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

M. Mistretta (✉)
Dipartimento Patrimonio Architettonico e Urbanistico,
Università degli Studi Mediterranea di Reggio Calabria,
Salita Melissari 89124 Reggio Calabria, Italy
e-mail: marina.mistretta@unirc.it

M. Beccali · M. Cellura · F. Guarino · S. Longo
Viale delle Scienze, University of Palermo, 90128 Palermo, Italy

F. Pacheco Torgal et al. (eds.), *Nearly Zero Energy Building Refurbishment*,
DOI: 10.1007/978-1-4471-5523-2_4,

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^2y), and a GWP of about 70–80 $kgCO_{2eq}/(m^2y)$). 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^2y). The other houses showed values of energy consumption between 122 and 187 MJ/(m^2y), 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_{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 ($Em_{PT,GWP}$), 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_{PT} was assessed for each action as:

$$E_{PT} = \mathrm{GER}/E_{s,y} \quad (1)$$

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). $Em_{PT,GWP}$ was defined as:

$$Em_{PT,GWP} = \mathrm{GWP}/\mathrm{GWP}_{a,y} \quad (2)$$

where

- GWP is calculated with regard to the life cycle of the retrofit action ($kgCO_2eq$).
- $GWP_{a,y}$ is the GWP avoided yearly after the retrofit ($kgCO_2eq/y$). 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:

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

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

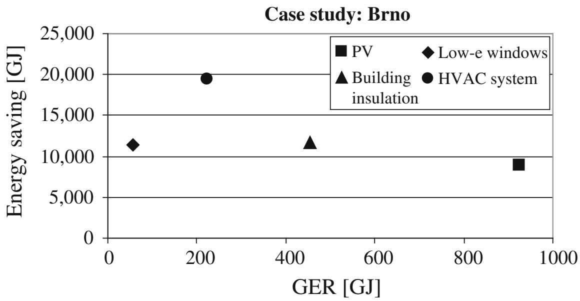


Fig. 1 GER compared to the total energy saving in Brno case study (brewery)

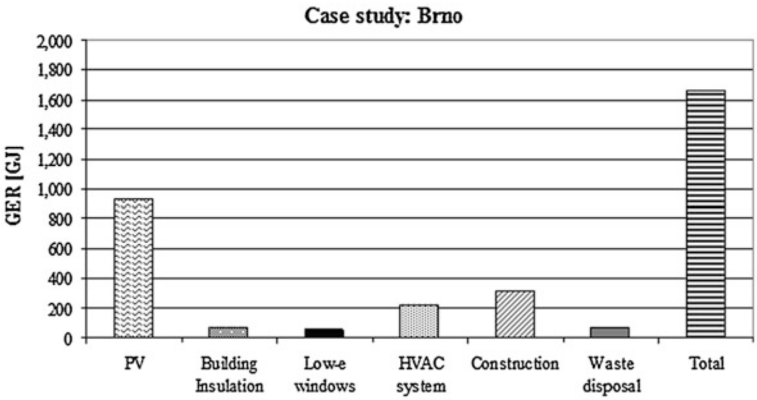


Fig. 2 Contribution of each retrofit actions to the GER in brno case study (brewery)

roof, and with 60 mm polystyrene boards for the ground floor, involved a primary energy saving of 126 MJ/(m^2y). The introduction of low-e windows saves 123 MJ/(m^2y). 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^2y)). 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^2y) for a total floor area of 2660 m^2).

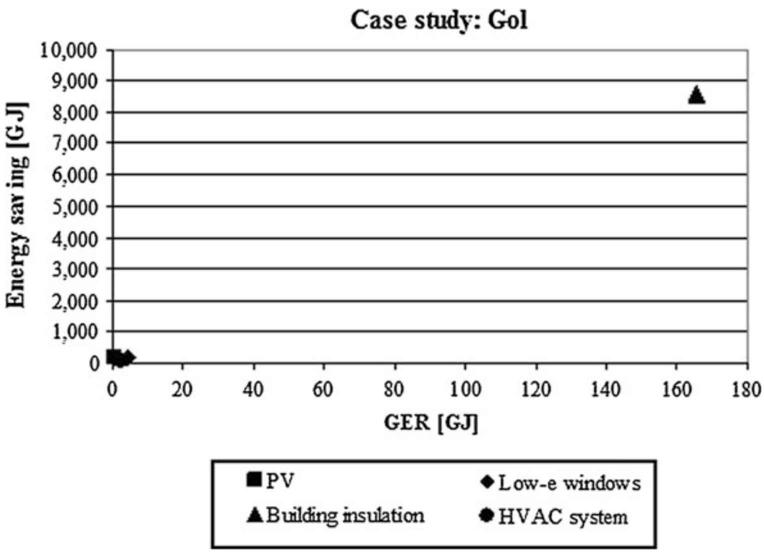


Fig. 3 GER compared to the total energy saving in Gol case study (Hol Church)

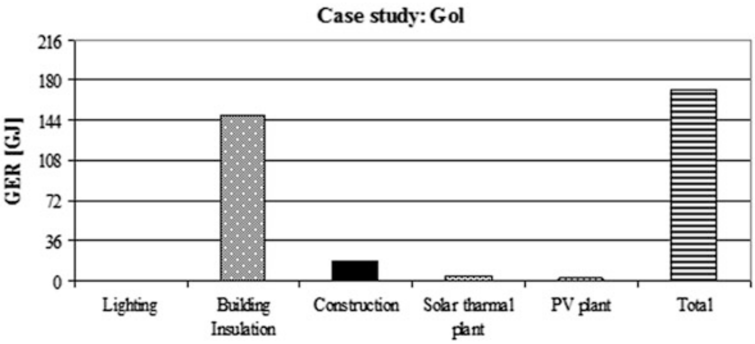


Fig. 4 Contribution of each retrofit actions to the GER in Gol case study (Hol Church)

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^2y) 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^2y)). The solar thermal system involved a primary energy saving of about 9 GJ/y (16.2 MJ/(m^2y)). 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^2y).

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^2y).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,

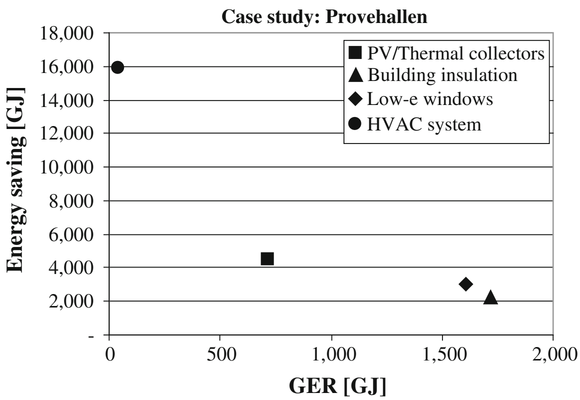


Fig. 5 GER compared to the total energy saving in Provehallen case study

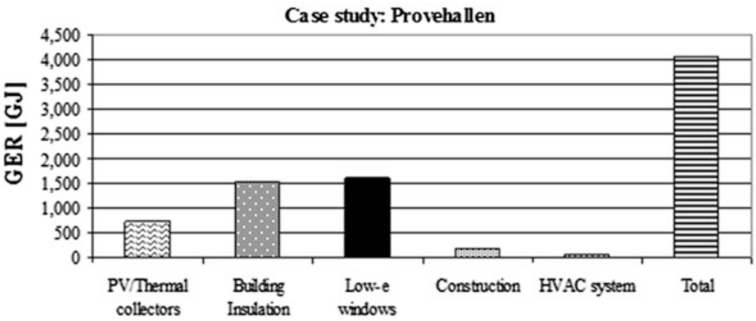
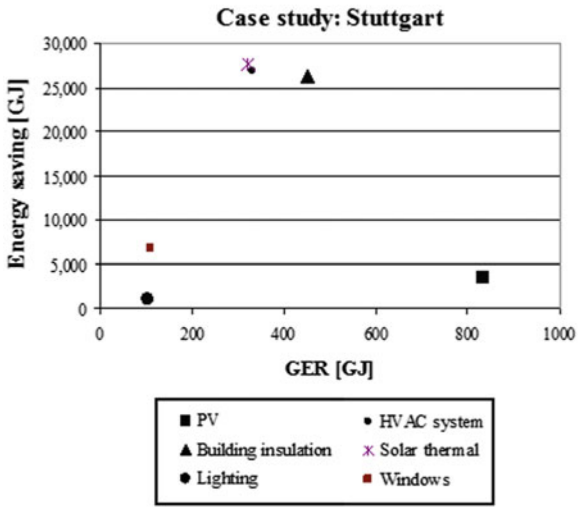


Fig. 6 Contribution of each retrofit actions to the GER in Provehallen case study

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^2y) were provided by the insulation of the envelope opaque elements, and 127 MJ/(m^2y) 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^2y). The solar thermal plant provides heat savings of 84 GJ/y, with and a primary energy saving of 866 MJ/(m^2y). The high-efficiency HVAC system saved 284 GJ/y (642 GJ/y), involving a primary energy saving of 841 MJ/(m^2y).

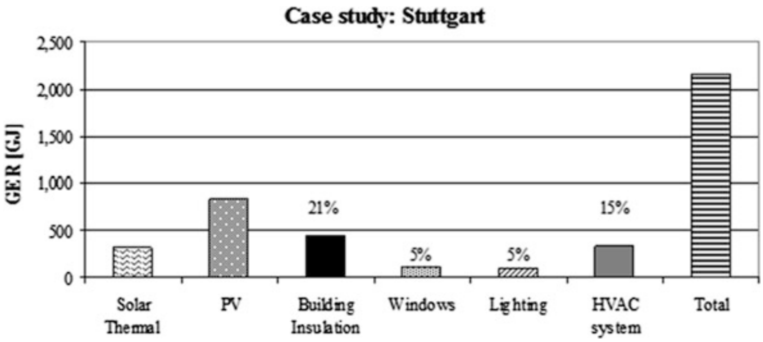


Fig. 8 Contribution of each retrofit actions to the GER in Stuttgart case study

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^2y)).

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^2y), while the insulation of the building envelope provided a primary energy saving of 125 MJ/(m^2y). 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^2y)).

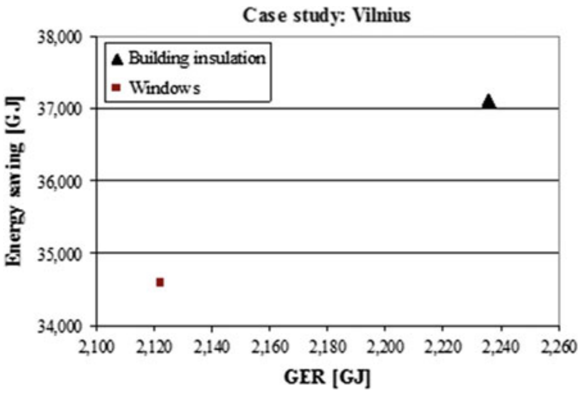


Fig. 9 GER compared to the total energy saving in Vilnius case study

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

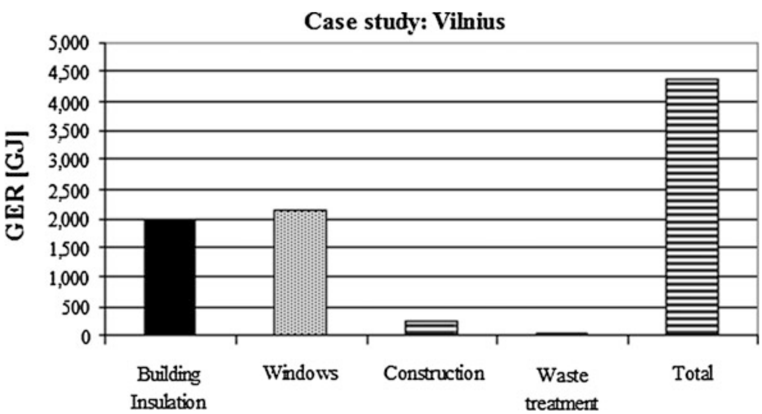


Fig. 10 Contribution of each retrofit actions to the GER in Vilnius case study

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_2eq]	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_2eq]	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_2eq]	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_2eq]	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_2eq]	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_2eq]	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