Chapter 11
Buildings that Perform: Thermal Performance and Comfort

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Developers, designers and contractors are increasingly using titles such as 'green', 'eco' and 'low energy' to describe their buildings and reassure the environmentally conscious consumer of the green credentials of the property that they are investing in. Unfortunately, relatively few construction companies engage in research and development (R&D) to underpin their marketing rhetoric. The exceptions to this observation are those companies investing in innovation and engaging with both experts and customers to ensure a real understanding of property performance. Such activity is critical if the aspirational living and performance standards that are being claimed by the developers are to be attained and replicated on a wider scale. Forward-thinking developers are continuously using the lessons learned to inform and enable best practice, within their organisation, and through their exemplars setting standards across the construction industry.

Interest in the in situ performance of low-energy buildings has seen an increase in building performance testing, energy monitoring and occupant consultation with the aim of determining the various impact of low-energy technologies and construction approaches. Those companies advancing the industry are using research data to inform the way they build and develop low-energy properties and by appreciating the holistic context of the built environment are adding value to what may be construed as social sustainability.

Typically, companies will engage dedicated research establishments to undertake testing and monitoring to determine how buildings respond to their environment and ascertain how easily a building can be controlled to meet the occupant's needs. These tests and evaluations are thorough, exploring in forensic detail the achievements and issues within all aspects of a building, from the energetic performance of one element of building fabric to the combined influence of all systems on occupant satisfaction.

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This chapter reports on the tests and monitoring undertaken on buildings, the common issues that they are designed to interrogate, and presents cases where developers are taking measures to achieve homes that function as expected and meet the requirements of the occupants, thus fulfilling their ‘green’ credentials.

11.1 Thermal Performance of the Built Environment

Before exploring the methods used to assess whether buildings are performing to their designed intention, it is relevant to consider the wider significance of building performance and why low-energy ‘eco’ buildings are gaining increased relevance in the construction industry.

The issues of anthropogenic climate change, fuel security and declining global fossil reserves require immediate efforts to be made to reduce our energy demand. In response to these global challenges, the UK government has made commitments to reduce greenhouse gas by at least 80% by the year 2050, relative to 1990 levels. The built environment plays a significant role in achieving this target. The housing sector is the UK’s biggest annual energy user, accounting for 29% of the total energy consumption in the UK and approximately 30% of CO_2 emissions. The average household is estimated to consume 18,600 kWh of energy per year, of which 62% is used for space heating. The burning of natural gas for space heating accounts for around 35% of household CO_2 emissions (Palmer and Cooper 2013).

To reduce this consumption, building energy efficiency must be increased. The building stock in the UK is old (a situation that is also prevalent in the rest of Europe), with more than 40% of the dwellings being built before 1960 and 90% before 1990 (Artola et al. 2016). As the standards that require buildings to be energy efficient are relatively recent additions to building regulations, it is of no surprise that older buildings typically use more energy than modern buildings. Old buildings typically require more than twice the energy to heat when compared to modern buildings, yet with over 90% of buildings being more than 25 years old, inefficient older dwellings represent the vast majority of housing.

New buildings offer an easier route to energy reduction, being able to utilise modern materials and methods developed specifically for enhanced energy performance. However, new buildings either replace or expand the total stock at just less than 1% of the total buildings each year (with the building of new homes generally ranging from 140,000 to 250,000 per year). With current rates of construction together with an increasing population, meaning that 75–80% of the current building stock will still be in use in 2050 (Power 2008), it is essential that existing buildings are addressed; however, there is a considerable amount of refurbishment required to bring existing buildings up to modern energy-efficient standards (DCLG 2017; Artola et al. 2016).

The renovation rate of the UK’s 28 million existing dwellings is low, with only 1–2% of the building stock renovated each year, with considerable variation in the level of upgrade (UK figures taken from: Valuation Office Agency 2016; National

Records of Scotland 2016; Eurostat 2017; Artola et al. 2016; DCLG 2017). Buildings are renovated differently, with some receiving superficial aesthetic upgrades, whilst others receive what has been termed 'deep retrofit', where the whole building fabric and services are upgraded to high-energy-efficient standards. Renovations that reduce both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels are insignificant in terms of national targets, representing less than 1% of all buildings renovated. Although the retrofit and upgrade market is small when compared to the whole building stock, construction activity related to renovation accounts for 57% of all building works.

Beyond the reduction of energy and greenhouse gas emissions, older buildings tend to be draughty, cold during the winter months and may experience some problems with condensation and mould, even in some cases affecting the health and wellbeing of the occupants. Evidence collected by the Leeds Sustainability Institute suggests many existing buildings are difficult to heat, with some occupants believing that such buildings had a negative impact on their family's health (Gorse et al. 2017a). The health risks to the occupants in some cases are acute, evidenced by the 40,000 excessive winter deaths in the UK, 9000 of which are associated with cold homes (ACE 2015; NEA 2016). During a 5-year period, up to 2015, there were 46,716 deaths attributed to cold dwellings. The annual death rate caused by cold and damp buildings is similar to that caused by alcohol and almost as high as breast cancer (ACE 2015). However, mortality is a particularly weak indicator of the impact of cold homes on the occupant; the years of healthy life lost and illnesses related to living in cold damp environments have much wider impact on the society; ill health caused as a result of living in damp, cold and draughty conditions has been estimated to cost the NHS £1.36 billion per year (NICE 2015).

Thermal upgrades have the potential to significantly improve the performance of a building, reducing energy demand and enhancing occupant satisfaction. To achieve high-energy-efficient standards and comfort gains, there is a need to understand the nature of the building stock and what is necessary to improve existing buildings and enhance new developments. Research activity facilitates this process by ensuring new products, and construction methods achieve their intended purpose and performance (Table 11.1).

11.2 Thermal Performance of the Building Fabric

Thermal performance is a major factor in the energy efficiency of buildings and is a function of the interaction of several building fabric elements and their influence on heat loss mechanisms. Maintaining comfortable conditions within a building can require a great deal of energy input, depending on the thermal performance of a given building. On average, 62% of household energy consumption is for space heating – this means that good thermal performance, either in new build design or in existing building retrofit, represents major potential for the reduction of energy demand for heating and thus considerable reduction in CO_2 emissions. In addition

Table 11.1 Overview of renovation market share in the UK (Artola et al. 2016)

Renovation undertaken	Market share and example of renovation	Approximate costs per m^2
Minor renovations	85% of the market: 1 or 2 measures (e.g. a new boiler) resulting in a reduction in energy consumption of between 0% and 30%	Average costs of €60/m^2
Moderate renovations	10%: 3–5 improvements (e.g. insulation of relevant parts of the dwelling plus a new boiler) resulting in energy reductions in the range of 30–60%	Average costs of €140/m^2
Extensive renovations	5%: In this approach, the renovation is viewed as a package of measures working together leading to an energy reduction of 60–90%	Average costs of €330/m^2
Almost zero-energy building renovations	Negligible: The replacement or upgrade of all elements which have a bearing on energy use, as well as the installation of renewable energy technologies in order to reduce energy consumption and carbon emission levels to close to zero	Average costs of €580/m^2

Note: current renovation represents less than 1% of the total building stock but accounts for over 50% of total building activity

to energy and CO_2 savings, there are also benefits to housing occupants: more comfortable internal conditions and reduced energy bills.

The majority of heat loss in buildings is through the plane elements: walls, roof, floor, windows and doors. The rate at which heat is lost through these elements is expressed as their thermal transmittance, or U-value (watts per square metre per degree Kelvin). A lower U-value represents lower heat loss and higher insulating properties. Achieving low U-values for elements of the building fabric is the first step in reducing the heat loss of a building. The primary method of reducing heat loss through the plane elements is through the application of insulation.

The external envelope can both act as a thermally resistant material, a medium that allows solar heat energy in, and a place to store heat energy, which can be released at a later time to smooth out the heating and cooling cycles (Fig. 11.1).

Household expenditure on space heating represents a significant portion of annual costs, and whilst the actual cost per household varies, reducing energy required for heating presents a desirable outcome for all occupants. In a recent study conducted by Leeds Beckett University, it was shown that for a small two-bedroom Victorian terrace house, the cost of heating the home could be reduced from £554 (where there was no thermal upgrade) to £206 (where a full deep retrofit had been applied) with annual CO_2e emissions associated with space heating reducing from 2.31 tonnes (no thermal upgrade) to 0.86 tonnes. The full thermal retrofit resulted in reduction of 63% heat loss through the fabric (Gorse et al. 2017) (Fig. 11.2 and Table 11.2).

This example illustrates the aggregate potential of multiple thermal upgrades, addressing several individual elements of the building fabric, i.e. the walls, glazing and loft. As previously noted, such deep retrofits are rare; it is more common for retrofits to be single interventions targeting specific aspects of the building fabric, i.e. the application of a single form of insulation. Whilst the example describes a retrofit, the principles for high thermal performance for new and existing buildings are largely the same – the key difference being the route to thermal upgrade being

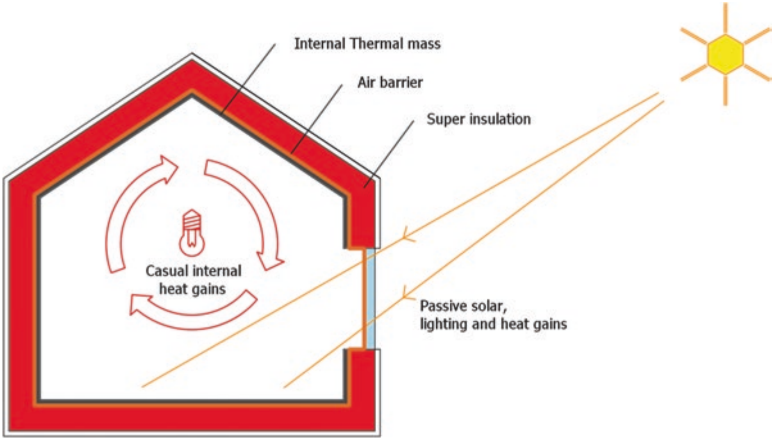

Fig. 11.1 Fabric first and passive approaches to creating energy-efficient and comfortable environments (Thomas and Gorse 2015; Gorse et al. 2016)

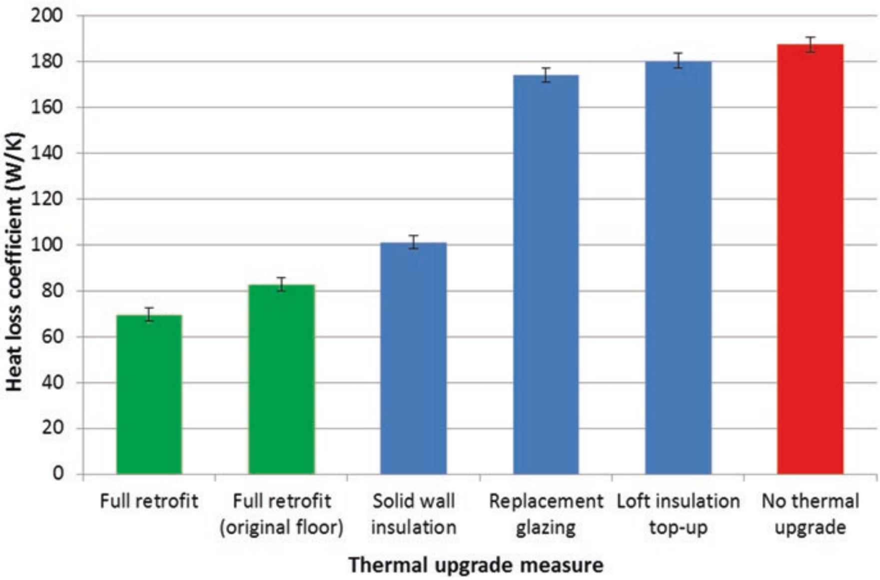

Fig. 11.2 Measured heat loss (heat loss coefficient HLC) of the test house at each test stage (blue bars represent the test house heat loss following a single thermal upgrade measure; green bars represent thermal upgrade measures in combination) (Gorse et al. 2017)

significantly more challenging for retrofit because of the limitations imposed by working with an existing building as opposed to the 'blank canvas' of a new build. In existing buildings, there are many parts of the external envelope that are difficult to access or treat. Internally, floors, cupboards and services will often disrupt internal insulation, whilst external insulation is affected by abutment, complicated detailing, services and junctions such as the eaves. Where the difficult to access areas remain uninsulated, they present a thermal weakness in the envelope.

Table 11.2 Impact of thermal upgrades on a Victorian two-bedroom end terrace in the North West of England (annual space heating demand and cost, and CO_2 equivalent emission reductions)

Thermal upgrade measure	HLC (W/K)	Reduction on baseline (W/K)	Annual space heating energy reduction (kWh)	Annual space heating cost reduction (£)	Annual space heating CO_2e reduction (kg)
Full retrofit	69.7	117.8	6497	348	1449
Full retrofit (original floor)	82.7	104.8	5777	310	1289
Solid wall insulation	101.2	86.4	4761	255	1062
Replacement glazing	174.2	13.4	737	39	164
Loft insulation	180.5	7.1	390	21	87
No thermal upgrade	187.5	n/a	n/a	n/a	n/a
Floor upgrade	n/a	13.1	720	39	161

Areas of lower thermal resistance than the surrounding building fabric are known as thermal bridges. Lower thermal resistance of the building fabric at thermal bridges leads to greater loss of heat through these parts of the building fabric than unbridged areas. This lower thermal resistance is often caused by a break in the insulation layer by a material of higher thermal conductivity than the insulation.

There are three kinds of thermal bridges that can be considered in a building: repeating thermal bridges, linear thermal bridges and point thermal bridges (Fig. 11.3). Repeating thermal bridges occur at regular intervals within the plane elements of the building fabric and are accounted for in the U-values of the element they are within. Linear thermal bridging often occurs along the length of junctions within the building fabric, due to the building geometry or detailing at these locations. Linear thermal bridging is represented by ψ (psi) values, in W/mK (watts per metre per degree Kelvin). Point thermal bridging occurs at isolated non-repeating locations within the building fabric, at a penetration through the building fabric or the location of a fixing. Point thermal bridging is represented by χ (chi) values, in W/K (watts per degree Kelvin).

When assessing the heat loss of a building, the total thermal bridging of all linear bridges and all point bridges are added together then divided by the total heat loss area of the building to give a y-value, in W/K (watts per degree Kelvin). As the thermal resistance of the plane elements of a building's fabric is increased through the addition of insulation, the heat loss through thermal bridges becomes a larger proportion of the total heat loss, unless consideration is given to mitigating thermal bridging (Fig. 11.4).

The basic principle of preventing thermal bridging is to ensure the continuity of the insulation layer throughout the fabric of the building envelope, though in practice breaks in the insulation layer are unavoidable, in almost all current building types. Where a bridge cannot be avoided, steps can be taken to reduce the extent of bridging. Reducing the amount of material bridging the insulation layer reduces the rate at which heat can be conducted over the thermal bridge. Additionally, introducing

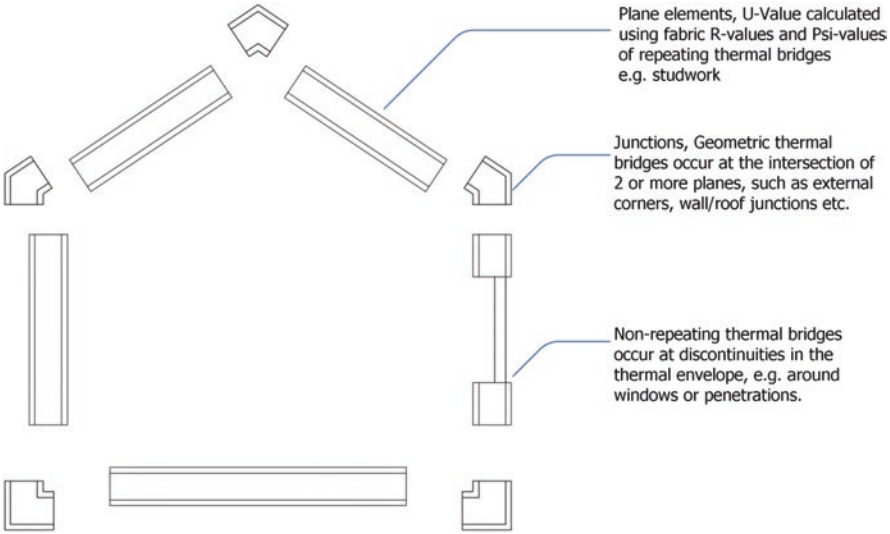

Fig. 11.3 Plane element, geometric thermal bridges and non-repeating thermal bridges (Thomas and Gorse 2015; Gorse et al. 2016)

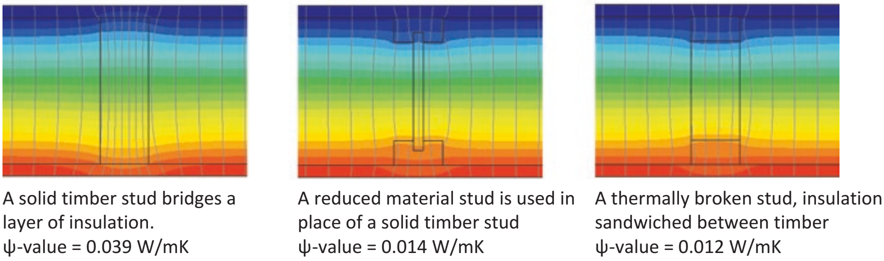

Fig. 11.4 Thermal bridges and ψ-values for stud sections (Thomas and Gorse 2015)

thermal breaks to the bridging elements, which involves using materials of high thermal resistance to isolate low thermal resistance elements, prevents a continuous bridge from the warm to cold side of the element.

In addition to heat lost via conduction through the fabric elements, the exchange of heated internal air with cold external air can be a significant source of heat loss from a building. In order to maintain a comfortable internal environment within a building, the air must be heated; however, air must also be refreshed through ventilation to prevent build-up of moisture, pollutants and odours that would make the internal environment unpleasant or unsafe. Heat loss through ventilation has two components: purpose-provided ventilation such as extractor fans, intended to maintain air quality, and uncontrolled ventilation through gaps in the building fabric, often referred to as air leakage. Exchange of warm internal air with cool external air represents a loss of heat from the internal environment of a building and a reduction in internal air temperature, requiring additional heat input.

Achieving low ventilation heat loss in buildings to reduce the volume of warm air lost and cold air entering the building is a key element of energy efficiency. Achieving a low air permeability requires that careful consideration be given to airtightness during design stages; a continuous airtight barrier should be specified and special consideration given to how the barrier will interact with junctions and openings.

Whilst a thermally efficient building fabric will reduce the energy required to condition the internal environment, it is not a complete solution and must be combined with appropriate low-energy systems for heating and ventilation. These in turn must be operated correctly by the occupant to ensure that predicted performance is achieved. A large component of the gap between the prediction of energy use and that actually used, ‘the reality – in situ use’, results from the interaction between systems and users; it is as important to explore the relationship between users and systems as is it to test the systems themselves.

To understand the building’s performance and its characteristic behaviour, it is essential that the building fabric and services are tested and commissioned, and it is also informative to see how the building system responds under different occupation patterns. Once the buildings can be controlled, then it is possible to influence occupant behaviour to achieve optimum performance, based on the user needs; however, buildings must first perform. The first step to understanding buildings is to ensure that the designed performance is tested in the field, under real operating conditions. The following sections outline tests and monitoring.

11.3 Methods for Testing the Performance of Buildings

11.3.1 Fabric Testing

As previously stated, heat loss through the building fabric is significant in terms of energy demand and occupant satisfaction and is composed of two elements: heat loss via conduction through the plane elements and heat loss via uncontrolled ventilation. This has encouraged the development of many designs, products and systems to reduce the heat loss through the fabric and improve building airtightness. The development of these energy-saving innovations often occurs in a laboratory environment under unrealistic environmental conditions. The result of this is that whilst a building may meet targets for thermal performance in theory, a physically completed building may not reach its expected design performance when exposed to realistic conditions.

This shortfall in performance is referred to as the ‘performance gap’ and is caused by several factors such as incorrect construction, poor workmanship, failings at the design stage, poor detailing and improvisation on site (Johnston et al. 2015). It is common to find that new buildings are some way off their expected performance. Where buildings have been in use for some time and remedial action, refits or refurbishment has been undertaken, the builders’ work and fitting of services are often incomplete, with penetrations through the fabric not being sealed. As well as affecting the building's thermal performance, such changes can impact on fire safety, allowing smoke and flames to breach compartmentation and spread through the fabric. If a fire takes hold of a building and such defects exist, the consequences for occupants can be deadly (Gorse and Sturges 2017). Thus, whilst the tests for thermal performance are useful, the forensic examination often reveals defects of the building that also have a potential impact on other aspects of performance.

It is important to undertake building performance evaluation to validate the fabric performance of finished buildings, demonstrate regulatory compliance and potentially locate faults leading to underperformance which can be corrected. In the case of multibuilding developments, findings of tests on early buildings can help remedy faults in later buildings before they are made.

It can be advantageous to undertake a number of tests concurrently, as the conditions required to undertake individual tests are also ideal for others. An intense programme of testing can thoroughly examine many aspects on a building's performance, helping to identify and remedy shortfalls in performance as well as inform future design and construction projects.

11.3.2 Coheating

The coheating test method is used to quantify the amount of heat energy a building loses through its fabric, in the form of a heat loss coefficient (HLC) expressed as W/K (watts per degree Kelvin). At its most basic, a coheating test is performed by heating a building to a set temperature, at least 10 degrees Kelvin above external air temperature, using electrical resistance heaters. The electricity required to maintain this continuous temperature difference is logged, and a HLC can then be calculated by plotting daily heat input (in kilowatt hours) against daily internal-external temperature difference (K). The gradient of the resulting plot gives the heat loss coefficient in W/K (Johnston et al. 2013). Taken by itself, the coheating test can only indicate the heat loss of the building fabric as a whole. Individual aspects of thermal performance must be investigated by other means, though a coheating test provides a good opportunity to carry out other tests concurrently (Fig. 11.5).

11.3.3 Heat Flux

Heat flux density measurement is used to measure the rate of heat flow into or out of a building element, effectively measuring the in situ U-value of an element that is tested. To perform heat flux measurement, a heat flux plate is placed on the element, avoiding any points of thermal bridging. During testing, heat flux density (W/m^2) is logged as well as air temperatures on either side of the element being tested so that when heat flux is divided by temperature difference, the resulting value is an effective U-value for the building element (W/m^2K).

Fig. 11.5 An example of a typical coheating setup: electrical resistance heater with thermostatic control to maintain constant internal temperature, electricity and temperature logging equipment and a circulation fan to ensure air temperature uniformity in the zone

Heat flux measurement is best undertaken with a constant elevated temperature on the internal side of the building element to ensure monodirectional heat flow from inside to outside for the duration of measurement. A coheating test provides ideal conditions to perform heat flux measurements; the effective U-values measured using heat flux tests will add to the findings of a coheating test.

11.3.4 IR Thermography

Infrared (IR) thermography uses specialised 'thermal cameras' that can detect the infrared band of the electromagnetic spectrum to visualise the temperature of objects and surfaces. IR thermography is often undertaken as a survey, examining a building to find temperature irregularities that may indicate a problem within building elements that could not be seen with the naked eye.

IR thermography should be carried out when the internal temperature of the subject building is elevated above external temperature; this will help make cold spots more apparent when viewed helping to identify building defects, such as air leakage paths or improperly fitted insulation. IR thermography is particularly useful for investigating thermal bridging, air leakage and moisture ingress, as these will cause temperature variations that are visible when viewed with a thermal camera. A coheating test provides an excellent opportunity to carry out IR thermography, as internal temperatures will be elevated to a homogenous temperature throughout a building. Caution should be exercised when reviewing IR thermography, as temperature differences can appear exaggerated or be understated if a camera is set to automatically set temperature range.

11.3.5 Air Permeability and Ventilation Tests

UK building regulations Part L1a require that new buildings undergo air permeability testing to demonstrate that they comply with the threshold air permeability of 10 $m^3/(h \bullet m^2)$ @ 50 Pa (an air leakage rate of 10 m^3 of air, per m^2 of building envelope, per hour at a pressure differential of 50 Pa). Allowances are made for large developments, permitting a sample of each dwelling type to be tested rather than every dwelling of that type. Knowing the air permeability of a building allows the rate of heat loss due to air leakage to be calculated.

Air permeability of a building is relatively quick and easy to test. The most commonly used method is the air pressure test, utilising a 'blower door' apparatus, using a controlled fan to depressurise the internal environment by blowing internal air out of the building and then pressurise the internal environment by blowing external air into the building. Purpose-provided ventilation is deactivated and sealed off before testing, as only uncontrolled, i.e. unwanted ventilation, should be measured. Airflow rate through the fan and pressure differential between the internal and external environments are recorded and plotted to calculate the air permeability at a pressure differential of 50 Pascale. Air permeability values from depressurisation and pressurisation can be averaged to account for the building's behaviour in both conditions.

A blower door test provides an opportunity to undertake air leakage path detection, as airflow and pressure differentials are increased above those expected during normal use. Detection of air leakage paths helps to guide remedial works where a building does not reach its target air permeability. During depressurisation, IR thermography can be used to locate paths of air movement into and around the building, as cold external air will be drawn into the building through gaps in the construction, cooling the building fabric. This cooling can be visualised with a thermal camera, thus identifying air infiltration paths. During pressurisation internal air is forced out gaps in the building construction; air movement can be detected using a handheld smoke generator, pinpointing the locations where internal air is escaping; the use of smoke allows air movement to be captured with a visual camera (Fig. 11.6).

11.3.6 In-Use Monitoring

Testing the building fabric performance under controlled test conditions using methods such as the coheating test is useful for providing benchmark figures of performance and understanding the physical capabilities of a building; however, the results do not necessarily reflect how a building will perform when occupied. In-use monitoring provides a way to measure energy consumption and performance of a building over time whilst occupied, giving a more realistic representation of building behaviour when exposed to transient heating and cooling cycles and variations of occupant behaviour.

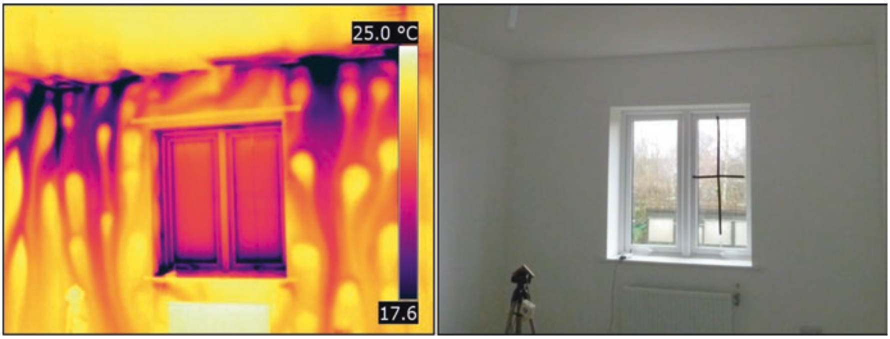

Fig. 11.6 Thermogram captured during building depressurisation, showing the leakage path of cool air not shown by visual methods

In-use monitoring may be as simple as monitoring monthly energy metre readings to determine the influence of seasonal change on monthly consumption. More intensive in-use monitoring can allow a more complex analysis of energy use behaviour and the performance of a building. An intensive in-use monitoring programme may make use of electrical submetres on individual circuits or appliances within a building to record energy consumption for specific end uses, record temperature and air quality data in multiple zones within a building and record external weather data. Where renewable technology is fitted, the performance of these systems can also be monitored to assess their performance. Intensive in-use monitoring can be used to gather a large volume of data over a long time period, subsequently requiring a greater investment of time and effort to analyse, in addition to requiring a large amount of equipment. For this reason, intensive monitoring is best deployed in pilot studies or exemplar buildings.

In addition to capturing energy data, in-use monitoring also investigates the internal environment by monitoring temperatures, humidity and CO_2. The appreciation of the internal environment is essential in establishing the experience of the occupant in a space and allows objective judgements to be made regarding their comfort and predicted satisfaction which can be later validated by consulting with the occupant. The monitoring of internal conditions also allows this relationship between the internal and external environment to be established.

11.4 The Role of the Occupant

11.4.1 Occupant Behaviour

The performance gap is often attributed to errors in the building's design or construction or because insufficient detail leads to confusion or improvisation on site. There is an additional source: the occupant. Whilst there is much discussion around reducing errors in design and construction, occupant behaviour is often regarded as too complex to characterise and therefore neglected. However, a research to explore occupant behaviour has identified several ways in which occupant behaviour can easily be addressed or at least understood. Behaviour that reduces the building's performance is often caused by occupants simply not understanding how to use the building. Such behaviour can be misinterpreted as wilfully misusing the features of their home, which leads to under- or overheating. Instead, such behaviour can often be because occupants did not receive a sufficient (or indeed any) handover of their home and so did not receive enough explanation of how their behaviour in the home influences its energy efficiency (Linden et al. 2006; Isajsson 2014) or any discussion of how their lifestyle needs could be met by the energy efficiency features in their home. Often, contractors can assume that disruption to occupants should be minimised. In practice, this can mean that occupants do not understand how best to interact with their home to maximise energy efficiency and comfort. This can lead to both over- and underheating. This can be addressed by producing a checklist of conversations to have with occupants about using the heating, cooling and ventilation features in their home.

One such example of this was observed during monitoring of the GENTOO Passivhaus development in Sunderland (Fletcher et al. 2017). The monitored dwelling is of high thermal performance, and following energy monitoring was shown to achieve its energy and carbon targets. However, the dwelling experienced significant overheating throughout the year. This was due in part to the occupants not engaging the summer bypass function of the mechanical ventilation with heat recovery (MVHR) system, in addition to limiting their window opening behaviour as they were advised that this limits system efficiency. Following re-education on the systems within the property temperatures returned to a more comfortable level. This example serves to illustrate that even when all energy and carbon objectives have been satisfied, occupancy can have a significant impact on how we view the success of high-specification buildings (Fig. 11.7).

Another aspect to consider is that the occupants' needs change over time. If this occurs around the time of retrofit, any in-use monitoring can indicate a performance gap, whereas in reality, the home is performing as designed, but the occupants are using more energy. In a retrofit study conducted by Leeds Sustainability Institute involving external wall insulation (Gorse et al. 2017b), many of the occupants experienced lifestyle changes in which affected their energy behaviour. Common changes included a family having a new baby, so they heat their home to a higher temperature, both during the day and the night. Retirement often means that the home is heated during the day as well as in the evening. Several of the homes in the study had additional people moving into or out of the home, so that the rooms are used to a greater or lesser extent. Illness could also mean that the home is heated or used in a different way. All these factors affect energy use, and whilst designers and construction companies would not want to stop occupants from changing how they use their home, any building performance assessment should include work to identify and understand such changes. This can be incorporated into a post occupancy evaluation (POE) questionnaire or qualitative work in the form of interviews or focus groups.

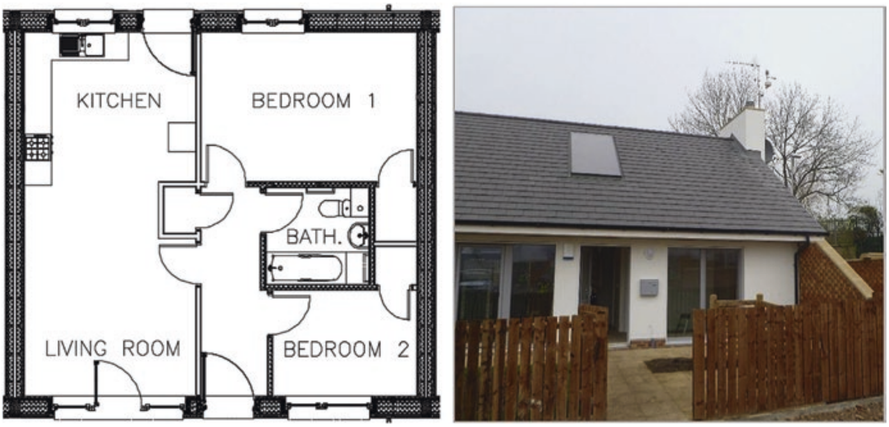

Fig. 11.7 GENTOO Passivhaus floor plan and front elevation

As well as understanding how occupants influence the performance gap, research with occupants can provide evidence on how housing influences quality of life. Living in a warmer more comfortable home could potentially lead to people feeling happier, and it has the potential to improve any long-term conditions they have.

Buildings should both be designed for energy efficiency and be capable of responding to the expectations and demands of the occupant. Detailed research observing occupant behaviour and building performance can help to understand and achieve optimum performance.

11.4.2 Post Occupancy Evaluation (POE)

Ultimately, occupants will behave in such a way as to ensure their own personal satisfaction even if this means bypassing the efficient technologies available to them and incurring an energy or carbon cost. As such, a sustainable development should aim to have minimal negative influence on the daily lives of the occupant. Therefore, in addition to energy monitoring for validation of performance, it is important to conduct post occupancy evaluation of novel designs and systems to gauge the impact on the user. Adaptive behaviours are significant when considering personal factors of thermal comfort, wellbeing and tolerance – as noted, if a sustainable technology places negative pressure on the occupant, then the likelihood is that either the system will be bypassed (thus negating its positive environmental impact) or the occupant will have an undesirable experience. The gap in performance between prediction and reality is well researched in the building fabric context (Johnston et al. 2015); however, it is equally important to evaluate the veracity of assumptions made with regard to the user and their behaviour within an environment as such assumptions underpin in-use performance predictions. POE is one such method to capture this information.

The most commonly used form of POE is the distribution of feedback questionnaires. The ubiquity of computers and smartphones has made the distribution, collection and analysis of online questionnaires increasingly cheap and simple. The Building Use Studies (BUS) methodology is an established example of this form of POE, comprising a three-page structured questionnaire which presents the occupant with various questions relating to the design, lifestyle and comfort of their building (Leaman 1995). Respondents are presented with various scales of different form and style which are specifically designed to deter feedback fatigue, in addition to several opportunities to enter their own comments. The data gathered is then compared with benchmarks generated from a database of exemplar buildings, with scores awarded and graphically represented in a ‘traffic light’ format for each category.

Whilst able to gather valuable information, the rigid format of structured questionnaires limits the possible richness of data by inadvertently establishing boundaries around how opinions may be expressed within the context of a specific question or topic group. For a comprehensive understanding of occupant experience, interviews and focus groups offer a more flexible approach and however come with increased complexity in terms of participation, cost and analysis.

The recommendations for what to include when designing research on occupant behaviour, based both on previous research and experience of researching the impact of occupants on energy use, are shown below:

- Who lives in the home (people and pets) and any regular visitors, such as grandparents providing childcare
- How the home is used, e.g. when people are in and out of the home, whether rooms are used differently in winter and summer, whether windows are kept open and doors are opened frequently
- Any health problems that people have that might affect the temperature of the home and the energy they use, together with a measure of their health status
- Preferred temperature within the home, the reason for this and reasons why the actual temperature is not the same as the preferred temperature
- Any life events that mean people might change the energy they use, such as spending more or less time in the home, having a baby, losing their job or retiring
- Understanding of how to use the heating and ventilation systems
- Confidence in the ability to use less energy (‘perceived behavioural control’)
- Beliefs about the advantages and disadvantages of using more or less energy
- Beliefs about what other people expect in terms of energy use (‘social norms’)
- How satisfied people are with factors such as how quickly their home heats up, how warm it gets, how draughty it is, how damp it gets, how much it costs to heat and how much noise it lets in
- How satisfied people are with living in their neighbourhood, for example, its appearance, how safe it feels and how much they feel they belong

11.5 Buildings that Perform

The acknowledgement of the role the built environment plays in global energy consumption has encouraged significant efforts to reduce the ecological footprint of buildings from both an energy and carbon perspective (UNEP, 2012). There are over 70 definitions for low- or zero-energy/carbon buildings in use globally (Williams et al. 2016), adding complexity to adoption on a wider scale and resulting in the creation of several assessment methods designed to facilitate environmentally conscious construction whilst offering differing views on what constitutes success. The foremost example in the UK is Part L of the building regulations (DCLG 2010, 2013) which emphasises the reduction of energy through improvement in the building fabric. Part L requires certain targets for building airtightness and fabric performance to be fulfilled, with compliance verified by the Standard Assessment Procedure (SAP) (BRE 2016). Whilst significant due to its legal status, Part L does not result in what may be termed as low-energy buildings, operating more to ensure an enforced lower limit on building energy performance. Described below are examples of buildings designed to energy performance standards that go beyond traditional requirements to achieve what may be fairly described as ‘green’, ‘eco’ or ‘low energy’.

11.5.1 Passivhaus and EnerPHit

The ‘fabric first’ logic present in Part L has been extended with the creation of the Passivhaus standard (Feist et al. 2005). Developed by Wolfgang Feist and Bo Adamson, the Passivhaus approach is to create a building with exceptional thermal performance and airtightness, with ventilation controlled by a mechanical ventilation with heat recovery (MVHR) system. This, coupled with a design to maximise both solar and additional incidental heat gains, allows the heating energy demand to be minimised. One example of a successful Passivhaus project in the UK is the Denby Dale Passivhaus in West Yorkshire (Fig. 11.8), which was the first building in the UK to receive Passivhaus certification using traditional cavity wall construction. The dwelling achieved the goal of using 90% less energy for space heating compared to the UK average (Green Building Store 2017). Due to the strict requirements for certification, Passivhaus construction is more suited to new build developments. The principles, however, may still be applied to existing buildings in a retrofit. The EnerPHit standard has been developed for this purpose, acknowledging the challenges of existing buildings and providing slightly relaxed targets whilst still following Passivhaus principles to ensure a significant thermal performance improvement.

Fig. 11.8 Denby Dale Passivhaus (Green Building Store 2017)

11.5.2 Nearly Zero-Energy Buildings (nZEB)

Whilst reducing the space heating energy demand of buildings, the fabric first approach in isolation does not offer a solution to the energy required for systems and appliances within the building. Nearly zero-energy buildings (nZEB) as defined by the Energy Performance Buildings Directive (European Union 2010) seek to address these in-use energy considerations, combining high-performance building fabric with on-site renewable energy generation to provide full building energy requirements. The aspiration is an annual net zero-energy cost, i.e. over the course of the year; the building will generate at least as much energy as it consumes.

The starting point of nZEB is to maximise operational efficiency to reduce in-use energy demand. Fabric first construction principles are combined with energy-efficient services to minimise energy use within the building. Heat pump systems are typically used in combination with MVHR to minimise energy for heating. Lighting and appliances within the building will also be low energy, and all systems will typically be powered electrically to maximise the energy generated by on-site renewables.

Once efficiency measures have been implemented, the result is a smaller demand which can feasibly be met by on-site generation. Due to peak energy demand and supply seldom occurring simultaneously and the complications of efficient energy

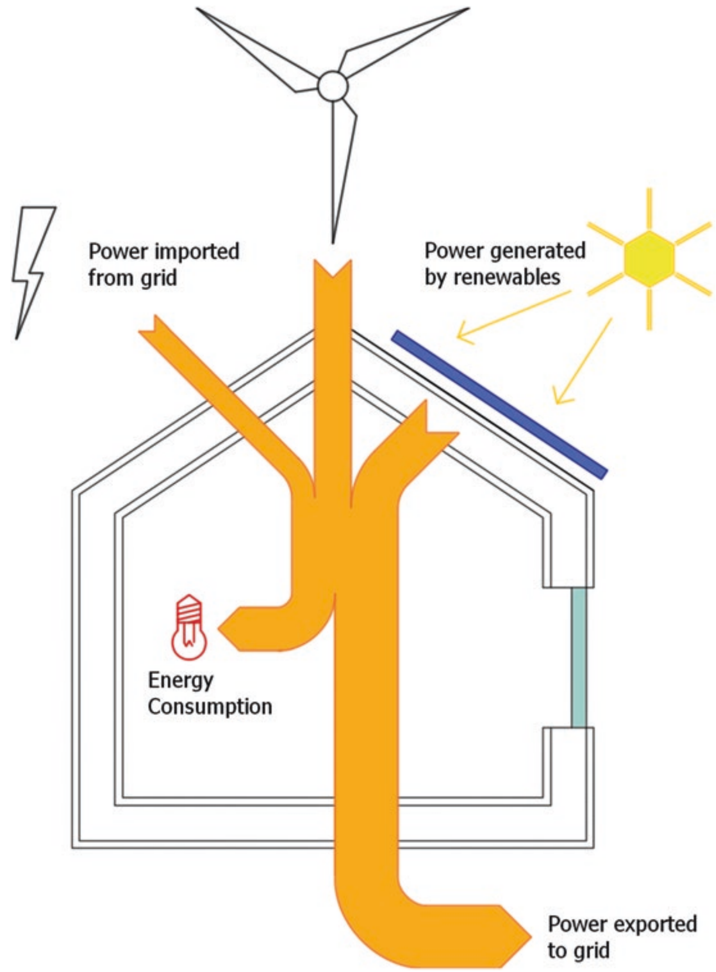

Fig. 11.9 Renewable technologies used to meet small demand requirements and create nZEB buildings (Thomas and Gorse 2015; Gorse et al. 2016)

storage, nZEB buildings typically maintain a connection to the electric grid network. This allows electricity to be exported to the grid during periods of excess supply and imported when supply is low, ultimately balancing over the course of the year. Whilst theoretically sound, the success of nZEB is extremely sensitive to occupant effects, with correct operation of efficient systems essential if projected energy use is to reflect operational reality (Fig. 11.9).

11.5.3 BREEAM

When considering sustainable construction, the focus is predominantly on the reduction of energy and carbon emissions, with success measured by their reduction against predefined levels. It is equally important, however, to consider the wider impacts of construction beyond these two elements. The Building Research Establishment EnergyAssessment Method (BREEAM) is one such assessment designed to capture the holistic factors of the built environment, covering not just energy and carbon but also water, waste and transport amongst other things (Fig. 11.8).

Energy	Health and wellbeing	Innovation	Land use	Materials
Management	Pollution	Transport	Waste	Water

BREEAM assessment categories (BRE 2017a)

Launched in 1990, the BREEAM method has grown to become one of the most widely accepted assessment methods globally, with over 562,000 certified developments across 78 countries (BRE 2017a). The BREEAM method considers the above categories with weighting for their significance, awarding points for good practice which are aggregated and used to generate an overall percentage score, translating to an award from unclassified (<30%) to outstanding (85% or greater). BREEAM may be applied to both new build and retrofit constructions, and one such example is the 119 Ebury Street development in London, which achieved an 'outstanding' score. This project involved the conversion of a grade two listed building previously functioning as a hotel into three duplex apartments (BRE 2017b).

Internal wall insulation and triple-glazed windows improve the existing building fabric whilst maintaining the external aspect of the building. This is supplemented by the addition of phase change materials in the upper and middle floor apartments to help stabilise internal temperatures (UK-GBC 2017), absorbing excess heat and releasing it slowly during cooler periods. Heating provision comes from modern boilers with flue gas heat recovery and is supplemented by solar thermal panels. The efficiency of the heating system is further improved with the inclusion of an MVHR system to minimise space heating requirement Photovoltaics provide electrical energy to the first floor apartment, and there are several other features designed to minimise the environmental impact of the building, such as a rainwater harvesting system.

In addition to the provision of efficient fabric and services, 119 Ebury Street also acknowledges the role that occupants play in determining the success of a sustainable building. The apartments are equipped with a 'smart home' system to provide feedback on energy use and limit poor energy behaviour such as heating spaces with open windows. The understanding and correct operation of low-energy systems is essential to their success; however, they are often complex and unfamiliar, leading to misuse which ultimately negates their positive impact.

11.6 Conclusion

There are many aspects of performance which can be monitored and measured to ensure the building performance desired is achieved. For those wanting to develop high-performing buildings, a systematic approach to research and development, iteratively improving design and build, is required. However, without obtaining feedback and data on the building's performance, it is difficult to identify which aspects of the building perform and where buildings require improvement. This chapter has provided a context to the building stock and why it should be improved and provided tools for monitoring and measuring to ensure the performance of buildings can be improved.

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