system and compared it with the model for a conventional solar water heater by Huang et al. (2001). Based on energy balance of each component of the system, an analytical expression for the temperature of PV module and the water has been derived. The simulations predicted a daily primary-energy-saving efficiency of about 58 %, which was in good agreement with the experimental value (61.3 %) obtained by Huang et al. (2001).

Dubey et al. (2009) developed an analytical model that indicated the electrical efficiency of PV module with and without cooling flow as a function of climatic and PV's physical/operational parameters. The four different PV configurations, i.e. case A (glass to glass-type PV module with duct), case B (glass to glass-type PV module without duct), case C (glass to tedlar PV module with duct), case D (glass to tedlar PV module without duct), were investigated. It was found that the glass to glass-type PV modules with duct give higher electrical efficiency and the higher outlet air temperature among the all four cases. The annual average efficiency of glass to glass-type PV module with and without duct was reported 10.41 and 9.75 %, respectively.

Chow (2003) developed an explicit dynamic model with seven nodes of a single-glazed flat-plate water-heating PV/T collector suitable for use in systems' dynamic simulation. This model, derived from the control-volume finite-difference formulation and incorporated with a transport relay subprogram, could provide information on transient performance, including the instantaneous thermal/electrical gains, their efficiencies and thermal conditions of various components. Further to an extension of the nodal scheme to include multidimensional thermal conduction on PV and absorber plates, this model was able to perform complete energy analysis on the hybrid collector.

Cox and Raghuraman (1985) explored several useful design features of air-based flat-plate PV/T collectors in order to determine their effectiveness and interaction on the basis of a computer simulation. They found that the air PV/T types are usually less efficient than the liquid ones due to low PV cell packing factor, low solar absorptance, high infrared emittance and low absorber to air heat transfer coefficient. Methods to tackle these drawbacks were mainly recommended on two major ways: increasing the solar absorptance and reducing the infrared emittance. The results showed that when the packing factor is greater than 65 %, a selective absorber could actually reduce the thermal efficiency when used with a gridded-back cell. The optimum combination for an air PV/T module was suggested to consist of gridded-back PV cells, a non-selective secondary absorber and a high-transmitting/low-emissive cover above the PV cells.

Grag and Agarwal (1995) developed a simulation model to investigate the effect of the design and operational parameters of a hybrid PV/T air-heating system on its performance. It was found that whether or not to use single- and double-glass covers in a PV/T air-heating system largely depended on its design temperatures as the extra glass cover might lead to the increased transmission losses, and beyond some critical point, the single-glass cover can collect more heat than double glass does. The parametric studies showed that the system efficiency increases with increase in collector length, mass flow rate and cell density, and decreases with increase in duct depth for both configurations. However, as material cost increases by increasing the number of glass covers, collector length, cell density, duct depth and mass flow rate, final selection of design parameters and operational variables of a PV/T system must be based on the cost-effectiveness of the system by minimising the LCC of the system.

Kalogirou (2001) carried out the modelling and simulation of the performance of a hybrid PV/T solar water system by using TRNSYS, which is a transient simulation program with typical meteorological year (TMY) conditions for Nicosia, Cyprus. The PV system consisted of a series of PV panels, a battery bank and an inverter, whereas the thermal system consisted of a hot water storage cylinder, a pump and a differential thermostat. The results showed that the hybrid system increases the mean annual efficiency of the PV solar water system from 2.8 to 22.7 % and in addition covers 49 % of the hot water needs in a house, thus increasing the mean annual efficiency to 31.7 %. The life cycle savings of the system were calculated at Cy£790.00, and the payback time was 4.6 years.

Tonui and Tripanagnostopoulos (2008) constructed an air-based PV/T solar collector which applied two low-cost approaches to enhance heat transfer between the air flow and PV surface. A finned metal sheet was attained to the back wall of the air channel to improve heat extraction from the PV modules. The experimental tests were carried out on the air-based PV/T system which used a 46-Wp-rated commercial pc-Si PV module and has 0.4 $m^2$ of aperture area as the absorber plate. The results showed good agreement between predicted values and measured data. It is found that the induced mass flow rate and thermal efficiency decrease with increasing ambient (inlet) temperature and increase with increasing tilt angle for a given insulation level. The results also showed that the optimum channel depth occurs between 0.05 and 0.1 m for this system. This type of PV/T system was practical and cost-effective, suitable for being integrated into the building with both heat and electrical demands.

Solanki et al. (2009) designed and constructed a PV/T solar air heater and studied its performance over different operational parameters under steady indoor conditions. Experimental simulator consisted of three PV modules (mono-crystalline silicon solar cells) of glass to tedlar type, each rating at 75 Wp, has 0.45 m width and 1.2 m length and was mounted on a wooden duct. They found that the thermal, electrical and overall efficiency of the solar heater obtained at indoor condition was 42, 8.4 and 50 %, respectively. They also proposed an indoor standard test procedure for thermal and electrical testing of the PV/T collectors connected in series. It is concluded that this test procedure can be used by manufacturers for testing different types of PV modules in order to optimise its geometrical sizes.

Shahsavar and Ameri (2010) designed and tested a direct-coupled PV/T air collector with and without glass cover at Kerman, Iran. In their study, a thin aluminium sheet suspended at the middle of air channel was used to increase the heat exchange area and consequently improve heat extraction from PV panels. This PV/T system was tested in natural forced convection conditions (with two, four and eight fans operating). Good agreement between the measured values and those calculated by the simulation model was achieved. It is concluded that there is an optimum number of fans for achieving maximum electrical efficiency. Also, results showed that setting glass cover on photovoltaic panels leads to an increase in thermal efficiency and decrease in electrical efficiency of the system.

Huang et al. (2003) studied an integrated photovoltaic–thermal system set-up. A commercial polycrystalline PV module was used for making a PV/T collector, which is part of the system configuration. The testing approach for conventional solar hot water heaters was used to evaluate the thermal performance rating of the system. The tested results showed that the solar PV/T collector made of a corrugated polycarbonate panel can obtain a primary-energy-saving efficiency of about 61.3 %, while the temperature difference between the tank water and the PV module was around 4 °C.

De Vries (1998) and Zondag et al. (2002, 2003) carried out testing of a PV/T solar boiler with a water storage tank in the Dutch and found that the covered sheet-and-tube system was the most promising PV/T concept for tap water heating. It reported that the water-based PV/T system can provide more architectural uniformity, minimise the usage of space on roof and achieve reduced payback period. This PV/T system could achieve annual average solar efficiencies of between 34 and 39 % for the covered designs and 24 % for the uncovered design.

Chow et al. (2006) illustrated an experimental study into a combined centralised photovoltaic and hot water collector wall system that can serve as the water preheater. The collectors were mounted at vertical facades, and different operating modes were implemented for different seasons. They found that natural water circulation was preferable to the forced circulation in this hybrid solar collector system. The thermal efficiency was reported 38.9 % at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56 %, during the late summer in Hong Kong. With the PV/T wall, the space thermal loads can be significantly reduced both in summer and in winter, leading to substantial energy savings.

Zhao et al. (2009) designed two experimental prototypes by integrating the flat-plate heat pipe with the mono-ci PV cells at the effective area of 0.0625 $m^2$, while the surplus heat was taken away, respectively, via the natural air flow and passive water circulation. In comparison with the solely PV system, the PV/T modules were found to be able to achieve the enhanced electrical efficiencies of 2.6 and 3 %, and the reduced cell temperatures of 4.7 and 8 °C, respectively, for air- and water-based conditions.

Ji et al. (2009) developed a novel solar PV/T heat pump (PV/T-SAHP) system that combined a Rankine refrigeration cycle with a PV/T solar collector. A dynamic model for the PV evaporator was established using the distributed parameter approach to investigate the effect of the refrigerant parameters (e.g. pressure, temperature, vapour quality and enthalpy) onto the system's solar efficiencies and study the temperature distribution across the evaporator channels. The results indicated that the PV electrical efficiency and evaporator thermal efficiency are around 12 and 50 %, respectively, during the testing period in Hefei, China.

On the basis of the above work, Ji et al. (2008) carried out the testing of the system under a range of operational conditions. The results indicated that the PV-SAHP system has a higher coefficient of performance (COP) than the conventional heat pump system and the PV's electrical efficiency is also higher. The COP of the heat pump was able to achieve 10.4, while the average COP value of the traditional heat pumps was around 5.4. The average PV solar efficiency was around 13.4 %. The highest overall coefficient of performance (COP—peak), taking into account the performance of PVs and evaporators, was around 16.1.

Zhao et al. (2011) designed a novel PV/e roof module to act as the roof element, electricity generator and the evaporator of a heat pump system. The energy profiles and system operating conditions were analysed, and temperature distribution across the module layers was simulated. This study indicated that the combined system should operate at 10 °C of evaporation and 60 °C of condensation temperature. Borosilicate as a top cover has better thermal performance than polycarbonate and glass, while the mono-crystalline photovoltaic cells are of higher electrical efficiency over the polycrystalline and thin films. Under a typical Nottingham (UK) operating condition, the modules would achieve 55 % of thermal efficiency and 19 % of electrical efficiency, while the module-based heat pump system would have an overall efficiency of above 70 %. It was also addressed that the integration of the PV cells and evaporation coil into a prefabricated roof would lead to large saving in both capital and running costs over separate arrangements of PV, heat pump and roof structure.

Apart from the above reports, many other achievements in this subject have been found and a few more examples of these are briefed as below.

*For air-based PV/T*, Komp and Reeser (1987) reported on the design and installation of a stationary concentrating glazed roof-integrated PV air collector for an off-grid dwelling. The hybrid collector is equipped with fins to enhance the heat transfer between the PV cells and air; the air was then drawn into the house using a fan in winter and by natural convection in summer. Fudholi et al. (2010) indicated that drying up agricultural and marine products is one of the most attractive and cost-effective applications for solar PV/T technology. Takashima et al. (1994) concluded that the surface temperature of the PV panels could be reduced when air gap was remained above the PV to form a thermal collector. Moshtegh and Sandbergy (1996a, b) numerically and experimentally studied the performance of air flow induced by buoyancy and heat transfer within a vertical channel heated from the PV side wall. The study reported that the induced velocity increases the heat flux non-uniformly inside the duct and its impact depends on the sizes and geometry of the air exit. Bhargvaa et al. (1991) and Parkash (1994) studied the performance of single-pass PV/T air collector using a computer model and analysed the influence of air mass flow rate, depth of air channel and packing factor to the system's overall efficiency. Sopian et al. (1996) analysed the performance of both single- and double-pass PV/T air collectors using steady-state computer models. The results showed that double-pass PV/T air collectors have higher efficiencies than the single-pass ones, but its capital cost is a bit higher. Kelly and Strachan (2000) and Tripanagnostopoulos et al. (2002) suggested several possible approaches to enhance the cooling effect, such as modifying channel geometries to create more turbulence for flows. Tiwari and Sodha (2007) indicated that the glazed air PV/T collectors have higher thermal efficiency than the paralleled unglazed ones, especially at low-temperature conditions where the double-glazing cover was found to be superior to the single-glazing cover (Garg and Ahhikari 1997). On the other hand, the glazing cover would slightly reduce the overall performance of the collector owing to unavoidable solar reflection occurring on the cover.

*For water-based PV/T*, Agarwal and Grag (1994, 1995) designed the prototypes of thermosyphonic and flat-plate PV/T water heaters. Bergene and Lovvik (1995) then conducted an energy transfer study on PV/T water system composed of flat-plate solar collector and PV cells, which indicated that an overall efficiency of 60–80 % can be achieved. It is found that the proposed system could be used to preheat the domestic hot water. More recently, Zondag et al. (2003) classified the water-based PV/T collectors into four major types, namely sheet-and-tube collectors, channel collectors, free-flow collectors and two-absorber collectors. Chow et al. (2006) suggested that implementing the water flow channels beneath the transparent PV module may be a good choice to achieve enhanced solar efficiency. However, the single-glazing sheet-and-tube hybrid PV/T collector is regarded as the most promising design as it has high overall efficiency and is easy to construct. Kalogirou and Tripanagnostopoulos (2001, 2006) simulated a PV/T water supply and storage system and found that the economic viability of PV/T water system was much better than the air-based type. Elswijk et al. (2004) installed large PV/T arrays on residential buildings and reported that the use of PV/T would save around 38 % in roof area, relative to a side-by-side system of PV and solar thermal. Ji et al. (2003) studied a facade-integrated PV/T collector for residential building in Hong Kong. The annual thermal efficiencies were found to be around 48 % for the thin-film silicon and 43 % for the crystalline silicon case, respectively. In addition, the building intergraded system was able to reduce the cooling requirements of the building substantially due to the reduced heat absorption by walls.

*For refrigerant/heat-pipe-based PV/T*, Nishikawa et al. (1993) studied a PV/T heat pump system using R22 as the refrigerant. When the PVs were effectively cooled, the system could achieve higher COP than a conventional heat pump could. Ito et al. (1997) worked on a similar PV/T heat pump and found that when the condensation temperature was set at 40 °C, the COP of heat pump could achieve as high as 6.0. Further, Ito et al. (1999) analysed the effect of a few physical parameters, e.g. collector area, width, length and thickness of the collector plate to the system's solar efficiency and COP. Zhao et al. (2008, 2009, 2010) initiated a PV/flat-plate heat pipe with micro-channel arrays inside to produce electricity and hot air/water simultaneously, which is detailed in Fig. 11. Further, Qian et al. (2008, 2010) invented a building integrated PV/T system using oscillating heat pipe for the combined heat and power generation using solar energy. This type of system was addressed in Fig. 12.

## 3.2 *Practical Application of the PV/T Technologies*

Although the PV/T technology is in the start-up stage, some commercial products or engineering projects related to PV/T application can still be found in practice. A number of PV/T practical works are addressed as follows:

'GRAMMER Solar GmbH' in Germany has developed an air-based PV/T solar collector titled 'TWINSOLAR', which is designed to preheat ventilation air in buildings and has the absorber area of between 1.3 and 12.5 m$^2$. The modules can be assembled vertically or horizontally, on the roof or on the south, south-east or south-west facing facades. It is observed that at maximum solar radiation of 700 W/m$^2$, the air temperature rose to 40 °C and nearly 70 % of the solar incident

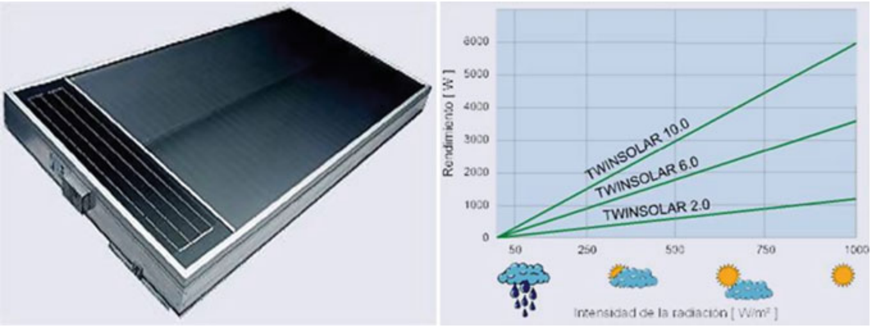


**Fig. 13** The 'TWINSOLAR' application and its performance curve (Zhang et al. 2012)

energy was converted into thermal energy and transported into the building, as shown in Fig. 13.

In Denmark, the SolarVenti units are mainly used for providing ventilation and supplementary heating and assisting in air dehumidification. The larger-capacity SolarVenti models have substantial thermal energy output and can drive significant amount of air due to the effect of the buoyancy force. The thermal energy is captured directly from solar radiation across the spectrum and can be used to supplement the existing space-heating system in any domestic or commercial building. Table 4 provides the energy outputs for different SolarVenti models.

The Canadian 'Conserval Engineering Inc' provides the SolarWall and the rooftop SolarDuct products. The SolarWall is a proprietary solar air-heating system that can heat up building using ventilation air and also be amounted on walls or roofs for various purposes including heating up buildings and running agricultural and manufacturing drying-up process. The SolarWall is a PV/T-combined system that has significantly lower payback period than a PV system. It can produce up to 400 % more usable energy than a solely PV system. The SolarDuct PV/T is a modular rooftop system with total operating efficiency of above 50 % where the thermal panels have doubled the output from the PV racking system. Figure 14 indicates the product series available in this company.

The Dutch-based 'PVTWINS' developed the PV/T water-heating products for niche market, as shown in Fig. 15. The PV/T water collectors can be used in individual and collective domestic hot water systems. This PV/T type can achieve a temperature as high as 90 °C. The electrical yield is measured with 125 Wp/m$^2$,

**Table 4** Energy output of different SolarVenti models (Zhang et al. 2012)

| Model | Air volume (m$^3$/H) | Temperature increase (°C) | Max output kW (per h) | Max output kW per year (1,000 h sun) |
|---|---|---|---|---|
| SV14 | 60 | ~30 | 0.6 | 600 |
| SV30 | 120 | ~40 | 1.6 | 1,600 |
| SV30H | 100 | ~40 | 1.3 | 1,300 |

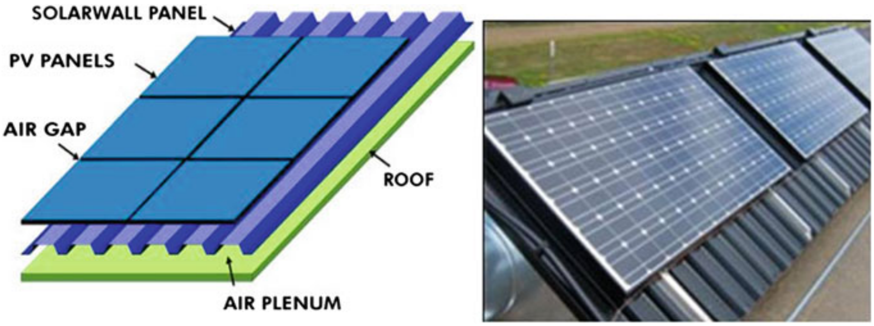


**Fig. 14** The solar air PV/T products of 'Conserval Engineering' company (Zhang et al. 2012)

**Fig. 15** PV/T liquid collector—PVTWIN from 'PVTWINS' company (Zhang et al. 2012)

**Fig. 16** 'MULTI SOLAR' PV/T system from 'Millennium Electric' (Zhang et al. 2012)

and the thermal yield is about 1.2 GJ/$m^2$ · year. The PV/T collectors have three available sizes, e.g. 1,800 × 1,800, 900 × 5,600 and 1,800 × 2,400 mm, and are suitable for being integrated into tilted or flat roofs using a common connection method.

The Israel-based 'Millennium Electric Ltd' has developed a MULTI SOLAR PV/T System that enables conversion of solar energy into thermal and electrical energy simultaneously using a single hybrid system, as shown in Fig. 16. The MULTI SOLAR PV/T System is made of facade/roof-tile-like panels which behave as a 'living' skin around the building allowing the flow of water to cool the PV cells, capture heat and store it in an insulated tank, thus enabling heat control of the living environment. The system can generate 30 % higher PV efficiency in production of electricity for domestic use.

In terms of PV/T concentrators, three major manufacturers in the world, namely Absolicon in Sweden, Menova Energy in Canada and HelioDynamics in the UK, involved with this kind of business. 'Absolicon' produced an X10 PV/T commercial heat and power system, as shown in Fig. 17. The system consists of a cylinder-parabolic reflector that concentrates ten times the solar light onto the receiver. It is also equipped with the latest generation of photovoltaic technology

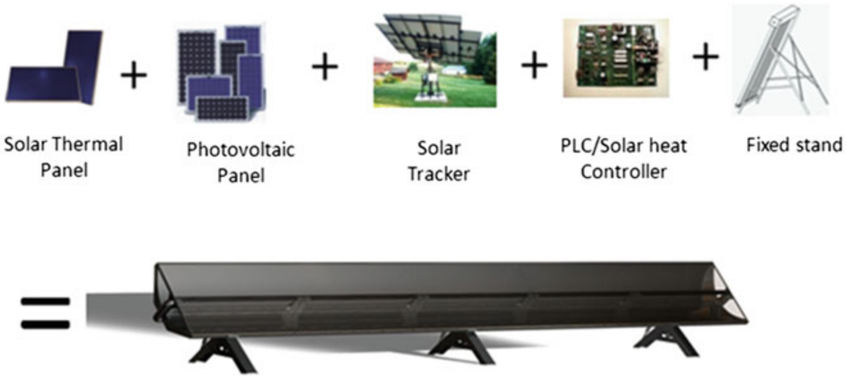


**Fig. 17** ‘X10’ PV/T system from ‘Absolicon’ company (Zhang et al. 2012)

and a solar tracking system using special electrical custom-designed high-quality linear actuators. The aim is to rotate the X10 concentrator to allow the sunlight to be focused onto the cells all the time. The tracking system has a built-in program that can automatically protect the photovoltaic cells from being overheated or from storms. If the temperature exceeds a certain value, the X10 automatically turns the receiver away from the sun.

‘Menova Energy’ provides the Power-Spar PV/T concentrator for use in domestic application, as shown in Fig. 18. The Power-Spar model has been specifically engineered to provide enhanced performance even when being exposed to extreme winter temperature.

‘HelioDynamics’ provides a tracking, modular PV/T concentrator, namely ‘Harmony HD 211’, as shown in Fig. 19. It is designed for being mounted on the flat and sloping roofs or pole-mounted over parking areas at the mid-latitudes (20°–40°).

The ventilated PV with heat recovery is a type of recently emerged PV/T air collector system. The system is designated to provide solutions for ventilating the PV cells to maximise the electrical yield and utilizing the PV heat for preheating the ventilation air. Standardised products for this purpose have been manufactured in Secco Sistemi, an Italian PV manufacturers, as shown in Fig. 20. This type of system has been used in various engineering projects including the Fiat Research

**Fig. 18** ‘Power-Spar’ from ‘Menova Energy’ company (Zhang et al. 2012)

**Fig. 19** ‘Harmony HD211’ from ‘HelioDynamics’ company (Zhang et al. 2012)

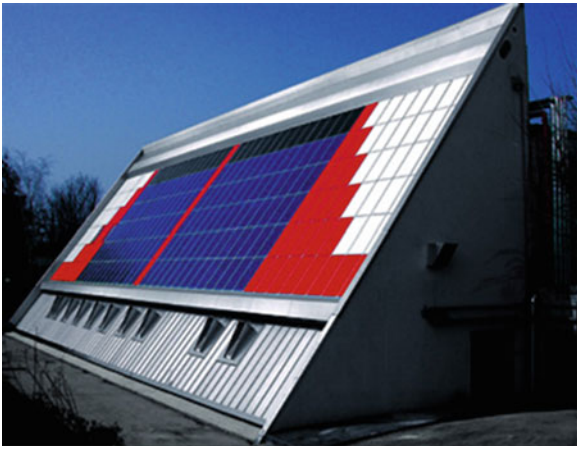


**Fig. 20** Ventilated PV with heat recovery—TIS from ‘Secco Sistemi’ (Zhang et al. 2012)

Centre, Imagina Studio in Barcelona and the Professional Training Centre in Casargo.

## *3.3 Analysis of the PV/T Research Achievements*

The research achievements of PV/T technologies were found very substantial, and the above case-to-case statement may be too scattered to capture the main sense of the research works in this subject. To allow clear justification of the research progress and engineering practice in PV/T, the above works are further analysed from two angles: (1) system type and (2) research methodology. These are summarised as follows:

### 3.3.1 Analysis of the Research Achievements in Terms of PV/T Types

In terms of the system types concerned, the research can fall into four categories, namely (1) air-based PV/T; (2) water-based PV/T; (3) refrigerant-based PV/T; and (4) heat-pipe-based PV/T. Of these systems, air- and water-based types are relatively mature technologies and have already been widely used in the practical projects, while the refrigerant and heat-pipe-based systems are still in research/laboratory stage and some technical/economic barriers still remain that prohibited their wide application.

*Air-based PV/T*

Air-based PV/T is one of the most commonly used PV/T technologies and has been developed into commercial units or/and used in many engineering practices. This type of system usually comprises of (1) commercial laminated PV modules; (2) specially designed air flow channels/ducts; (3) active fans; (4) air-handling unit or air/air heat exchangers (TWINSOLAR 2010 and SolarWall 2010), and its solar efficiency behaves as the function of geometrical parameters and external climatic conditions. The most favourite unit configuration and material are the integrated frameset of aluminium absorber and lamina-separated channels with either the presence or absence of built-in commercial PV cells. A diagram showing the relation between the solar thermal and electrical efficiencies and operational parameters is given in Fig. 21 (Solanki et al. 2009).

In overall, a typical air-based PV/T type can achieve maximum electrical efficiency of around 8 % and thermal efficiency of around 39 % (Solanki et al. 2009). Its performance is largely dependent on the air flow speed and temperature. Researches related to this type of PV/T system usually focus on (1) studying the more favourite air flow patterns, e.g. buoyancy-driven and forced flow, (2) determining the optimised channel's geometry and sizes to enable creating effective turbulence within the channels, and (3) selecting proper glazing modes, e.g. uncovered or covering with single/double glass. The major problem

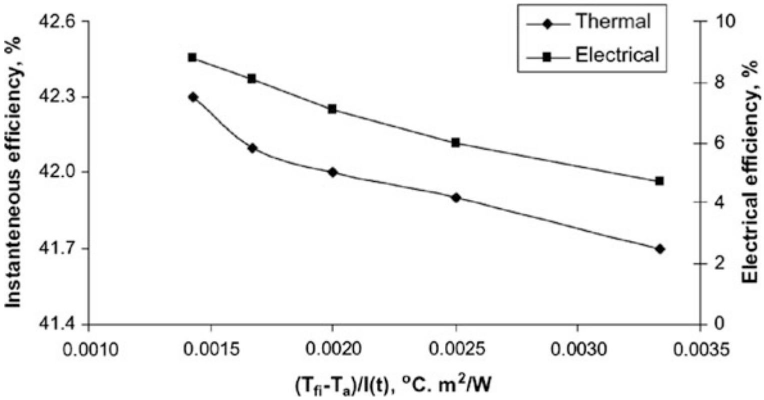


**Fig. 21** Variation in efficiencies with operating conditions (Solanki et al. 2009)

with the air-based system lies in its relatively poor heat-removal effectiveness owing to the low density, specific heat capacity and thermal conductivity of the air.

*Water-based PV/T*

Water-based PV/T is secondary popular PV cooling approach, which has gained growing application in practice over recent years. Numerous commercial products have emerged on markets, and most impressive examples include 'PVTWIN' series products by PVTWINS and 'MULTI SOLAR' by Millennium Electric. The performance of the water-based PV/T technology is usually indicated by its electrical and thermal efficiencies which are found to vary with the water temperature, flow rate, water flow channel's geometry and sizes, PV type, as well as external climatic conditions. The most favourite unit configuration and material are the PV/T laminate with the single-glazing and sheet-and-tube absorber in an aluminium frame and insulation on the back side, which is regarded as the most promising design as it has relatively high overall efficiency and is easy to construct (PVTWINS 2010). A diagram showing correlation between solar efficiencies and the operational parameters is presented in Fig. 22 (Huang et al. 2001), which is established on the basis of the fixed geometrical conditions and PV type.

In overall, a typical water-based PV/T type can achieve maximum electrical efficiency of around 9.5 % and thermal efficiency of around 50 % (Huang et al. 2001). Its performance is largely dependent on water temperature, flow rate, water flow channel's geometry and sizes, PV type, as well as external climatic conditions. Researches related to water-based PV/T system usually focus on (1) determining appropriate water flow velocity and temperature, (2) optimising water

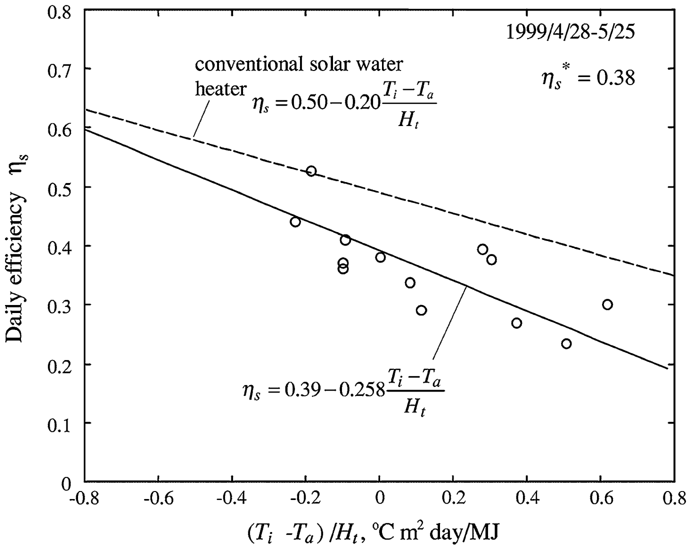


**Fig. 22** Daily efficiency test results of integrated PV/T system (Huang et al. 2001) ($H_t$ daily total solar radiation; $\eta_s$ characteristic efficiency; $T_i$ initial temperature of tank water)

flow channel's geometry and sizes and (3) suggesting the configuration of the integrated PV/T panels including covers, PV cells and their connections.

Compared to the air-based system, the water-based system could improve the electrical efficiency of the PVs and increase the solar heat energy utilisation. However, the scope for improvement is severely limited due to some inherent technical difficulties. Firstly, the water-based system remains continuously rising temperature over the operating period which results in poor heat-removal effectiveness and falling solar efficiency; secondly, additional heating prior to the heat devices (to achieve required water temperature) would increase the complexity of the system and reduce its efficiency. Furthermore, the freezing may be a problem when the system operates at a cold climate region.

*Refrigerant-based PV/T*

Refrigerant-based PV/T is a recently emerging technology, and research into this subject showed that the technology could significantly improve the solar utilisation rate over the air- and water-based systems and therefore has potential to replace the former two systems in near future. The system usually operates in conjunction with a heat pump, and its performance is justified by the electrical and thermal efficiencies of the PV/T modules and the COP of the PV/T heat pump system. These parameters (efficiencies and COP) vary with the flow rate of the refrigerant, its preset evaporation and condensation temperature/pressure, flow channels, geometrical sizes and external climatic conditions. The most favourite configuration and material are the solar cell encapsulation laminated on the front surface of an aluminium alloy base plate, followed by the serpentine copper coils tightly positioned in the Ω-shaped grooves of another aluminium fin plate, together with insulation and outside frame forming up a unitary evaporator module (Ji et al. 2008, 2009). A diagram showing interrelation between solar efficiencies and the operational parameters is presented in Fig. 23 (Zhao et al. 2011), which is developed on the basis of the fixed geometrical conditions and PV type.

In overall, a typical refrigerant-based PV/T type can achieve maximum electrical efficiency of around 10 % and thermal efficiency of around 65 % (Zhao et al. 2011). Researches related to refrigerant-based PV/T system usually focus on (1) determining appropriate refrigerant type, flow rate, evaporation/condensation temperature and pressure, (2) optimising refrigerant flow channel's geometrical shape and sizes and (3) suggesting the configuration of the integrated PV/T and heat pump including panel configuration, e.g. PV cells and combination between PVs and refrigerant channels, and connection between the PV/T panels and the heat pump.

Compared to the air- and water-based systems, the refrigerant-based system could significantly improve the electrical efficiency of the PVs and increase the solar heat energy utilisation. This initiative represents a step forward in Building Integrated Photovoltaics (BIPV) cooling technology, but its practicality faces many challenges: the refrigerant piping cycle needs a perfect seal in order to maintain its higher (positive) or lower (negative) pressures at different sections and prevent air being sucked into the system during operation, which is very difficult to

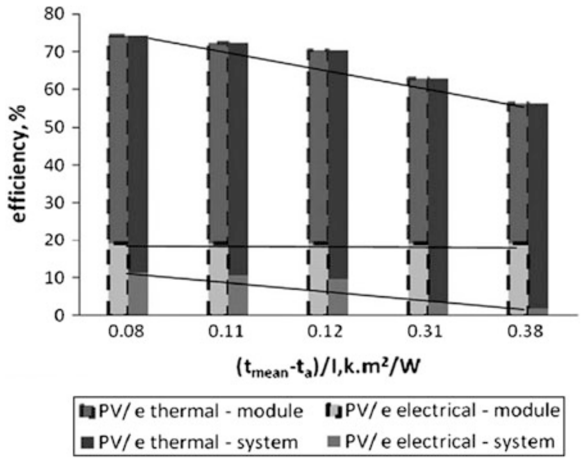


**Fig. 23** Variation in efficiencies with external and operating conditions (Zhao et al. 2011) (PV/ e photovoltaic/evaporator; $t_{\mathrm{mean}}$ mean temperature at PV cells; $t_a$ air temperature)

achieve owing to the numerous joints in existence. There is also high risk of refrigerant leakage, and achieving balanced refrigerant distribution across the multiple coils installed at a large PV panel area is technically difficult.

*Heat-pipe-based PV/T*

Heat-pipe-based PV/T is also a relatively new technology, and researches into this subject were found very limited. Up-to-date, flat-plate and oscillating heat pipes were studied for potential use in PV cooling, and the results indicated that the heat pipes may have potential to overcome the problems existing in refrigerant-based system, e.g. possible leakage of refrigerant, unbalanced distribution of refrigerant flow and difficulty in retaining pressurisation or depressurisation states in different parts of the system.

This system usually operates in conjunction with a heat pump or a heat cycle, and its performance is justified by the electrical and thermal efficiencies of the PV/T modules and the heat pipe heat transport capacity. These performance parameters (efficiencies and heat transport capacity) vary with the structure/material and vacuum degree of the heat pipe, type of the heat pipe fluid, temperature and flow rate of the secondary fluid, PV type and external climatic conditions. The most favourite unit configuration and material are the commercial PV wafers attached on the aluminium flat-plate heat pipes, while its headers locate in a water manifold and all the unit joints are connected with thermally conductive silicon grease (Zhao et al. 2010). A diagram showing interrelation between solar efficiencies and the running time is presented in Fig. 24, which is developed on the basis of the fixed geometrical conditions and PV type.

In overall, a typical heat-pipe-based PV/T type (Zhao et al. 2010) can achieve maximum electrical efficiency of around 10 % and thermal efficiency of around 58 %. Researches related to heat-pipe-based PV/T system usually focus on (1) determining appropriate heat pipe structure/material and vacuum degree, heat pipe fluid type and volume, flow rate and inlet temperature of the secondary fluid, (2)

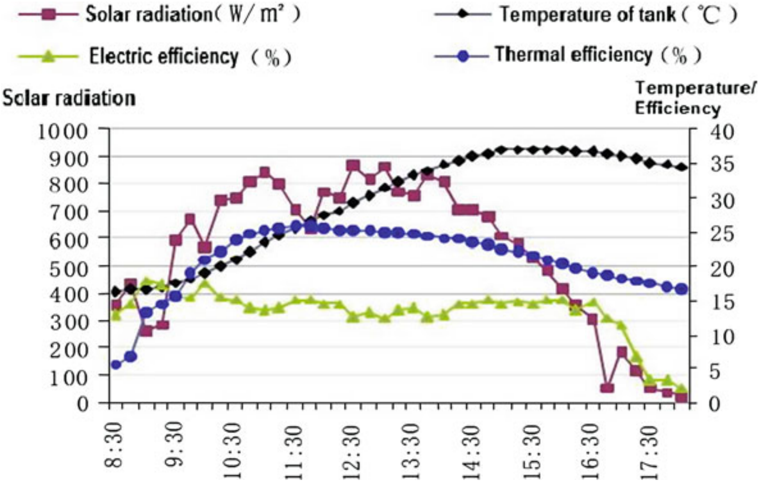


**Fig. 24** Variation in daily test efficiency with running time (Zhang et al. 2012)

optimising heat pipes' geometrical shape sizes and (3) suggesting the configuration of the integrated PV/T and heat pipe and other heat-removing system including panel configuration, e.g. covers, PV cells and combination between PVs and heat pipes and connection between PV/T panels and secondary fluid cycle.

Compared to the refrigerant-based system, the heat-pipe-based system could achieve an instant equivalent performance if the heat pipes operate at an adequate temperature. This system may overcome the difficulties existing in the refrigerant-based system and become the next-generation technology for removing heat from PVs and effectively utilizing this part of heat. However, this type of system also found some disadvantages that require further resolutions, e.g. high cost of the heat pipes and good control of the heat pipe performance.

### 3.3.2 Analysis of the Research Achievements in Terms of Research Methodology

In terms of research methodology used, the research works can be classified as (1) theoretical analysis and computer modelling; (2) experimental study; (3) combined modelling and experimental study; (4) economic and environmental analysis; and (5) demonstration of the technology and the associated feasibility study.

*Theoretical Analysis and Computer Modelling*
Many theoretical works have been carried out to study the performance of the PV/T modules and the associated heat and power system. These works were dedicated to (1) reveal the temperature distribution across the various layers of the PV/T modules and energy (heat and power) conversion mechanism; (2) optimise the

structural/geometrical parameters of the PV/T modules including the constitution, connection, geometrical shape and sizes; and (3) recommend the favourite operational conditions, e.g. fluid flow rate, temperature, pressure.

Theoretical works done so far cover (1) simple analytical model addressing heat transfer and heat balance across different parts of the PV/T modules and module-based energy system (Hendrie 1980); (2) one-dimensional thermal model derived from the conventional solar thermal flat-plate collectors with inclusion of PV electrical yields (Raghuraman 1981); (3) two/three-dimensional model addressing the energy transfer and distribution across the PV/T modules and the module-based energy system (Zondag et al. 2002); (4) transient energy model simulating the dynamic characteristics of the PV/T modules and module-based system (Chow 2003); and (5) energy and exergy analytical models to study the overall energy performance of the integrated systems (Anand and Tiwaria 2007).

In summary, established theoretical models have sufficient breadth and depth to reveal the nature of the technology and predict its performance and further optimise the system's configuration and suggest the favourite operational conditions. The further work on this methodology category may fall into the system's dynamic performance study under long-term operational conditions, e.g. seasonally and annually scheme.

*Experimental and Combined Modelling/Experimental Study*

Experimental study, running from individual modules to whole system scheme, measured various operational parameters including temperature, flow, heat and power conversion rates. The aims are to (1) reveal the real performance of the PV/T components and the whole system under the specified operational conditions; (2) examine the reliability and accuracy of the established computer model and provide the clues for further tuning and modification to the model; and (3) establish the correlation between the theoretical analysis and practical application.

Experimental and combined modelling/experimental works done so far cover (1) PV electrical efficiency and its relevance with various operational parameters, particularly with PV cells temperature (Huang et al. 2001); (2) heat-removal effectiveness of the various cooling mediums, e.g. air, water, refrigerant and heat pipe fluids (Solanki et al. 2009); (3) temperature and fluid flow characteristics of the PV/T modules and module-based energy system (Jin et al. 2010, Cristofari 2009); (4) thermal and electrical conversation rates of the PV/T modules and the module-based energy system (He et al. 2006); (5) comparison between the modelling results and experimental data and error analysis (Ji et al. 2009); and (6) validation, accuracy analysis, tuning and modification of the computer model (Tiwari and Sodha 2006).

In summary, experiment and combined modelling/experimental works done are also very substantial and have found good agreement with most theoretical results. These works also provided the feasible approach to lead the theoretical findings towards the practical application. The further work may lie in the measurement of the system's dynamic performance under long-term operational conditions, e.g. seasonal and annual scheme.

*Economic and Environmental Analysis*

Some research achievements focused on economic and environmental analysis of the PV/T technology by comparing its performance against those for individually arranged PV and solar thermal technologies. In terms of economic issues, simple payback time and LCC were addressed taking into account primary fossil fuel energy saving and increase in capital cost and maintenance cost needed during the system operation. In terms of environmental issues, energy and exergy efficiencies of the system, EPBT and greenhouse gas payback time were calculated and used as the indexes to justify the benefits of the system in terms of the capacity of carbon emission cut.

Achievements of economic and environmental analysis cover (1) PV/T energy saving potential, its cost augment, estimated payback time and LCC saving (Tripanagnostopoulos et al. 2005); (2) PV/T EPBT and greenhouse gas payback time and their relevance with the system's energy and exergy efficiencies (Tripanagnostopoulos et al. 2005); and (3) comparison between different PV/T configurations, PV alone, solar thermal alone and separately laid PV and solar thermal arrangements (Zondag et al. 1999).

In summary, economic and environmental analysis works done so far are adequate to indicate the performance of the PV/T technology in terms of its economic and carbon benefits. The further work may be extended to long-term (seasonal and annual) analysis of the system's performance by taking into account the influence of the climatic conditions to the system performance.

*Demonstration of the PV/T Technology and Associated Feasibility Study*

Although PV/T technology has been used in many practical projects, there are very little report found by literature search to focus on assessing the long-term performance of PV/T technology under real climatic conditions, and consequently, feasibility of the system used in practical projects as a long-term measure has not yet been fully studied. This may be the area to be further explored in near future in relation to the PV/T technology development.

### 3.3.3 Summary of the PV/T Research Achievements

The established researches so far in PV/T technology are very substantial and have clear focuses on (1) revealing the nature of the energy transfer and conversation occurring in the PV/T modules and module-based system; (2) identifying the favourite system type; (3) optimising the structural/geometrical parameters of the systems and suggesting the appropriate operational conditions; (4) building the link between the theoretical analysis and practical application; and (5) analysing the economic and environmental benefits of the PV/T systems and studying their feasibility for long-term operation. All these efforts contribute to a single purpose, to create as much energy-efficient PV/T system as possible at the least possible cost and simplest structure.

## 4 Opportunities for Further Works

Although significant works have been completed, there are still obvious opportunities to catch up to further develop this technology, which are outlined as below.

### *4.1 Developing New Feasible, Economic and Energy-Efficient System*

The aforementioned system types were found their own disadvantages that have prohibited wide application of these systems in practice. The opportunity to develop new system types to replace the existing systems still remains open, and very recently, a new method to remove PV heat and utilise this part of heat was proposed (Zhao 2010). In further study, the emulsified PCM slurry, as a latent heat convertor/conveyor, will be brought into the PV/T system to remove the PV heat, and this part of heat will be used to provide space heating, hot water supply and ventilation of the buildings, by running a combined operation of the PV/T modules, a heat pump, a heat storage and a slurry-to-air heat exchanger. This will open up a new way to develop a more feasible, economic and energy-efficient PV/T system; however, the claimed advantages of the system will need further validation through in-depth theoretical and experimental studies. Apart from this, other types of PV/T configurations are also open to exploration.

### *4.2 Optimising the Structural/Geometrical Parameters of the Existing PV/T Configurations*

Of the four existing PV/T system types, air- or water-based types are technically and commercially very mature and have no obvious room to improve their performance. The refrigerant-based type is still in the research stage and space still remains to improve its performance through the optimal study of the structural/ geometrical parameters of this type of the PV/T module. The key issue is to find a route to overcome the difficulties remaining in the existing refrigerant PV/T type, i.e. potential refrigerant leakage, unbalance refrigerant distribution and challenges in retaining pressurisation and depressurisation conditions at different parts of the system. Heat-pipe-based system is also in the start-up stage and remains large space to develop the optimised system configurations. The low-cost flexible loop heat pipes with built-in capillary would be a good choice to replace the existing parallel laid heat pipes and have potential to reduce the cost of the system and build up the excellent heat transfer between PVs and secondary fluid (Zhang et al. 2013). This work is currently being undertaken by the authors as part-work of an industrial-funded research project.

## 4.3 Studying Long-Term Dynamic Performance of the PV/T Systems under Real Climatic Conditions

Steady-state performance of various PV/T systems has been theoretically and experimentally studied as a result of the previous researches, and no obvious space could be seen to further develop the research work in this regard. However, dynamic performance of the PV/T systems under real climatic conditions has not yet been fully examined, particularly at long-term (seasonal or annual) scheme. This work remains certain challenges as several uncertain factors, e.g. influence of irregular variation in the solar radiation, ambient temperature and wind speed onto the system performance, are difficult to predict. Combined theoretical and experimental study may enable a solution to the problem.

## 4.4 Demonstration of the System Operation in Real Building and Feasibility Study

It is known that PV/T technology has been used in many practical projects. However, there is little report found that focused on assessment of the system's performance under real climatic conditions. Research could be developed from this angle to develop, install and monitor the PV/T systems in real buildings. This will allow assessment of the real performance of the system including reliability and commercialisation potential. Further, feasibility of the system used in real buildings could be examined. This work could possibly channel up the research outcomes to commercial application.

## 4.5 Economic and Environmental Analysis

Current works on economic and environmental analysis of the PV/T system have been conducted on laboratory and computer modelling bases. Further work could be extended in this regard to take into account effect of the climatic conditions to the system's performance through long-term measurement.

# 5 Conclusions

The overview and critical analysis into R&D achievements and practical application of the PV/T technology have been carried out. This would help understand the current status of the PV/T technical development, identify the existing barriers remaining in this field, establish the associated strategic plans, standards and regulations related to PV/T design and installation, develop the potential research topics/directions for further improvement, and promote its potential market exploitation throughout the world.

PV/T is a technology combining PVs and solar thermal components into a single module to enhance the solar conversion efficiency of the system and make economic use of the space. The dual functions of the PV/T result in a higher overall solar conversion rate than those of sole PV and solar thermal collector. PV/T modules are architecturally adaptable and have the potential to develop into a range of standardised and aesthetically appealing commercial products. Its market potential is expected to be high compared to the individual PV and solar thermal systems due to its obvious benefits over the independent systems.

PV/T modules could have very different structures. In terms of coolants used, currently available PV/T configurations could be classified as air, water, refrigerant and heat-pipe-based types. Technical performance of a PV/T system is usually evaluated using energy and exergy efficiencies, whereas the economic performance is measured with LCC and CPT, and the environmental benefit is justified by EPBT and GPBT.

Air-based PV/T is one of the most commonly used PV/T technologies and has been developed into commercial units in many engineering practices. This type of system can achieve maximum electrical efficiency of around 8 % and thermal efficiency of around 39 %, and its performance is largely dependent on the air flow speed and temperature. The major problem with the air-based system lies in its relatively poor heat-removal effectiveness owing to the low density, specific heat capacity and thermal conductivity of the air.

Water-based PV/T is also a very popular technology and has gained growing application in practical projects. This type of system can achieve maximum electrical efficiency of around 9.5 % and thermal efficiency of about 50 %, and its performance is largely dependent on water temperature and flow rate, and water flow channels' geometrical shape and sizes. Compared to the air-based system, the water-based system could improve the electrical efficiency of the PVs and increase the solar thermal energy utilisation. However, the scope for improvement is limited by a few of its inherent technical difficulties, such as arising water temperature during the operation and complex system layout.

Refrigerant-based PV/T could significantly improve the solar utilisation rate over the air- and water-based systems and therefore has potential to replace the former two systems in near future. The system usually operates in conjunction with a heat pump, and its performance is largely dependent on the type and thermal/physical properties of the refrigerant used and structural/geometrical parameters of refrigerant flow channels. The refrigerant-based PV/T can achieve maximum electrical efficiency of around 10 % and thermal efficiency of around 65 %. This system represents a step forward in BIPV cooling technology, but it practicality faces several challenges, namely potential refrigerant leakage, unbalanced refrigerant distribution across the panel coils, as well as difficulty in pressure maintenance over the operation duration.

Heat-pipe-based PV/T is also a relatively new technology, and its operation is often in conjunction with a heat pump or a heat cycle. A heat-pipe-based PV/T system can achieve maximum electrical efficiency of around 10 % and thermal efficiency of nearly 58 %, and its performance is largely dependent on the structure/material and vacuum degree of the heat pipe, type of the heat pipe fluid, temperature and flow rate of the secondary fluid. This system may overcome the difficulties existing in the refrigerant-based system and become the next-generation technology for removing heat from PVs and effectively utilizing this part of heat. However, this type of system also found some disadvantages that require further resolutions, e.g. high cost of the heat pipes and effective control of the heat pipe performance.

The researches established on PV/T technology were very substantial and mainly focused on (1) revealing the nature of the energy transfer and conversation occurring in the PV/T modules and module-based system; (2) identifying the favourite system type; (3) optimising the structural/geometrical parameters of the system configuration and suggesting the appropriate operational conditions; (4) building the link between the theoretical analysis and practical application; and (5) analysing the economic, environmental benefits of the PV/T systems and evaluating their feasibility for long-term operation. All these efforts aimed to create as much energy-efficient PV/T system as possible at the least possible cost and simplest structure.

Although significant achievements have been completed in PV/T study, there are still some opportunities existing for further developing this technology, including (1) developing new feasible, economic and energy-efficient systems such as PCM-slurry-based PV/T; (2) optimising the structural/geometrical parameters of the existing PV/T configurations; (3) studying long-term dynamic performance of the PV/T systems; (4) demonstration of the PV/T systems in real buildings and feasibility study; and (5) advanced economic and environmental analysis taking into account effect of the climatic conditions onto the performance of the system through long-term measurement.

## References

Agarwal RK, Garg HP (1994) Study of a photovoltaic-thermal system—thermosyphonic solar water heater combined with solar cells. Energy Convers Manage 35(7):605–620

Anand SJ, Tiwaria A (2007) Energy and exergy efficiencies of a hybrid photovoltaic–thermal (PV/T) air collector. Renew Energy 32(13):2223–2241

Bergene T, Lovvik OM (1995) Model calculations on a flat plate solar heat collector with integrated solar cells. Sol Energy 55(6):453–462

Bhargava AK, Garg HP, Agarwal RK (1991) Study of a hybrid solar system-solar air heater combined with solar cells. Energy Convers Mgmt 31:471–479

Bosanac M, Sørensen B (2003) Photovoltaic/thermal solar collectors and their potential in Denmark. Final Report EFP Project, 2003, 1713/00-0014

BP (2009) Statistical Review of World Energy 2009. http://www.bp.com/statisticalreview. Assessed on 1 Nov 2011

Brinkworth BJ et al (1997) Thermal regulation of photovoltaic cladding. Sol Energy 61:169–178

Mark CE (2010) http://www.ce-marking.org/what-is-ce-marking.html. Accessed on 15 Dec 2010

Chow TT (2003) Performance analysis of photovoltaic–thermal collector by explicit dynamic model. Sol Energy 75(02):143–152

Chow TT (2010) 2010. A review on photovoltaic/thermal hybrid solar technology, Applied Energy 87:365–379

Chow TT, He W, Ji J (2006) Hybrid photovoltaic-thermosyphon water heating system for residential application. Sol Energy 80:298–306

Cox CH, Raghuraman P (1985) Design considerations for flat-plate photovoltaic/thermal collectors. Sol Energy 35(03):227–241

Cristofari C, Notton G, Canaletti JL (2009) Thermal behaviour of a copolymer PV/Th solar system in low flow rate conditions. Sol Energy 83(8):1123–1138

de Vries DW (1998) Design of a photovoltaic/thermal combi-panel, PhD report, UT

Dubey S, Sandhu GS, Tiwari GN (2009) Analytical expression for electrical efficiency of PV/T hybrid air collector. Appl Energy 86:697–705

Duffle JA, Beckman WA (1991) Solar engineering of thermal processes, 2nd edn. Wiley, New York

Elswijk MJ et al (2004) Photovoltaic/thermal collectors in large solar thermal systems. In: 19th EPSEC, Paris, 2004

EN 12975-1(2006a) Thermal solar systems and components, solar collectors, general requirements

EN 12975-2 (2006b) Thermal solar systems and components, solar collectors, test methods

EN 12976-1 (2006) Thermal solar systems and components, factory made systems, general requirements

EN 12976-2 (2006) Thermal solar systems and components, factory made systems, test methods

EN 12977-1 (2010) Thermal solar systems and components, custom built systems, general requirements for solar water heaters and combisystems

EN 12977-2 (2010) Thermal solar systems and components, custom built systems, test methods for solar water heaters and combisystems

EN 12977-3 (2008) Thermal solar systems and components, custom built systems, performance test methods for solar water heater stores

EN 12977-4 (2010) Thermal solar systems and components, custom built systems, performance test methods for solar combistores

EN 12977-5 (2010) Thermal solar systems and components, custom built systems, performance test methods for control equipment

Enerdata (2009) Global Energy Review in 2009. Enerdata Publication

ESTIF (2007) Solar thermal action plan for Europe: heating and cooling from the Sun. European solar thermal industry federation

ESTTP (2009) Solar heating and cooling for a sustainable energy future in Europe (Revised). European solar thermal technology platform

Florschuetz LW (1979) Extension of the Hottel–Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. Sol Energy 22(04):361–366

Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY (2010) Review of solar dryers for agricultural and marine products. Renew Sustain Energy Rev 14:1–30

Garg HP, Ahhikari RS (1997) Conventional hybrid photovoltaic/thermal (PV/T) air heating collector: steady-state simulation. Renew Energy 11:363–385

Grag HP, Agarwal RK (1995) Some aspects of a PV/T collector/forced circulation flat-plat solar water heater with solar cells. Energy Convers Manage 36:87–99

He W, Chow TT, Ji J (2006) Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water. Appl Energy 2006(83):199–210

Hendrie SD (1980) Evaluation of combined photovoltaic/thermal collectors. In: ISES international congress and silver jubilee, vol 3. Atlanta, USA, 28 May–1 June 1980, pp 1865–1869

Hottel HC, Willier A (1958) Evaluation of flat-plate solar collector performance transactions of the conference on the use of solar energy, vol. 2. University of Arizona Press, Tucson, Arizona

Huang BJ (1993) Performance rating method of thermosyphon solar water heaters. Sol Energy 50:435–440

Huang BJ, Liu TH, Hung WC, Sun FS (2001) Performance evaluation of solar photovoltaic/thermal systems. Sol Energy 70:443–448

IEA (2007) Renewables in global energy supply: an IEA facts sheet. International Energy Agency

IEA (2010) Technology roadmap-solar photovoltaic energy. International Energy Agency

IEC 61215 (2005) Crystalline silicon terrestrial photovoltaic (PV) modules—design qualification and type approval

IEC 61646 (2008) Thin-film terrestrial photovoltaic (PV) modules—design qualification and type approval

IEC 61730-1 (2004) Photovoltaic (PV) module safety qualification part 1: requirements for construction

IEC 61730-2 (2004) Photovoltaic (PV) module safety qualification part 2: requirements for testing

IEEE 1262 (1995) IEEE recommended practice for qualification of photovoltaic (PV) modules

IEEE 929 (2000) IEEE recommended practice for utility interface of photovoltaic (PV) systems

ISO 9806-1(1994) Test methods for solar collectors—part 1: thermal performance of glazed liquid heating collectors including pressure drop

ISO 9806-2 (1995) Test methods for solar collectors—part 2: qualification test procedures

ISO 9806-3 (1995) Test methods for solar collectors—part 3: thermal performance of unglazed liquid heating collectors (sensible heat transfer only) including pressure drop

Ito S, Miura N, Wang K (1997) Heat pump using a solar collector with photovoltaic modules on the surface. JSEE 1997(119):147–151

Ito S, Miura N, Wang K (1999) Performance of a heat pump using direct expansion solar collectors. Sol Energy 65(3):189–196

Ji J, Chow TT, He W (2003) Dynamic performance of hybrid photovoltaic/thermal collector wall in Hong Kong. Build Environ 2003(38):1327–1334

Ji J et al (2008) Experimental study of photovoltaic solar assisted heat pump system. Sol Energy 82:43–52

Ji J et al (2009) Distributed dynamic modelling and experimental study of PV evaporator in a PV/T solar-assisted heat pump. Int J Heat Mass Transf 52:1365–1373

Jin GL et al (2010) Evaluation of single-pass photovoltaic-thermal air collector with rectangle tunnel absorber. Energy Res J 1(1):1–6

Kalogirou SA (2001) Use of TRNSYS for modelling and simulation of a hybrid PV–thermal solar system for Cyprus. Renew Energy 23:247–260

Kalogirou SA, Tripanagnostopoulos Y (2006) Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Convers Manage 47:3368–3382

Kelly N, Strachan PA (2000) Modelling enhanced performance integrated PV modules. Proceeding of the 16th European PV solar energy conference. Glasgow, UK, 1–5 May 2000, pp 2025–2028

Kern JREC, Russell MC (1978) Combined photovoltaic and thermal hybrid collector systems. In: Proceedings of the 13th IEEE PV specialist conference. Washington, DC. 5–8 June 1978, pp 1153–1522

Komp R, Reeser T (1987) Design, construction and operation of a PV/Hot air hybrid energy system. ISES Sol World Congr, Hamburg

Kranter S et al (1999) Combined photovoltaic and solar thermal systems for façade integration and building insulation. Sol Energy 67:239–248

MCS 004 (2008) Microgeneration certification scheme: product certification scheme requirements: solar collectors

Messenger RA, Ventre J (2003) Photovoltaic system engineering, 2nd edn. CRC Press, Florida, pp 54–55

Moshtegh B, Sandbergy M (1996a) Investigation of fluid flow and heat transfer in a vertical channel heated from one side by PV elements, part I–numerical study. Renew Energy 08:248–253

Nishikawa M, Sone T, Ito S (1993) A heat pump using solar hybrid panels as the evaporator. In: ISES solar world congress. Budapest, 1993

Prakash J (1994) Transient analysis of a photovoltaic thermal solar collector for cogeneration of electricity and hot air water. Energy Convers Manage 35:967–972

Qian J et al (2008) Closed loop capillary solar photovoltaic thermoelectric board. Patent CN 200810228051 A

Qian J et al (2010) Analysis of a new photovoltaic thermal building integration system and correlative technology. Build Energy Environ 29(02):12–16

Raghuraman P (1981) Analytical prediction of liquid and air photovoltaic/thermal flat plate collector performance. J Sol Energy Eng 103:291–298

Moshtegh B, Sandbergy M (1996b) Investigation of fluid flow and heat transfer in a vertical channel heated from one side by PV elements, part II—experimental study. Renew Energy 08:254–258

Sandnes B, Rekstad J (2002) A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. Sol Energy 72(1):63–73

Shahsavar A, Ameri M (2010) Experimental investigation and modeling of a direct-coupled PV/T air collector. Sol Energy 84:1938–1958

Solanki SC, Dubey S, Tiwari A (2009) Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. Appl Energy 86:2421–2428

Solar Keymark (2010) The quality label for solar thermal products in Europe. http://www.estif.org/solarkeymark/. Accessed on 12 Dec 2010

Sopian KS et al (1996) Performance analysis of photovoltaic/thermal air heaters. Energy Convers Manage 37(11):1657–1670

Takashima T, Tanaka T, Doi T et al (1994) New proposal for photovoltaic-thermal solar energy utilization method. Sol Energy 52:241–245

Tiwari A, Sodha MS (2007) Parametric study of various configurations of hybrid PV/thermal air collector: experimental validation of theoretical model. Sol Energy Mater Sol Cells 91:17–28

Tiwari A, Sodha MS (2006) Performance evaluation of solar PV/T system: an experimental validation. Sol Energy 80:751–759

Tonui JK, Tripanagnostopoulos Y (2008) Performance improvement of PV/T solar collectors with natural air flow operation. Sol Energy 82:1–12

Tripanagnostopoulos Y et al (2002) Hybrid photovoltaic thermal solar system. Sol Energy 72:217–234

Tripanagnostopoulos Y, Souliotis M, Battisti R, Corrado A (2005) Energy cost and LCA results of PV and hybrid PV/T solar systems. Prog Photovoltaics Res Appl 13:235–250

UL 1703 (2002) UL standard for safety flat-plate photovoltaic modules and panels

UL 1741 (2010) UL standard for safety inverters, converters, controllers and interconnection system equipment for use with distributed energy resources

UL 4703 (2005) Photovoltaic wire

Wikipedia (2011) Global warming. http://en.wikipedia.org/wiki/Global_warming. Assessed on 02 Nov 2011

Zhang X et al (2012) Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. Renew Sustain Energy Rev 16(01):599–6122

Zhang X et al (2013) Characterization of a solar photovoltaic/loop-heat-pipe heat pump water heating system. Appl Energy 102:1229–1245

Zhao X (2010) Developing a novel BIPV façade module enabling enhanced solar heat/electrical efficiency by using PCM slurry, EUPF7 EeB.NMP.2011-3 energy saving technology for building envelope retrofitting

Zhao X et al (2011) Theoretical investigation of a novel PV/e roof module for heat pump operation. Energy Convers Manage 52:603–614

Zhao Y et al (2008) Photovoltaic cell radiating and combined heat and power system. Patent CN 200820123998 U

Zhao Y et al (2009) The experimental research of using novel flat-plate heat pipe for solar cells cooling. Proceeding the Chinese thermal engineering physics of heat and mass transfer conference. 13–16 Nov, pp 239–241

Zhao Y et al (2010) The experiment research for solar PV/T system based on flat-plate heat pipes. Proceeding the 17th Chinese national HVAC&R academic conference, 2010

Zondag HA et al (2002) The thermal and electrical yield of a PV-thermal collector. Sol Energy 72(02):113–128

Zondag HA et al (1999) Thermal and electrical yield of a combi-panel. In: Proceedings of ISES Bi-annual conference on CD-ROM, Jerusalem

Zondag HA et al (2003) The yield of different combined PV-thermal collector designs. Sol Energy 74:253–269