Department of Mechanical and Aerospace Engineering

Investigation of Strategies for Thermal Energy Efficiency in the Hospitality Sector

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Copyright Declaration

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Signed: Ramón Prieto Trigo Date: 24 August 2017

Abstract

Strategies for energy efficiency in the hospitality sector have been investigated in terms of energy savings and greenhouse gas emissions reductions. The work has focused on an already existing building, as it is forecast that the existing stock will be responsible for most of the emissions and energy consumption in the next years to come.

The project was accomplished using dynamic building simulation through ESP-r software, using a hotel situated in the United Kingdom as a case study, which is representative of the higher end of the market. Energy consumption data of the building were acquired by live monitoring.

The effects of supply-side and demand-side interventions were studied, including fabric upgrades, insulation of hot water tanks, installation of a new gas boiler and air-to-air and water-to-water heat pumps. Sensitivity analysis was performed about how future changes in the electricity mix can influence the results.

The main findings show that up to 73% of reductions in heating and hot water loads and CO_2 emissions are possible through technically feasible solutions such as water-to-water heat pumps. The study confirmed the importance of the interdependence of the different systems operating in a building and the need for an integrated analysis. The emissions reductions advantage of natural gas based systems decreased in favour of electricity based systems with the de-carbonisation of the electricity generation mix. The main limitations of the work include assumptions made regarding operational parameters and steady-state calculations of hot water heat losses.

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1. Introduction

1.1. Motivation

The challenge of providing energy for a growing population with rising living standards without threatening the world's ecosystems and at the same time mitigating disruptions in the climate is considered one of the most difficult to be faced by our civilisation in this century. Solving it will require major changes both in energy supply, with the implementation of renewable energy technologies on a big scale, and a significant demand reduction, by a shift in consumer behaviour and vast advances in the field of energy efficiency.

It is widespread knowledge that the building sector represents at least 40% of the energy consumption in the European Union (EU), which is responsible for a 36% of global greenhouse gas emissions [1]. Energy efficiency in the building sector is regarded as having a huge potential in terms of climate change mitigation and can be seen as a promising clean energy resource, with reductions of 50% in emissions associated with energy use in existing stock using technically feasible, mature technologies [2].

The new Energy Efficiency Directive being proposed by the European Commission in 2016 is aiming for a 30% increase in energy efficiency by 2030 [3]. The UK government has set its own target of reducing greenhouse gas emissions by 80% by 2050 by the Climate Change Act [4]. Whereas the new buildings comply with strict regulations regarding energy use, it is estimated that a substantial amount of the buildings that will be standing in 2050 have already been built [5]. That is why retrofit strategies represent both great opportunities and challenges to reduce energy consumption and emissions.

The tourism industry is at the forefront of employment creation worldwide. It is estimated that this sector supports 292 million people in employment, or one in ten jobs in the planet growing at a rate of almost 4% annually [6]. As seen in Figure 1, in some of the EU countries, this figure can represent as much as 16% of the total employment [7]. In the UK, the sector is the country's fourth biggest industry representing 4% of the gross domestic product and providing 9% of all UK jobs [8].

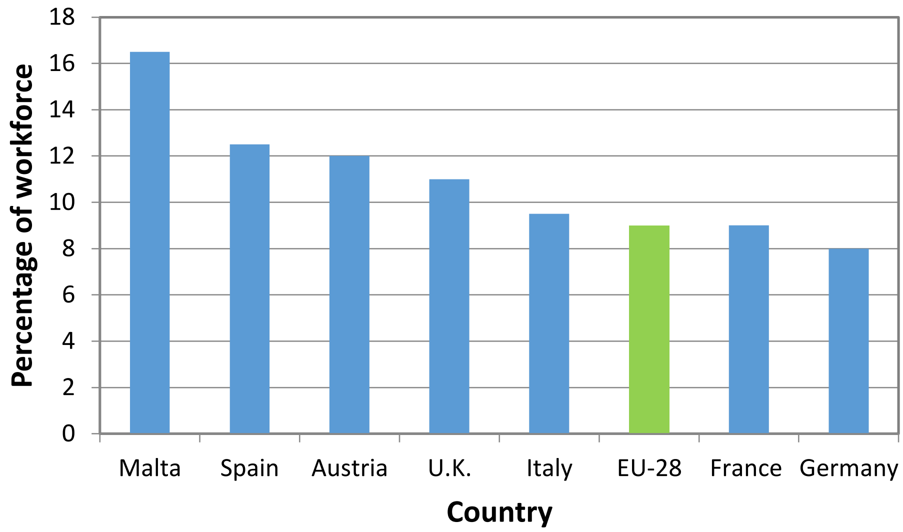


Figure 1: Employment in the tourism sector by country. Adapted from [7].

The hospitality industry often provides its services to its guests with a low level of energy efficiency [9], which in turn derives in higher emissions and pollution in the air, soil and water resources with both local and global impacts. According to BRE [10], the hospitality sector belongs to the highest energy consumers and emitters in the UK, with energy costs in excess of £1.3 billion in 2015 [11]. Although energy costs in hotels account typically for only 3-6% of all operational costs [12], it often represents the second most important controllable cost after labour, and it can reach even 10% of revenue in historic and luxury hotels [13].

There has been a great number of research papers on energy efficiency in hotels, however, most concentrate in Mediterranean climates where the weight of the industry in the total economy tends to be higher. As areas with colder climates will have different patterns in energy use, there is a clear need for a closer examination of energy efficiency practice of hotels in northern areas of Europe. Energy auditing ought to play a major role in defining priorities for the future improvement of energy use in this sector, while at the same time reducing costs and encouraging sustainability perception among management and clients.

The challenge for any type of energy efficiency strategy is to implement low-carbon energy efficiency intervention measures in a way that minimises both the energy consumption and the environmental impact of the buildings. They are usually assessed using an optimisation process measured by two key performance indicators (KPIs): economic (cost-effectiveness of measures) and environmental (emissions reduction potential) [14] [15]. The maximisation of both indicators will require both engineering and environmentally sound solutions. In the hospitality sector, there is an additional obstacle due to the fact that there is a strong need to ensure guest comfort and fulfil their expectations. In order to avoid being discarded by the hotel management, any proposed strategy would need to ensure an almost negligible impact on the guests' wellbeing and reduce visual impact to the minimum [2]. There is, therefore, a need to develop a robust decision-making methodology regarding energy efficiency, specific for the hospitality sector.

A number of tools have been developed to advise and support building owners regarding retrofit decisions for energy savings [16] [17] [18] [19], which are generally aimed at reducing costs. In this work, the environmental viewpoint will also be considered in the decision-making process.

1.2. Aim

The aim of this project is to determine the thermal energy efficiency strategy that would yield the best results from both the energy use and the environmental points of view for an upmarket, medium-size hotel belonging to a hospitality chain in the United Kingdom. The hotel chosen as a case study is situated in a rural location in Lancashire, England. It has sixty-two bedrooms and includes facilities such as a conference and banquet centre for up to 350 people, a spa with a lap pool, steam room and sauna, a gym and a fully-equipped restaurant and bar.

This work will evaluate measures designed to improve the fabric of the building, such as an increase of insulation of walls or lofts, or a change of glazing; the provision of thermal energy for space heating and hot water use through more efficient technologies such as modern gas boilers, air-to-air and water-to-water heat pumps.

1.3. Objective

The objective deemed necessary to achieve the above aim is the identification of the optimum energy efficiency strategy assessed in terms of energy savings and greenhouse gas emissions reductions. The main output will be a series of graphs where the solutions that maximise both energy and carbon savings can be spotted.

1.4. Overview of methodology

In order to achieve the aim of every project, it is essential to develop a robust methodology, which sets the modes of procedure in order to solve a problem in a logical way through smaller tasks. Although the specific methodology for the different upgrade strategies will be detailed in dedicated sections later on, a general overview is described here.

Firstly, the current building performance will be assessed using electricity measured data through a whole year. The data will then be processed to separate the different energy uses, such as heating, hot water, air conditioning and lighting. This information will be subsequently used to establish a baseline, which represents the current situation or "business as usual" strategy. The following step will be the modelling of the building in ESP-r, a dynamic simulation software, using information from a field visit and publicly available satellite images. The results from this simulation will be then post-processed to account for differences such as occupancy levels and climatic factors, and compared to the measured data for validation. Next, changes will be made to the model to reflect the proposed strategies of energy efficiency and to assess their impact by comparison with the baseline conditions. Finally, a comparison will be carried out among the different interventions in terms of energy savings and carbon emissions reduction.

1.5. Structure of dissertation

This document is comprised of fourteen sections. After a general introduction to the problem to be solved and an overview of the methodology to be used, Section 2 will incorporate a literature review of topics related to the subject of energy efficiency which are relevant to this Dissertation. A description of the building used as a case study and its energy systems is carried out in Section 3, while Section 4 presents an analysis of the hotel's energy consumption for space heating and domestic hot water, among other uses. The model constructed to represent the building in the simulation software, with the construction and operational details used, is described in the following Section 5, where it is also checked through a comparison between the consumption obtained from a baseline simulation and the measured energy use. Sections 6 to 10 characterise the different energy efficiency strategies tested, including supply-side and demand-side approaches, and analyse the results obtained from the simulations. A summary of the findings, which will compare the diverse interventions in terms of energy use and emissions, can be located in Section 11, preceding the conclusions that can be drawn from the results. Section 13 will point out the limitations of the present work and the recommendations for further work related to the subject and Section 14 will include a list of references used to produce this project.

2. Literature review

2.1. Buildings and energy

The relevance of the impacts on the environment associated with energy consumption in buildings and its associated greenhouse gas emissions, which were explained in Section 1.1 of this document, are forecast to continue increasing with the improvements in the world's standards of living and its growing population. In a planet with finite resources, it is sensible to use them as efficiently as possible. Numerous studies show that there is plenty of room for improvement compared to the business-as-usual scenario regarding energy use in buildings: according to the Carbon Trust, there is a potential for a 35% reduction in CO_2 emissions in buildings in the UK using only cost-effective measures, and a 70% reduction at no net cost [20].

Within all types of buildings, hotels are one of the most demanding energy consumers in the building stock [21], and it is believed that a large amount of this is not used efficiently, therefore opening wide opportunities for a more adequate use of natural resources and significant reduction of their carbon footprint [22].

A typical breakdown in the use of energy in hotels situated in the UK climate region can be seen in Figure 2. Together, space heating and hot water commonly account for almost 70% of the total demand. A similar conclusion can be drawn from other sources, such as the survey conducted on over fifty UK hotels by BRECSU [23]. For different climatic regions, there will be a change in the proportion between heating and cooling demand, but typically over half of the energy will be spent for space conditioning purposes [24] [25] [26].

The existence of auxiliary services such as catering, laundry, swimming pools and conference centres can significantly alter the distribution of the remaining energy use, and will be very site-specific. The use related to these facilities is sometimes difficult to assess, as many hotels are not capable of providing disaggregated information on energy use. A study on two hotels in Dorset (UK) concluded that breakfast and laundry services can represent 19% and 14% of the annual energy use, respectively [27].

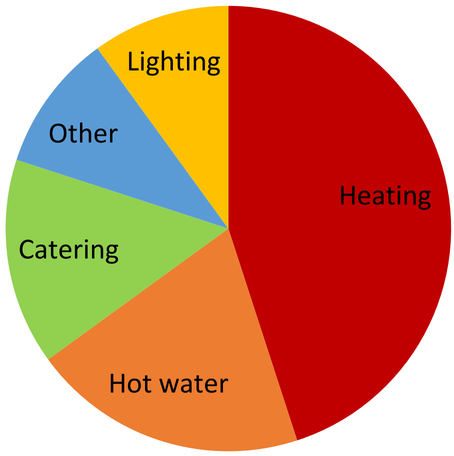


Figure 2: Breakdown of energy use within the average UK hotel. Adapted from [11].

In order to measure energy efficiency in hotels, several indicators can be used. Filimonau et al. [27] used the energy consumption per one guest night stay as a primary benchmarking indicator. However, the most common method is the energy use intensity (EUI), which is defined as the building's energy consumption per unit of gross floor area. Although there has been criticism about the adequateness of this indicator, it is still widely used throughout the industry [28].

The EUI for a specific hotel can be compared to benchmarks, allowing the assessment of how the building is working and helping to identify poor performance and areas of improvement. Annual figures of 215 kWh/m^2 in Italy, 287 kWh/m^2 in Spain, 280 kWh/m^2 in Greece and 420 kWh/m^2 in France have been reported [29]. In the UK, CIBSE TM46 provides energy benchmarks for a variety of non-domestic buildings, including hotels, which can be observed in Table 1. These represent 435 kWh/m^2 of annual consumption. Depending on the climatic area where the hotel is situated, the EUI corresponding to fossil-thermal energy can be adjusted by up to 8% from the average value to account for the higher or lower need for heating.

Type of energy	**Energy Use Intensity (kWh/m^2)**
Electricity	105
Fossil-thermal	330

Table 1: Energy benchmarks for hotels [30]

2.2. *Greenhouse gas emissions related to energy use*

In order to perform analyses of emissions associated to energy consumption, conversion factors need to be established based on the amount of carbon dioxide emitted per unit consumed. In the case of electricity drawn from a national grid such as the UK's, this factor will vary every hour as production from the different generation technologies, which have different emission factors, increases or decreases. When wind or solar production make up a high percentage of the total generation, the emission factor associated to electricity will be lower. In the same way, a low renewable production which will trigger the start of more coal-fired power plants will cause the opposite effect.

Standard practice in energy emissions assessments, however, is to the use a yearly average in order to simplify the calculations. The average CO_2 emission factor for grid electricity in the UK has been falling in the recent years according to the Department for Business, Energy and Industrial strategy [31]. Its evolution can be seen in Figure 3.

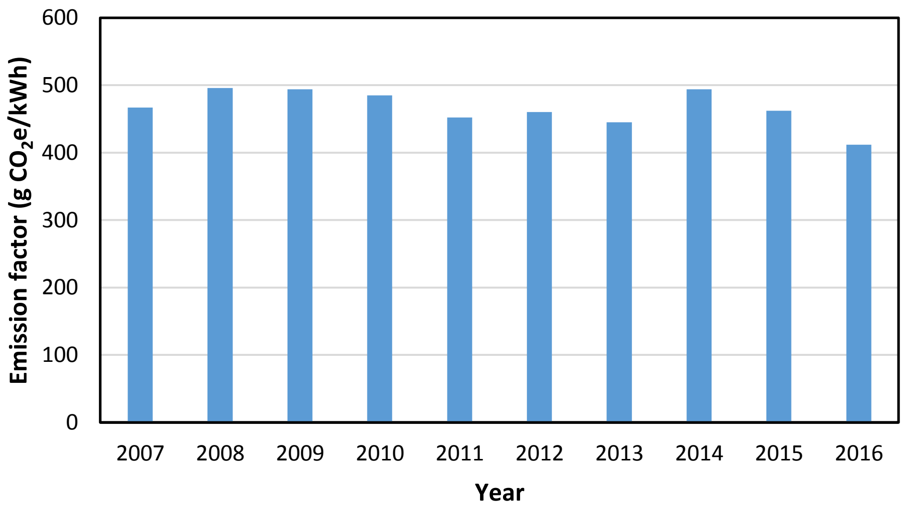


Figure 3: CO_2 emission factor for grid electricity 2007-2016. [31]

The drop in the last years has been caused by a shift from coal generation to gas, favoured by a lower carbon tax which favours the latter. From 2015 to 2016, the share of gas in the electricity generation increased from 29% to 42%, whereas the coal share dropped from 22% to 9%. The proportion of the different generation technologies in the UK electricity mix can be seen in Figure 4.

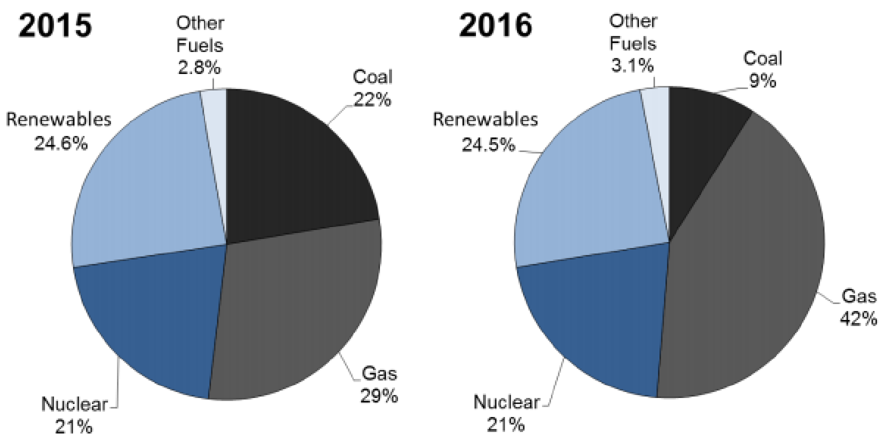


Figure 4: Share of electricity generation, by fuel. [32]

Further decreases in the emission factor are forecast as an increasing number of coal-fired power plants go off-grid and its production is replaced by renewable technology or other sources of low-carbon electricity such as nuclear. Figure 5 shows a projection regarding the sources for electricity generation from the UK Government, which shows the predicted trend until 2035. Although there is a high amount of uncertainty in this type of forecasts, which include a considerable amount of political and economic unpredictability, a shift to more carbon-neutral technologies is certainly to be expected in the near future.

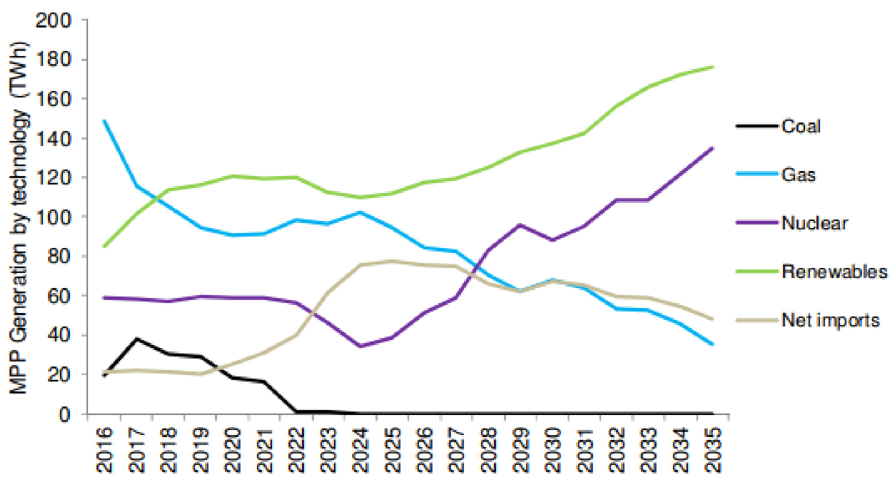


Figure 5: Forecast UK mix of generation by technology. [33]

2.3. *Energy efficiency in hotels*

In the European Union, the main piece of legislation covering the reduction of energy consumption in buildings is the Energy Performance in Buildings Directive (EPBD) [1], which introduces the concept of nearly zero energy buildings (NZEB). These are defined as those with a very high energy efficiency, whose energy needs are covered in a significant extent by local renewable energy. The EU-wide aim is that all new buildings by the end of 2020 should be NZEB, and all buildings occupied by public authorities should obtain that status by the end of 2018. Member states are required to develop a national definition and to set plans with measures to promote them, but the achievement of a common NZEB concept across all Europe is far from being reached [34]. The UK national legislation has subsequently defined NZEB as "zero carbon buildings", but a strict definition is yet to be specified in the legislation.

Specifically in the tourism industry, the HOTRES project had the objective of setting the conditions for a general implementation of renewable energy sources, focusing on solar thermal, passive and photovoltaic, biomass and geothermal technologies. As a case study, a luxury hotel in Crete (Greece) attained fuel savings of 29% annually through the installation of the then largest solar thermal facility in Europe [35]. The project also identified key positive impacts related to this implementation through surveys in five Mediterranean countries, such as the promotion in environmental awareness of the facilities and their green image, its fuel savings and the increased autonomy, especially for rural locations away from conventional energy sources. As a main barrier, the authors pinpointed the initial investment, especially for small and medium enterprises, due to the shortage of finance and the unsure payback time. The lack of experienced engineers to support and promote energy projects, together with the reluctancy to implement new technologies also play a major role [21].

The European project "Near Zero-Energy Hotels" aims to tackle the issues mentioned before by helping businesses in this sector to gain competitiveness, providing technical support and advice through reduction in energy consumption and adoption of green energy technologies. It aims to reduce average annual energy consumption from 350 kWh/m^2 to just 100 kWh/m^2, producing 80% of both heat and electricity by renewable sources [36].

The specific strategy for achieving these levels of energy efficiency will be different in each case, depending on the energy sources available and the hotel features. Sometimes, due to lack of physical space, the solutions that seem best "a priori" cannot be implemented, but there is still a wide array of different technologies which can deliver a NZEB such as PV panels combined with high-efficiency heat pumps [37].

2.4. *Passivhaus standard*

Promoted by the need towards a more energy-efficient design, the German Passivhaus approach to energy efficiency in buildings has grown rapidly in the past years. The concept is a voluntary construction standard for new buildings which requires the fulfilment of specific criteria, which can be seen in Table 2. In the case of retrofitted buildings, as it is often difficult to achieve these strict levels of energy efficiency, an alternative, more flexible set of requirements called EnerPHit has been developed.

Criteria	Passivhaus	EnerPHit
Specific heat demand	≤ 15 kWh/m^2 yr	≤ 25 kWh/m^2 yr
Primary energy demand	≤ 120 kWh/m^2 yr	≤ 132 kWh/m^2 yr
Air tightness at 50 Pa	≤ 0.6 ACH	≤ 1.0 ACH

Table 2: Criteria for Passivhaus and EnerPHit standards [38].

The strategy to achieve such levels of energy efficiency is based on techniques such as a high level of insulation with minimal thermal bridges, an excellent level of airtightness, passive solar gains and utilisation of internal heat sources, and at the same time maintaining good indoor air quality by mechanical ventilation. A schematic of the concepts involved in Passivhaus designs can be seen in Figure 6.

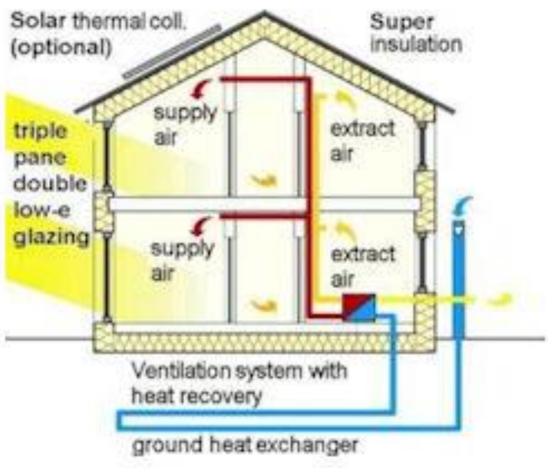


Figure 6: Indicative section of a Passivhaus building. [38]

This standard has successfully been applied to a growing number of buildings worldwide. Specifically in the UK, a community centre in London undergoing a deep retrofit to comply with the standard saw energy savings of 75%, a reduction in carbon dioxide emissions of 65% and increased thermal comfort for its users [39]. However, in areas such as social housing issues such as overheating in summer have been reported [40]. Due to the need of mechanical ventilation to provide adequate indoor air quality, any issues with maintenance of the ventilation systems can cause CO_2 levels to rise above the desirable level of 1,000 ppm depending on the occupancy and user behaviour [41].

2.5. Sustainable building certifications

A Green Building Rating System is 'a tool used by the building industry to evaluate, enhance and promote development sustainability' [42], trying to enhance the buildings' operational performance, minimise environmental impact, measure its effect on the environment and evaluate its development. In these systems, a project is measured by being awarded points grouped in different sustainability categories. Although there are a series of different green building rating schemes around the world, the most recognised ones are BREEAM and LEED.

The British Building Research Establishment Environmental Assessment Method (BREEAM) was launched in 1990. It evaluates projects as a percentage of success on the total available points in different categories such as management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology, pollution and innovation. There are five classification categories depending on the grade awarded: Pass (30%), Good (45%), Very Good (55%), Excellent (70%) and Outstanding (over 85%) [43].

Leadership in Energy and Environmental Design (LEED) started in 1998 and it is the most popular rating system worldwide. The latest version 4 assesses seven evaluation categories and has four levels of classification depending on the number of points achieved: Certified (40-49), Silver (50-59), Gold (60-79) and Platinum (80 or more points) [44].

Green building systems try to assess projects from a wide sustainability perspective, including social, economic as well as environmental aspects, although the environmental category is given the most importance in both BREEAM and LEED [45]. In particular, enhanced energy performance is given a capital role in both systems, and so the energy category score weighting stands between 23 and 26% of the overall available points. This includes measures related to energy efficiency, carbon emissions reduction, efficient lighting and renewable energy credits, and at the same time highlights the need for metering and verification that all the systems installed work as intended.

2.6. Life Cycle Assessment

When assessing buildings' environmental footprints, research tends to focus on the operational energy, as this is the most "visible" part of the impacts. However, there are significant impacts that remain "hidden" in this analysis, such as those associated with the construction, maintenance, refurbishment and demolition. The impacts deriving from activities such as mining of raw materials, manufacturing, transportation and assembly are often ignored.

Life cycle assessment is an established tool to evaluate environmental results of products or services through their complete lifecycle, including variables such as fossil-fuel energy and emissions to air, water and soil. It is regarded as the most detailed method for evaluation and comparison of materials, products and services from an environmental point of view [46].

The method of assessing lifetime building energy is called Life Cycle Energy Analysis, a simplified form of life cycle analysis, which uses energy as the only measure of environmental impact. This method can be used to estimate the net savings of a retrofit strategy over the whole building's life with the following equation [47]:

$$LCE = E_i + E_r + (E_o \; x \; lifetime) \tag{1}$$

Where LCE is the life cycle energy, E_i the initial embodied energy of the building, E_r the recurrent embodied energy associated with future maintenance and refurbishment, and E_o the total annual operational energy.

The term associated with the operational phase is, indeed, the principal source of energy demand over a building's lifecycle and hotels are not an exception [48]. There is evidence that in conventional buildings the operational energy use, and thus, their carbon footprint, account for up to 90-95% of the total [49]. This is the reason why energy audits and environmental assessments focus on it as a primary target to reduce environmental impacts.

The quantification of the embodied energy is however, controversial due to the limited knowledge available, the difficulty in data procurement and the different methods used. A majority of authors in the literature estimate the share of embodied energy as 10-15% [49]. A study of life cycle assessment in hotels concluded that the amount of energy necessary to construct a hotel equals to 20% of the total consumption of the building when an operational life cycle of 80 years is considered, but could vary depending on climatic conditions and could be lower [50].

2.7. *Demand-side strategies to energy efficiency*

Around 60% of heat in a building is lost through its fabric [51]. The “fabric first” approach in retrofit strategies prioritises the improvement of the fabric of the building through its thermal properties, by applying high levels of thermal insulation and air tightness. After this step, the efficiency of systems such as heating, air conditioning, lighting or electrical appliances can be improved with the aim of reducing overall demand.

2.7.1. Insulation improvements

In a typical building located in a climate like the UK, a high proportion of its heat losses arise due to the exchange of air from the inside of the construction to the normally colder exterior, through infiltration and ventilation. Windows and roofs make the second and third most important factors. A graphical representation of the main heat losses in a building can be seen in Figure 7.

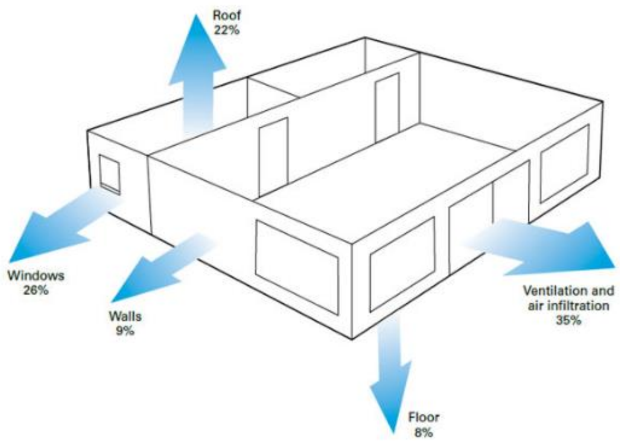


Figure 7: Typical building’s energy loss. [51]

It has been documented that a well-designed thermal insulation can significantly reduce the building’s energy consumption, by reducing heat losses during winter and cooling loads during summer, up to 20% compared to non-insulated buildings in a Mediterranean climate [52]. This saving will be even greater in a colder climate like the UK’s. Therefore, it makes sense from an energy efficiency point of view, to implement insulation upgrades. The main strategies are described in this section.

External wall insulation involves fixing insulation material directly to the wall or to a structure, and then covering it with plasterwork or cladding. It is often regarded as the less disruptive technique and it can improve the appearance of some properties, but it may be not practicable in buildings with special architectural value. Special attention has to be drawn to minimise thermal bridging and to avoid rainwater from getting behind the insulation, which could cause an excessive amount of moisture being diffused through the fabric into the inner side of the wall, thus increasing the risk of internal condensation. A typical construction can be seen in Figure 8.

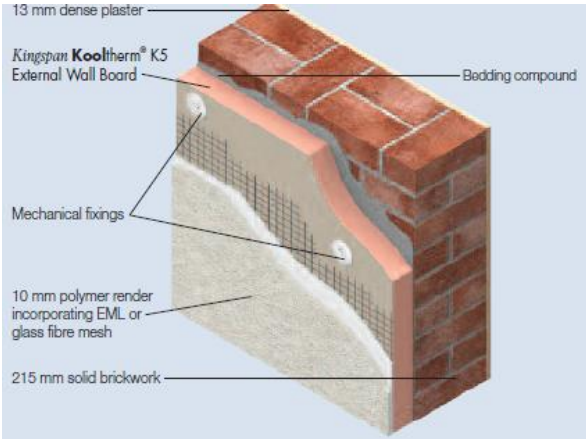


Figure 8: External wall insulation. [53]

Internal wall insulation comprises fitting insulation boards to the inside of the wall or constructing a frame to be filled with insulation material, which is then normally covered by plasterboard, as it can be observed in Figure 9. It is an option that can be considered especially in conservation areas, when the outside appearance of the building cannot be altered. It has significant drawbacks such as the reduction in useful space for the occupants and disruption throughout the installation. If designed or installed incorrectly, it can also exacerbate problems of moisture build-up inside the building since a part of the wall can become colder than the dew point of moist air being diffused through the construction, leading to mould growth or even rot. Façades with a high exposure to wind driven rain, especially when combined with sunshine, are especially sensitive to this insulation technique [54].

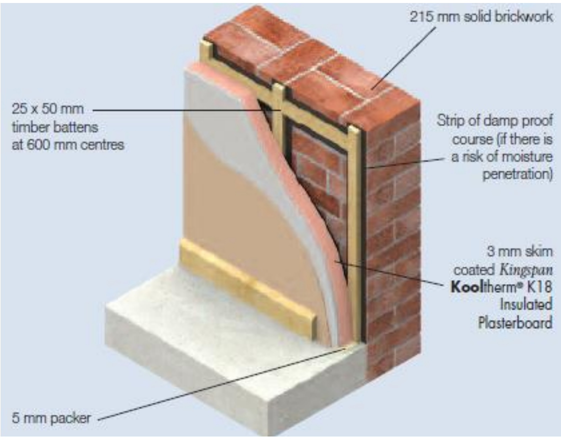


Figure 9: Internal wall insulation. [53]

Cavity wall insulation consists in filling the air gap between the external and internal layers of walls with a material with a low thermal conductivity such as mineral wool or a rigid phenolic thermoset insulation board (see Figure 10). This technique requires the existence of sufficient space in the cavity for the new insulation to be installed, and it may not be suitable for buildings with severe risk of wind-driven rain [54].

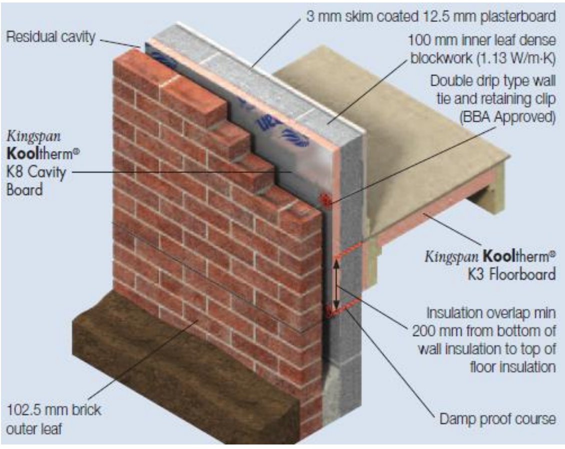
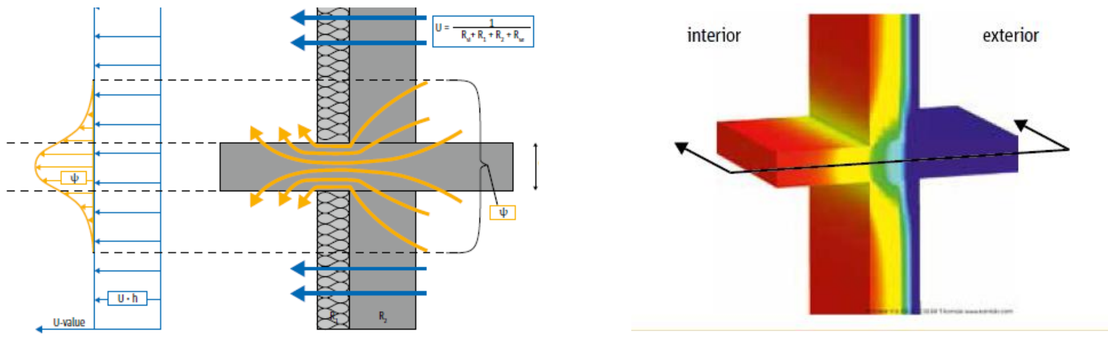


Figure 10: Cavity wall insulation. [53]

Loft and floor insulation can be one of the most cost effective fabric upgrade techniques, as heat losses through these two parts of the building can represent up to 30% of total and refurbishment actions tend to be more economic than in other parts of the construction [55]. There are several techniques and insulation methods for lofts, which can include up to 300 mm of insulation material such as glass wool, mineral wool or sheep wool, or rigid insulation boards made of synthetic polymers or wood fibres. Floor insulation usually includes installing an additional layer of insulation material under the floor covering.

Windows upgrades to double or triple glazing, which include two or three sheets of glass with a gap between them, are considered a main point in energy upgrades because of the positive impact in comfort levels, not only due to the reduced heat loss but also to reduced condensation and noise. Modern double glazing windows can achieve U-values ranging from 1.0 to 2.8 W/m^2 K, resulting in heat loss reductions between 63 and 73% compared to single glazing [56]. However, the need to maintain the original aesthetic appearance can limit the implementation of this measure in protected buildings with historic or architectural value.

When implementing fabric upgrades, specific attention has to be drawn to thermal bridges, which are areas with significantly higher heat transfer than their surroundings, creating an "easier" flow path for heat loss. A graphic representation of thermal bridges can be seen in Figures 11 and 12.



Figures 11-12: Representation of thermal bridges. [57].

Thermal bridges can have a considerable influence on overall heat transfer in buildings. A study conducted on two educational buildings in a cold climate estimated incremental heat loss due to thermal bridges between 10% and 40% [58]. Another study regarding constructions with high thermal inertia predicted an underestimation of 25% of the total heat transfer if thermal bridges had not been accounted for [59].

2.5.2. Heat recovery systems

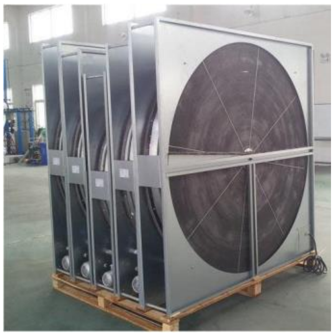
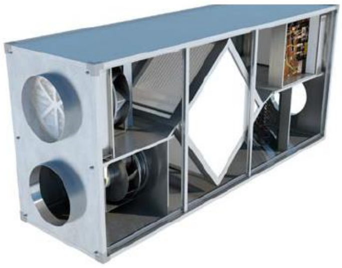
The collection and re-use of heat produced by a process that otherwise would be lost is known as heat recovery. This captured heat can, in turn, be used to meet the building's demand and reduce its overall energy consumption. There are several heat recovery applications that can be implemented depending on the type of building and its installed systems. For a hotel, its main sources of heat will be the ventilation and the refrigeration system.

Mechanical ventilation heat recovery systems (MVHR) take advantage of the residual heat of exhaust air. Instead of being vented out directly to the atmosphere, it is passed through a heat exchanger with cold fresh air, thus reducing significantly the heating load of the building. An example of how an air/air heat recovery system works can be seen in Figure 13:

Figure 13: Schematic of a heat recovery system [60].

However, in order to be effective, they require a high level of airtightness, with fabric permeability lower than 3 m^3/m^2h [61]. They also require room for ducts and heat exchangers, which can be problematic in a small building.

Ventilation heat recovery systems are based on a few main technologies, namely plate thermal wheels, plate heat exchangers and run-around coils. Thermal wheels allow the recovery of thermal energy by a single rotating wheel with a high thermal capacity. They offer the greatest heat recovery potential, although they have limitations due to their size and the possibility of cross-contamination between the two air streams. Plate heat exchangers are by far the most common heat recovery system because of their simplicity, reduced cost and easy maintenance. They are normally built of parallel plates, allowing the supply and exhaust streams to exchange heat without mixing. Run around coils are used when the two air streams are located separately. Graphic representations and its typical efficiencies can be observed in Figures 14, 15, 16 and Table 3. It is worth noting that heat recovery ventilation systems cannot easily be applied to contaminated air streams, as for example those originating in cooker hoods, due to fouling of the ducts and the presence of smells.


Figures 14, 15, 16: Thermal wheel [62], plate heat exchanger [63], run around coil [63].

Technology	Typical efficiency (%)
Thermal wheel	65 – 75
Plate heat exchanger	55 – 65
Run around coil	45 – 50

Table 3: Typical efficiency for ventilation heat recovery systems [60].

Refrigeration heat recovery systems. The most common refrigeration technology is based on a cycle of compression and expansion of a refrigerant, which circulates around the system at different pressures and temperatures, alternating between liquid and vapour phase. Around 20% of the heat is lost due to the refrigerant being super-heated prior to condensation [60]. The refrigerant leaves the condenser typically between 60 and 90ºC, so there is a potential for recovery of high-grade heat by the installation of a heat exchanger between the compressor and the condenser. A typical installation can be seen in Figure 17:

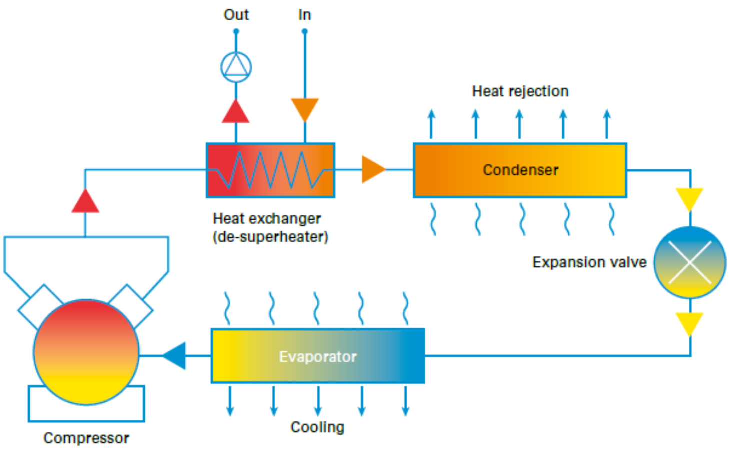


Figure 17: De-superheater for high-grade heat recovery [60].

The rejected heat from the condenser can also be recovered almost in full as low-grade heat, at a temperature of around 20-40ºC, either by using the waste heat to warm air for space heating purposes or by using a water-cooled condenser to pre-heat domestic hot water, as it can be observed schematically in Figure 18.

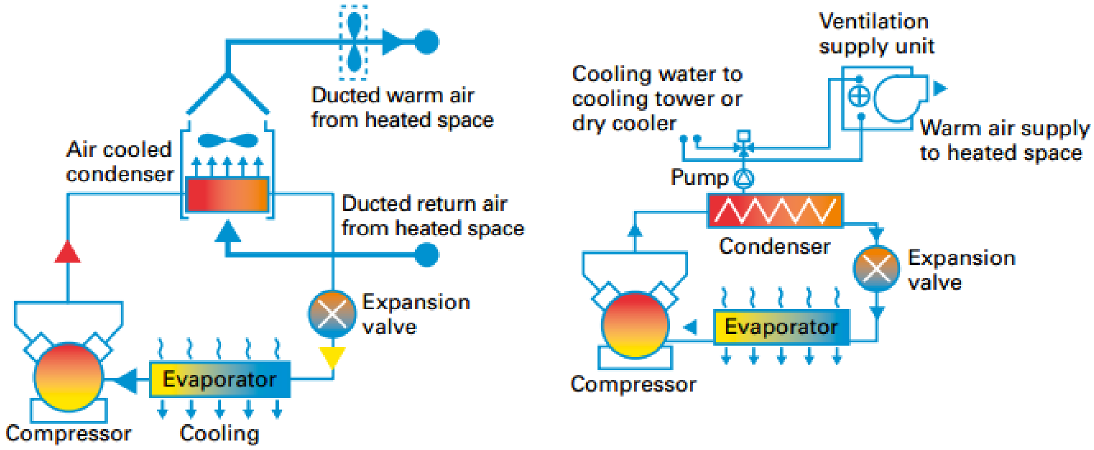


Figure 18: Low-grade heat recovery [60].

Research on domestic refrigerators retrofitted with building-integrated water-cooled condensers show that a reduction of up to 27% in overall energy consumption is to be achieved, increasing the COP of the refrigerators up to 75% [64]. In Hong Kong, research using the compressor reject heat from residential air conditioners to meet domestic hot water demand shows a saving of 9% in the total energy consumption of the residential sector [65].

Other energy efficiency measures specific to the hotel industry, like the implementation of key cards to control energy use when guestrooms are unoccupied, can provide significant savings: the annual energy savings of this measure can be estimated at 15% of the total consumption, with a payback period of just 1.5 years [66].

2.8. Supply-side strategies. Renewable energy

Considerable effort has been done to increase the renewable share of the electricity production in the recent years. However, only 6% of the heat demand in the United Kingdom is currently supplied by renewable sources (19% in the EU) [67]. The hotel industry is not an exception to this situation. In this sector, a number of technologies are being currently used to reduce the carbon footprint and the dependence on fossil fuels for space heating or hot water purposes, the most common of which will be detailed in this section.

2.8.1. **Biomass-fired heating systems**.

These systems provide heat through the combustion of wood pellets, chips or logs. Biomass is considered a low carbon option as the carbon dioxide emitted in the burning process is the same that was absorbed during the period that the plant was growing. It is also a normally affordable option, especially for areas which are not connected to the main gas grid, compared to other energy sources such as electricity or heating oil.

There are, however, emissions related to cultivation, manufacture and transportation of the fuel that should be considered. In order to be considered sustainable, the biomass needs to originate from responsibly managed sources, ensuring that the resource can be regrown at the same pace that it is extracted, and does not cause deforestation or land displacements. Distance from the source to the consumer is a crucial factor as well. When local biomass sources are used, the major contributor to the total life cycle cost is the production of fuel feedstock [68]. However, the impact of the emissions due to transportation would greatly increase if the fuel has to travel long distances, jeopardising its consideration as a carbon neutral energy source. Biomass burning can also be a concern to air quality in urban areas due to the emissions of black carbon aerosols and carbon monoxide [69].

2.8.2. **Solar water systems**

Domestic hot water or space heating can be provided by capturing the radiation coming from the Sun through this type of systems. The most common installation method consists of solar collectors attached to the roof of the building. The collected heat warms up a fluid, normally a water-glycol mixture to prevent freezing in winter. This fluid heats domestic hot water through a heat exchanger in a tank, where it is stored and from where it can be drawn on demand. The temperature in the tank can then be increased further by means of an immersion heater or a boiler if there is an increase in demand or during the periods where there is not sufficient available solar radiation. A typical configuration can be observed in Figure 19.

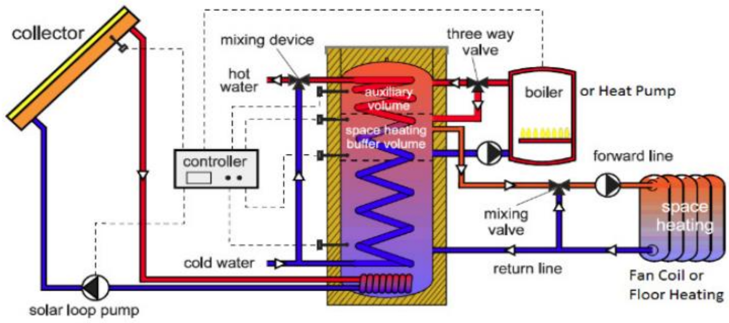


Figure 19: Typical solar combi system [70]

In a study conducted for a hotel in Greece it was found out that such a system can reduce CO_2 emissions by 67% when compared to an oil boiler, and be cost-effective [71]. However, the availability of solar resource will greatly influence the amount of energy provided by the Sun, and the potential savings in areas with lower solar irradiation such as Northern Europe.

2.8.3. **Heat pumps**.

These devices use electricity to extract heat from a source at a colder temperature, normally situated outside the building, and transfer it to a heat sink at a higher temperature inside the building. Heat sources can include outside air, the ground or water, and the typical heat sinks are air or water.

Heat pumps work by means of circulating a refrigerant through successive cycles of condensation and evaporation. In one coil, situated in the heat source, the refrigerant is evaporated at low pressure, absorbing heat from its surroundings. The fluid is then compressed to high pressure at the compressor, and subsequently condensed in a second coil, rejecting its latent heat inside the building. The refrigerant is then finally passed through a valve, where it expands, repeating the cycle. An expansor could be used instead of an expansion valve in order to exploit the pressure drop and convert it into useful work, which could then in turn drive the compressor, but this is only installed in bigger facilities due to practical reasons [72]. A schematic of how a heat pump works can be observed in Figure 20.

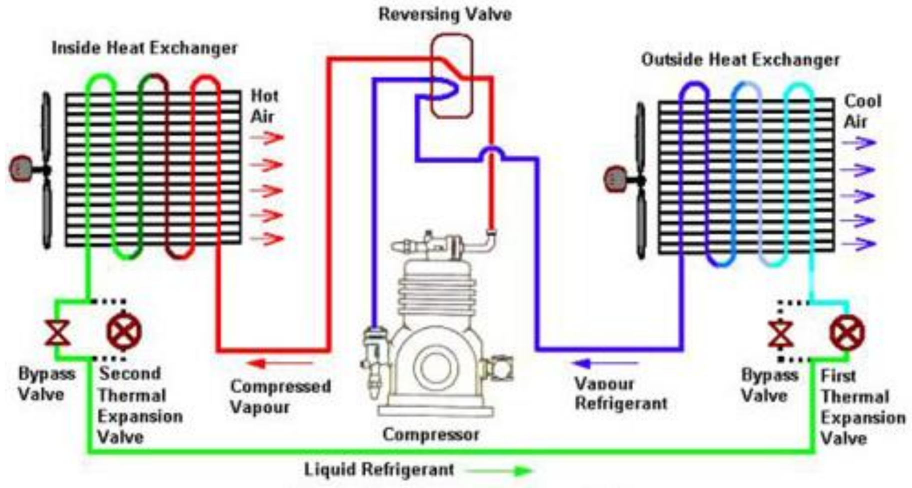


Figure 20: Heat pump in heating mode [73].

An important advantage of this technology is that can also be used to provide cooling, just by reversing the circulation of the refrigerant in the cycle, as seen in Figure 21.

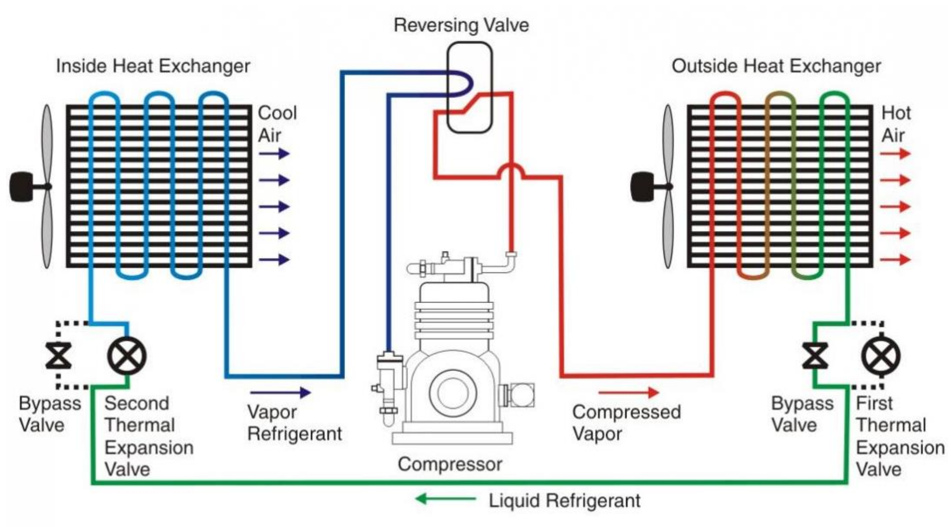


Figure 21: Heat pump in cooling mode [73].

Unlike direct electric heaters, which rely on the Joule effect to produce heat, the main benefit of heat pumps is their ability to convert one unit of electricity used in the compressor into several units of useful heat. Their performance is measured by the Coefficient of Performance (COP) which is the ratio between the amount of useful heat provided at the condenser and the electric input to the compressor, and it can be defined as:

$$COP = \frac{Q\ output}{W\ electrical} \tag{2}$$

The COP of heat pumps depends on several factors. The most important is the difference in temperature between condensation and evaporation, or ΔT. The smaller the difference, the higher the COP. The theoretical maximum value is given by the Carnot efficiency, which considers isothermal processes of heat addition and rejection and isentropic expansion and compression. For this ideal case, the maximum COP to be obtained is given by:

$$COP_{Carnot} = \frac{T_{condenser}}{T_{condenser} - T_{evaporator}} \quad (3)$$

The difference in ΔT can be minimised either by reducing the temperature at which the heat is supplied at the condenser, by for instance installing a low temperature heating system such as underfloor heating, or by increasing the temperature at which the heat is collected at the evaporator, for instance by using anthropogenic or natural low exergy thermal sources [74].

In practical terms, heat pumps are tested in standardised conditions according to EN14511 using steady state and virtually steady state measuring points. Nominal working conditions under which devices are tested are different if the fluid to which heat is transferred is air or water. In the first case, the test specifies a temperature of 20ºC for the delivered heat; in the case of water four different temperature levels are tested: 35, 45, 55 and 65ºC. As the performance will also vary according to the source temperature, several test points are defined for the evaporator temperature depending on the system from which heat is extracted: 12ºC, 7ºC, 2ºC, -7ºC, -15ºC for air source heat pumps, 10ºC and 15ºC for water source devices and -5ºC, 0ºC and +5ºC for ground source machines [75].

The main advantage of air source heat pumps is the simplicity and reduced cost. However, the temperature of the outside air can vary significantly, thus affecting the COP especially on colder days when the heat demand is the highest. Icing on the evaporator can occur, especially with low outside temperature and high humidity. This issue is normally corrected by a defrost cycle, which reverses the normal process transferring heat to the outside unit. The energy required is taken into account in COP calculations, and can cause a reduction of the rating between 0.3 and 1.0 depending on the defrosting parameters [75].

Ground source heat pumps extract heat from boreholes dug into the soil. Compared to the outside air, the ground keeps a more constant temperature throughout the year, which typically yields higher COP. However, cases have been reported where the performance starts falling after several years due to the decrease in ground temperature over time, especially in colder climates. A way to counteract this is to combine the system with a solar thermal collector, which would heat the ground again during the warmer season [76].

In water source heat pumps, heat is extracted from a nearby body of water, aquifer or sewage. Similarly to ground source heat pumps, they benefit from the fact that water temperatures are more constant than air temperatures, thus enabling higher efficiencies.

The refrigerant choice is an important factor influencing not only the efficiency of heat pumps but also several other issues. The first is the range of temperatures at which they can operate. Figure 22 shows the range of operating pressures for different common refrigerants. Other important factors to be considered when choosing a refrigerant include cost, cooling capacity, ozone depletion potential, global warming potential, toxicity and flammability [77].

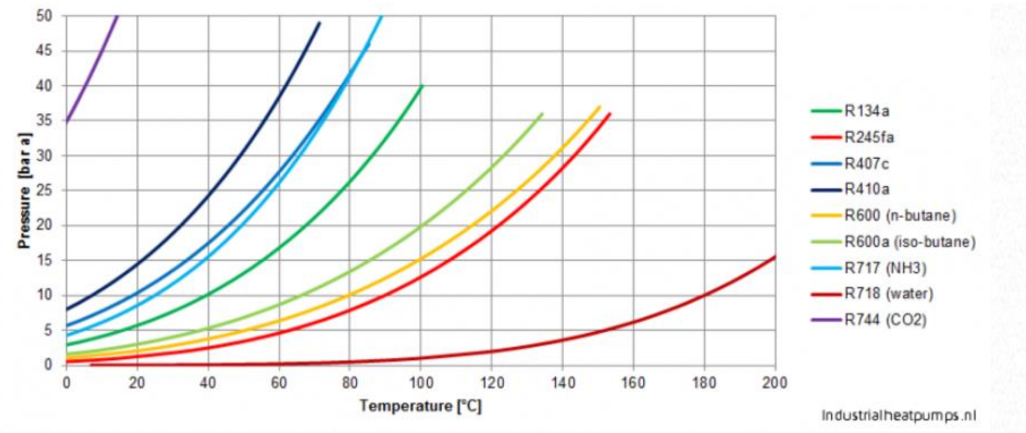


Figure 22: Condensing temperatures and pressures for common refrigerants [78].

With regards to the sustainability of the heat produced by these systems, it will be greatly influenced by the way of generating the electricity used: the more renewables integrated into the energy mix at the moment when the electricity is consumed, the lower carbon emissions. Thus, the installation of heat pumps will make more sense from an emission reduction point of view as the grid decarbonises.

2.9. Calculation methods for energy performance in buildings

Following the publication of the EPBD, EU Member States should define a common methodology to calculate buildings' energy performance. One of the main standards use in these calculations is the ISO EN 13790 Energy performance of buildings - Calculation of energy use for space heating and cooling, which allows two simplified methods: a monthly quasi-steady state method and a simplified hourly method, as well as validated detailed simulation programmes [79].

On a national level, each Member state has defined its own national calculation method. In the UK, the procedure calculates the annual energy use of a building and its CO_2 emissions, and compares it with a notional building with a standard set of data. This calculation can be performed either by approved simulation software or by a simplified tool, the Simplified Building Energy Model (SBEM) for non-domestic buildings, which uses the simplified monthly method [80]. The tool can be used either to determine compliance with the Building Regulations or to generate energy performance certificates, but it is not intended as a design tool [81].

2.10. Building modelling

Traditionally, building design was based on analytical calculations, which had to be simplified by a great amount of assumptions, including that of the system being in steady state. However, all energy systems, of which buildings are no exception, entail an extremely high level of complexity: they are systemic, as they are composed of many different parts; dynamic, as these parts evolve with time at different rates; non-linear, due to the fact that the parameters defining the system depend on the thermodynamic state; and the interactions between its parts are stochastic by nature [82]. Figure 23 gives an idea about the possible interactions in energy flow within a building.

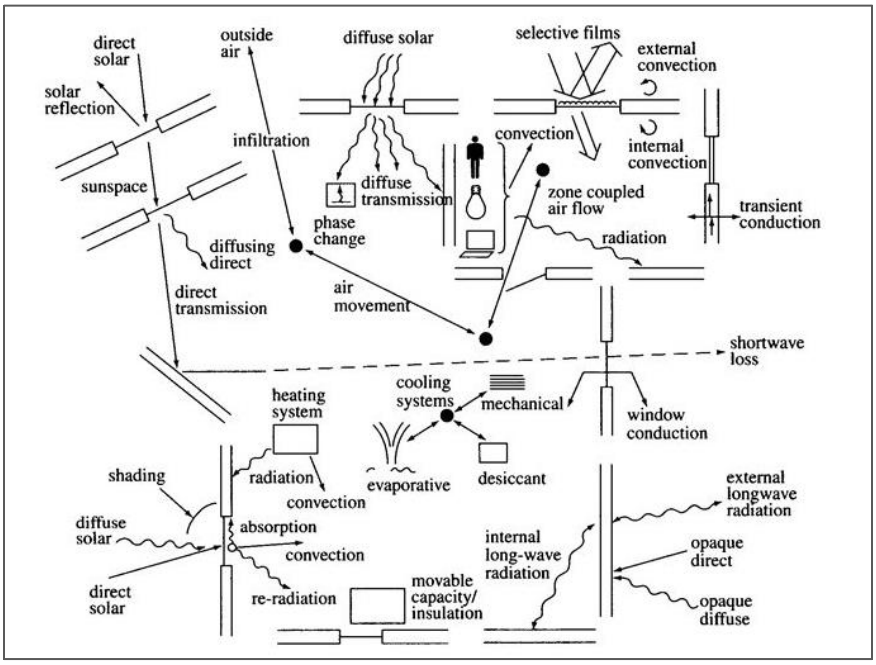


Figure 23: Energy paths in a building [82].

Today, dynamic simulation techniques allow the assessment of buildings' behaviour with increased accuracy. In these systems, the different physical volumes or nodes, such as construction elements, boundary surfaces, room air or renewable energy components, are interconnected to represent interactions between them. These interactions, for instance conduction, surface convection, longwave radiation exchange, shortwave solar radiation, casual gains or air flows, are represented in a mathematical model. Numerical methods are then used to solve the non-linear equations resulting from the balances of energy, mass and momentum applied to each interaction.

Although they can provide greater accuracy, building simulation methods often require the input of a more detailed set of variables, such as the building structure, including orientation, with specification of construction materials and layer thicknesses for surfaces such as walls, windows and doors; climate data for the location; air flow rates caused by ventilation and infiltration and details of casual gains, that is, heat being emitted by occupants, lights and diverse equipment within the building.

There is a wide range of simulation tools based on the approach described before, including EnergyPlus, IES and ESP-r. The latter has been continuously developed by the University of Strathclyde in Glasgow and it is one of the most extensively validated software in building design [83].

3. Description of the building

3.1. Location and climate

The hotel which will be used as a case study is situated next to a fresh water reservoir in a rural part of the Lancashire County in North England (see Figures 24 - 25) and approximately 40 km (25 mi) from the cities of Liverpool and Manchester. The geographical coordinates for the site are: 53.5 ºN 2.6 ºW.

Figures 24, 25: Location of hotel

The local climate is a temperate oceanic climate, with a Köppen classification of Cfb, which implies few temperature extremes a precipitation evenly distributed throughout the year, with relatively high cloud cover.

One of the most common methods to evaluate the severity of the climate, and thus the need for heating is through the use of heating degree days. For a given base temperature, set by convention at 15.5 ºC in the UK, degree days measure the difference between the outside temperature and the base temperature for a given day. This amount is then calculated for every day of the year and added together. For the site's location, the calculated average heating degree days for the period 2012-2016 are 2,199.

3.2. Geometry and use of buildings

The hotel is comprised by three buildings, marked by letters A, B and C in Figure 26. Views from each of them can be seen in Figures 27, 28, 29.

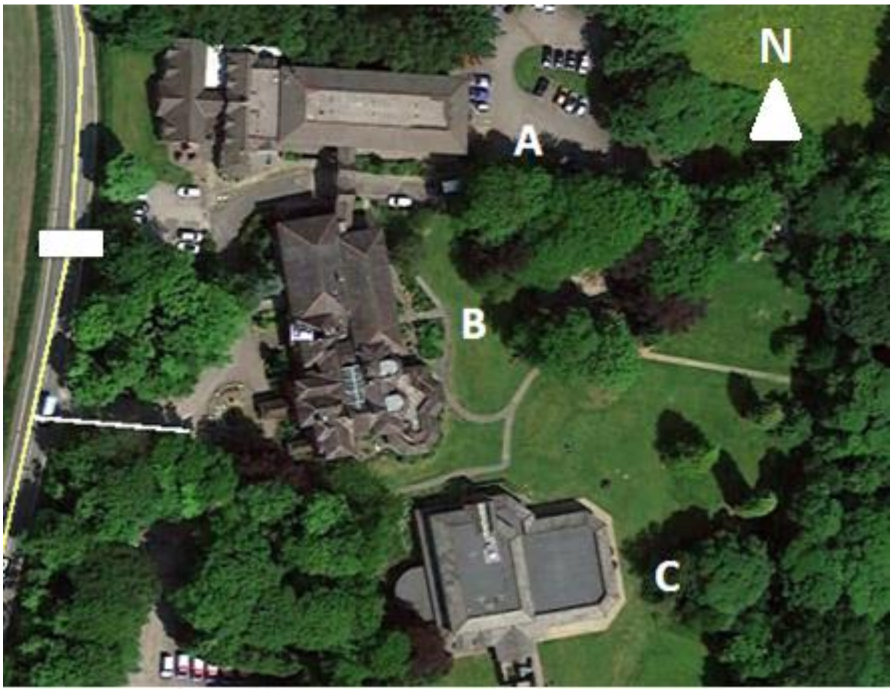


Figure 26: Hotel lay-out

Building A was built around 1990 and covers a size of approximately 1,100 m^2 in three different floors. Its west part includes the spa, swimming pool, gym and spa reception, with six bedrooms on the top floor. In the east part, the ground floor includes four staff offices with computer servers and air conditioning. The two other floors host the guest rooms. There are twelve rooms in each level, half of each facing North and half facing South, separated by a corridor.

Building B is a historic Victorian country manor with a surface of 1,100 m^2, which includes the main reception, restaurant and bar, main kitchen and four suites, as well as the old conference rooms.

Building C is the new conference and events centre built in the early 2000, with a surface of 1,200 m^2. It has areas for conference and banqueting in the ground floor and four meeting rooms on the first floor.

Figures 27, 28, 29: Views of buildings A, B and C.

3.3. Space heating and hot water systems

In Building A, space heating and hot water are provided through two different systems. In the west part, gas-fired boilers such as the one pictured in Figure 30 heat the swimming pool, provide space heating for the spa, the gym, the reception and the six bedrooms.

Figure 30: Gas boilers with expansion tank

The system installed in the east part is all electric. Electric radiators provide the space heating for the rooms, corridor and offices. There is no centralised control over the setpoints for these radiators: they are normally activated remotely by the reception personnel once the guest receives the key to his room. Domestic hot water is provided by six 550-litre electric hot tanks situated in the roof space above the third floor, with a nominal power of 9 kW each. The tanks are not insulated and the piping is only partly so, as it can be observed in Figures 31 and 32.

Figure 31: Uninsulated hot water tank

Figure 32: Partly insulated pipes

4. Analysis of the building's energy consumption

4.1. Energy monitoring

The energy performance of the building regarding the electricity usage is being monitored on a constant basis through thirty separate circuits, which include trackers that register the hotel's consumption in real time with a minute resolution for the three phases. Each of the circuits is assigned to a specific area of the building, which allows the Energy Manager to study the variations in consumption and to take corrective actions if necessary. Figure 33 shows the installed sensors for every circuit, which are integrated in a switchroom pictured in Figure 34.

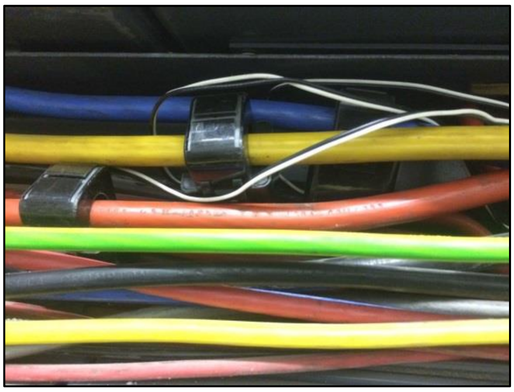


Figure 33: Circuit sensors

Figure 34: Switchroom

The individual registers for every circuit can be aggregated into functional categories, depending on the purpose for which the electricity is being used:

- Hot water & Plant includes the consumption for the electric hot water in the bedroom building, the electric supply to the pumps in the gas-fired systems serving the swimming pool and spa and part of the air conditioning.
- Conference & Events registers the use of electricity of the conference facilities (building C), including heating, air conditioning, lighting and the usage of the bar and the secondary kitchen.
- Kitchen & Restaurant monitors the main kitchen, equipped with electric ovens, dishwashers and fridges, as well as the lights and small power in the restaurant area.

- Guest Rooms & Administration controls the electric space heaters, light and small power for the guests' bedrooms and the administrative floor. It includes light and power in the main reception as well.
- Fitness & Pool oversees the light and power of the leisure club and Spa and the pool plant.

Figure 35 shows the annual electricity use of these five categories. The set of Hot Water & Plant and Guest Rooms & Administration represents 41% of the total usage of the hotel.

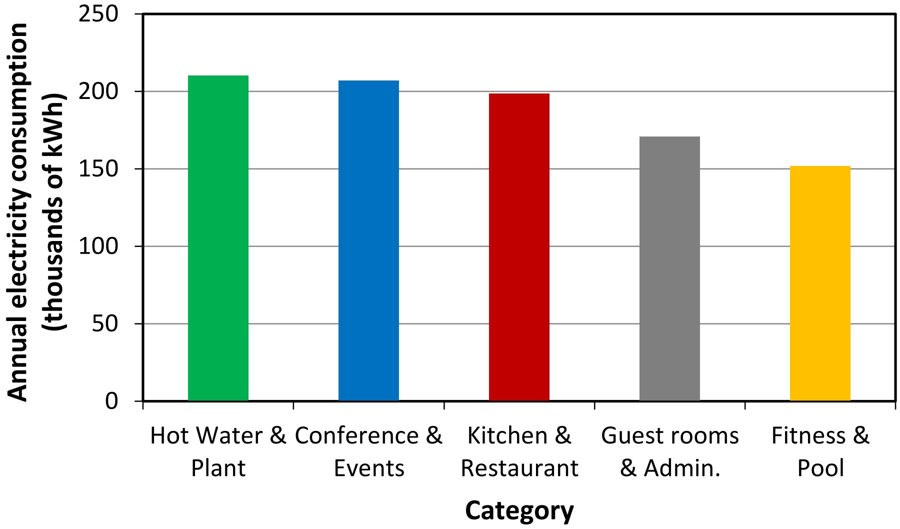


Figure 35: Electricity consumption per year separated by final use. [84]

A depiction of the consumption of these categories throughout the year can be seen in Figure 36. Kitchen & Restaurant circuits have an increase in consumption during the summer months due to an increase in occupancy, with more meals being served and thus increased use of electric appliances. The increased summer occupancy also results in a higher demand for hot water. On the other side, circuits related to Conference & Events and Guest Rooms & Administration uses show reduced electricity usage in summer as heating is not needed. The Fitness & Pool use remains fairly constant throughout the year.

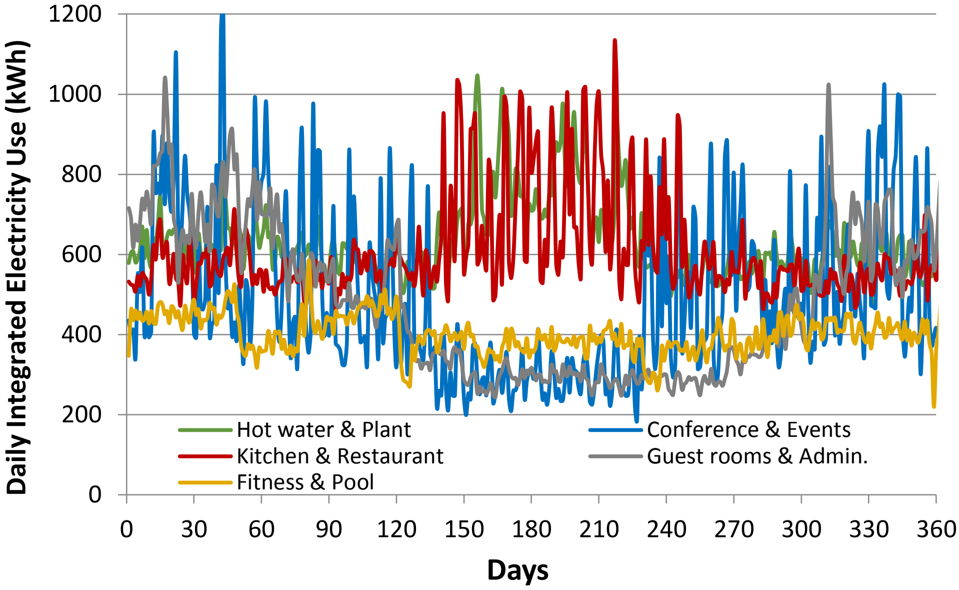


Figure 36: Daily integrated hotel electricity consumption based on type of use [84].

4.2. Space heating analysis

The two bedroom floors are monitored by two different circuits. Each one of them serves the electric radiators, lights and power sockets for all rooms and the corridor. The measured annual electricity consumption from July 2016 to July 2017 equalled to 29,217 kWh for the third floor and 31,417 kWh for the second floor. As the surface of each floor is 570 m^2, this represents an annual average use of 53 kWh/m^2. Figures 37 and 38 show the variation in the electricity consumption for these two circuits throughout the year. A higher-than-normal usage can be observed by a spike in consumption for the month of November, which was due to atypically cold weather.

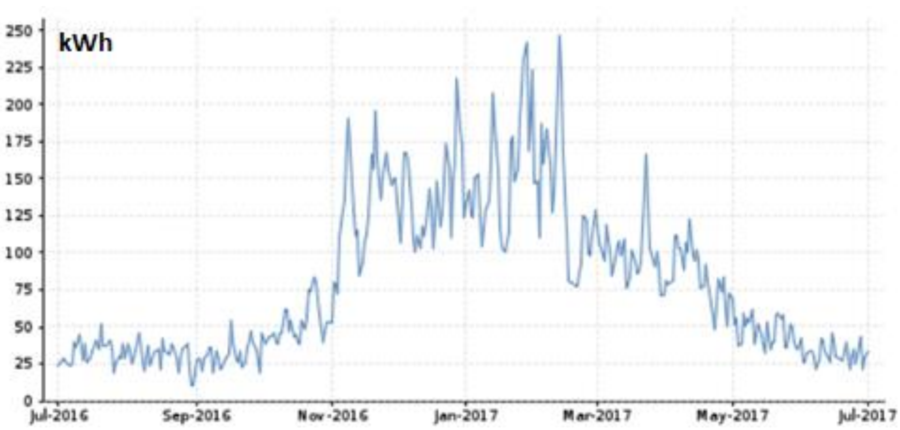


Figure 37: Daily integrated electricity consumption from the third floor circuit [84].

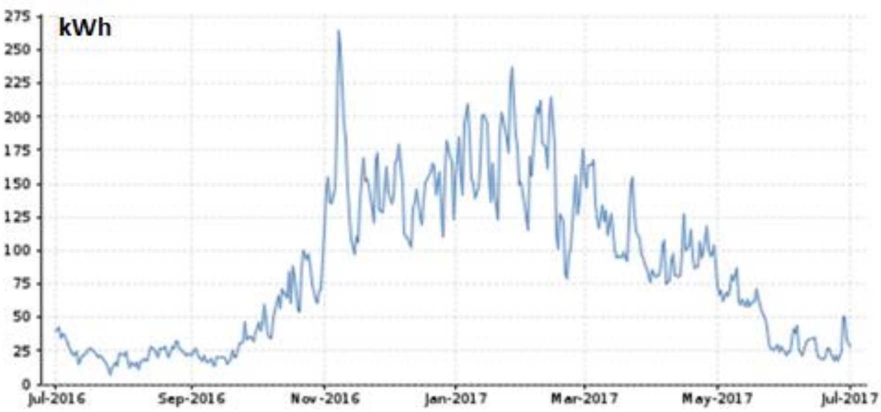


Figure 38: Daily integrated electricity consumption from the second floor circuit [84].

The graphs show relatively stable daily consumption rates during the summer season, when it is assumed that no heating is used: 25 kWh per day in average. This can be associated with lights and small power and it is assumed to be constant throughout the year. The annual usage for this purpose can then be estimated at 16 kWh/m^2/year. The remaining is attributed to space heating, representing 37 kWh/m^2/year for the measured period.

The ground floor, which is dedicated to administrative purposes, has a significant electricity consumption of 23,510 kWh per year. Its pattern of use throughout the year, which includes servers, heating, lights and air conditioning can be seen in Figure 39. As no disaggregated data can be obtained for the different energy uses, estimations were conducted using monthly average consumptions. It was assumed that the lowest average, 55 kWh/day in June represented the base level situation where neither heating nor air conditioning is needed. From July to September it is considered that the difference in consumption with the base level is due to the usage of air conditioning; the rest of the year due to heating. The annual electricity consumption for space heating purposes can then be estimated at 2,400 kWh, or 4 kWh/m^2/year, which represents just 10% of the total of the building.

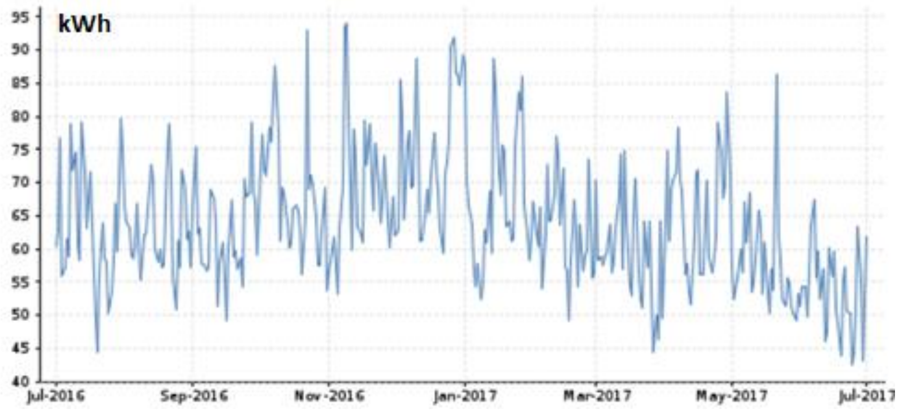


Figure 39: Daily integrated electricity consumption for the ground floor [84].

CIBSE benchmarks for hotels refer an annual consumption of 105 kWh/m^2 of electricity and 330 kWh/m^2 of fossil thermal energy. Around half of the total energy consumption is typically used by space heating. Assuming an efficiency of 70% for the fossil thermal systems, and 100% for electricity, the annual energy consumption for space heating according to the benchmarks ought to be in the region of 168 kWh/m^2. The measured value of 37 kWh/m^2 is thus extremely low, as it represents only 22% of the benchmark. This is due to the high losses on the hot water system, which significantly reduce the heating needs of the building, as it will be explained in detail further on.

4.3. Domestic hot water analysis

The annual electricity consumption measured by the two circuits connected to the hot water tanks is 127,000 kWh or 349 kWh per day. A typical pattern in consumption for one of the circuits is shown in Figure 40, which depicts a higher consumption in the winter months due to the increased amount of electricity needed to heat the hot water from a colder mains temperature and to increased losses in the tanks and the piping.

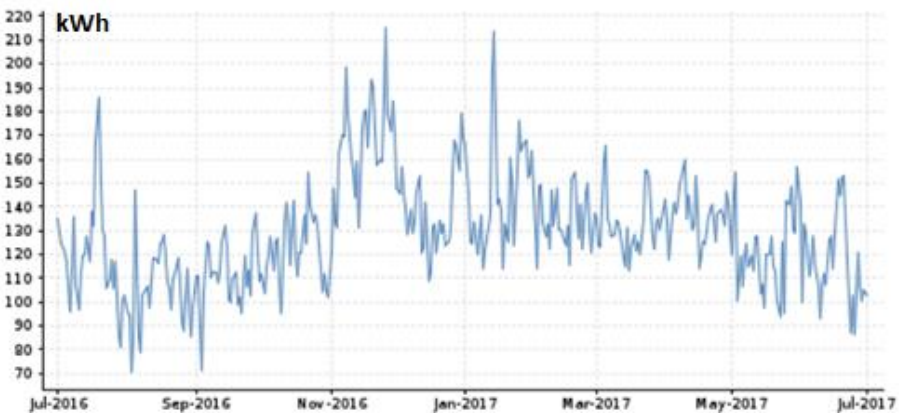


Figure 40: Daily integrated electricity consumption for one of the hot water circuits [84].

CIBSE benchmarks for energy use for domestic hot water in hotels estimate it around 20% of the total, or 67 kWh/m^2/year. The hotel’s consumption, at 111 kWh/m^2/year, exceeds the benchmark by 66%. This is mainly due to the poor insulation of the tanks and pipes, which results in a significant amount of the energy used to heat the water being dissipated into the ambient. As this represents a significant amount of the energy usage, a further analysis was conducted to estimate these losses in Section 5.7.

5. Construction of the model

5.1. Climate

The first aspect to establish in the simulation is the climate to be used. The ESP-r software includes climate files for different locations in the UK, so an analysis was carried out to determine which would be the most suitable. Based on an assessment of geographical location and temperature distribution, the climate file corresponding to Birmingham in 1995 with 2,299 degree days was found to be the most similar one to the one corresponding to the hotel's location. The monthly distribution of the site and the model's degree days can be seen in Figure 41.

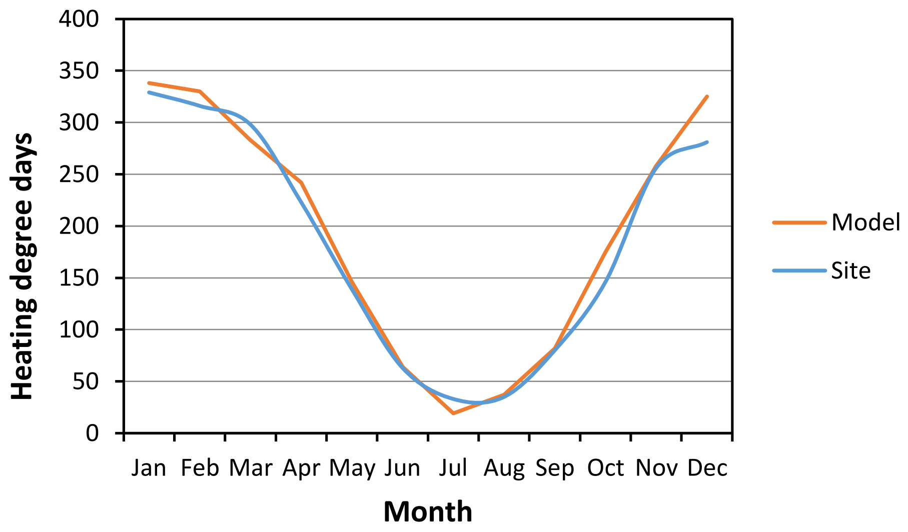


Figure 41: Heating degree days for model and site [87].

The modelled climate is considered a good match to the site's as the difference in degree days for the whole year is less than 5%, showing a similar distribution through the individual months. The inter-year variability can however reach 10%.

The climate file used to model the buildings contains hourly parameters for ambient temperature and humidity, direct normal and diffuse solar radiation, wind speed and direction. Graphical representations of the ambient temperature and solar radiation can be seen in Figures 42 and 43.

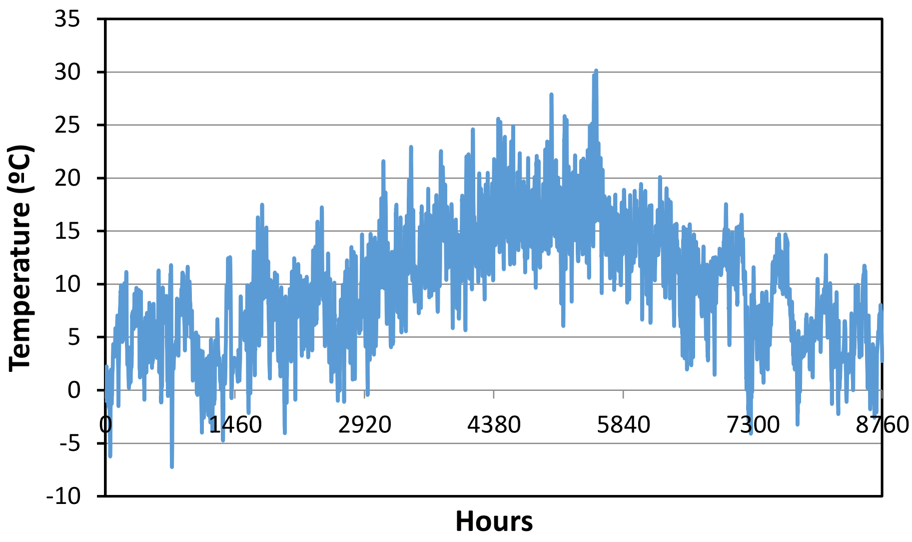


Figure 42: Ambient temperature throughout the year in the climate file.

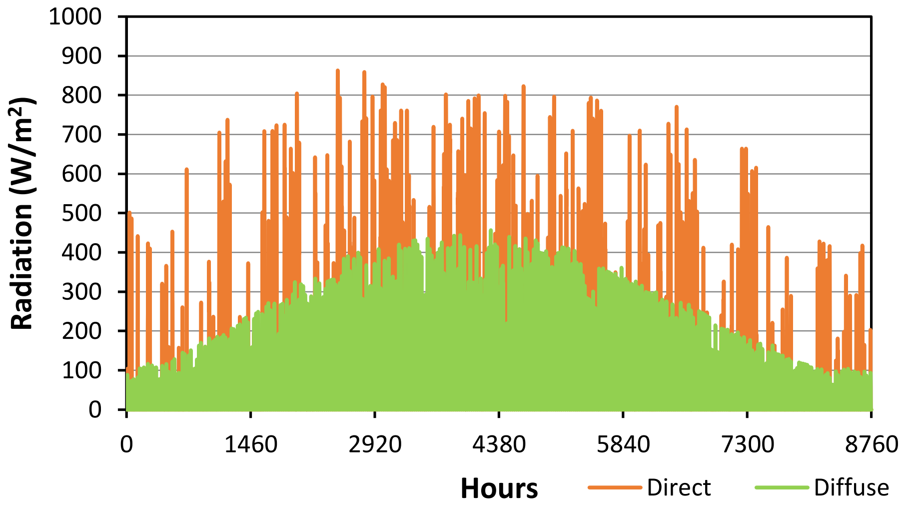


Figure 43: Direct normal and diffuse solar radiation throughout the year in the climate file.

5.2. Geometry

In this project, the east part of building A, which contains the guest bedrooms, was modelled (see Figure 44). The model represents one sixth of the area of the top floor with two rooms and the corresponding piece of corridor and roof space, each represented as an individual thermal zone. The glazed surface on every outer wall was estimated according to the site inspection. A sketch can be seen in Figure 45.

Figure 44: East part of Building A

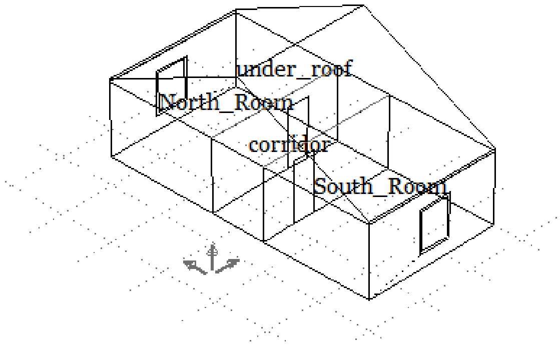


Figure 45: four-zone ESP-r model

Based on the electricity consumption data, which show similar values for the top and middle floors, the latter will be assumed as analogous to the former. The ground floor was not modelled due to the fact that its heat load represents only 10% of the total for this part of the building.

5.3. Construction materials

The construction materials used in the building simulation were estimated based on visual inspection during the site visit and on information about the construction year and the requirements of the building regulations in force at the time. The Building Regulations 1985 in its Approved Documents L specify a minimum U-value of 0.6 W/m^2K for exposed walls, roofs and floors [88]. As no specific detailed documentation could be obtained, the constructions specified in Tables 4 to 9 were assumed:

External Walls				
Material	**Thickness (mm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**
Brick	100	0.77	1700	1000
Air Gap	80	R = 0.17 m K/W		
Mineral fibre	25	0.04	105	1800
Concrete Block	100	0.24	750	1000
Dense plasterboard	13	0.50	1300	1000
Light plasterboard	13	0.16	600	1000
Total	**331**	**U = 0.62 W/m^2 K**		

Table 4: Materials and properties for external walls

Internal partitions				
Material	**Thickness (mm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**
Plasterboard	12	0.18	800	840
Breeze block	150	0.44	1500	650
Plasterboard	12	0.18	800	840
Total	**174**		**U = 1.55 W/m^2 K**	

Table 5: Materials and properties for internal partitions

Intermediate floor				
Material	**Thickness (mm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**
Carpet	6	0.06	186	1360
Rubber underlay	6	0.10	400	1360
Flooring screed	50	0.41	1200	1000
Concrete high density	150	1.93	2400	1000
Air gap	100		R = 0.17 m K/W	
Plasterboard	13	0.19	950	840
Total	**325**		**U = 1.30 W/m^2 K**	

Table 6: Materials and properties for floors

Roof				
Material	**Thickness (mm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**
Tiles	10	1.50	2100	1000
Air Gap	200		R = 0.20 m K/W	
Glass wool	80	0.04	250	840
Plasterboard	10	0.21	900	1000
Total	**300**		**U = 0.41 W/m^2 K**	

Table 7: Materials and properties for roof

Windows				
Material	**Thickness (mm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**
Plate glass	6	0.76	2710	840
Air Gap	12	R = 0.17 m K/W		
Plate glass	6	0.76	2710	840
Total	**24**	**U = 2.73 W/m^2 K**		

Table 8: Materials and properties for double glazed windows

Window frame				
Material	**Thickness (mm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**
PVC	3	0.16	1380	1000
Air Gap	8	R = 0.17 mK/W		
EDPM membrane	4	0.17	1180	1470
Air Gap	8	R = 0.17 mK/W		
PVC	3	0.16	1380	1000
Total	**26**	**U = 1.75 W/m^2 K**		

Table 9: Materials and properties for window frames

Thermal bridges within the building envelope were also accounted for, according to literature studies in similar constructions, as an overall increase in the U-value of 25%, which was directly input into the software.

5.4. *Internal gains*

Factors such as gains due to lighting, occupancy and small power can have a significant effect on the building’s heat demand. An estimation was carried out based on typical hotel operation. As there are no significant differences in occupancy patterns for weekdays and weekends, only one day type was taken into consideration. It was assumed that the average occupancy per room is 1.5 people. Gains for lights and small power are based on the typical equipment available in a hotel room, such as lamps, minibar, television, hair dryer and kettle, complemented by the use of power for laptop and mobile charging. The profile for the casual gains in the rooms can be seen in Figure 46. For the corridor, a steady gain of 12 W/m^2 due to lighting was assumed for 24 hours. The internal gains caused by the hot water tanks and pipes in the loft space under the roof were modelled as a steady gain.

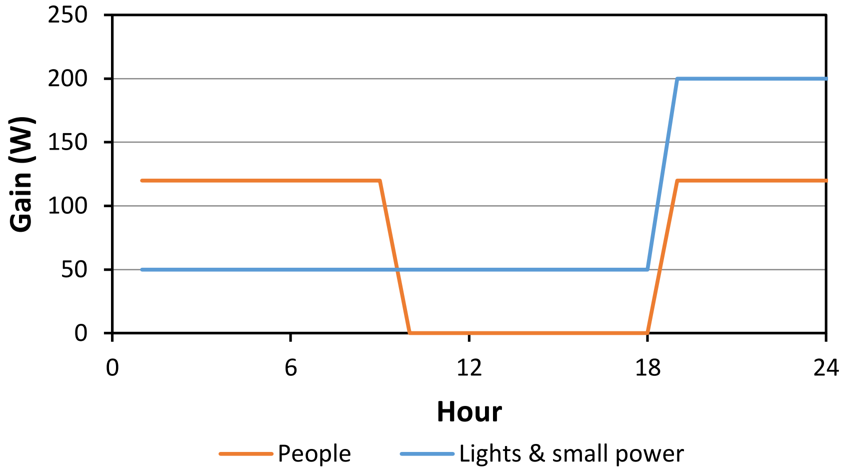


Figure 46: Defined casual gains for rooms

5.5. Infiltration and ventilation rates

The provision of enough fresh air to a room is capital to ensure a good indoor air quality, by diluting the contaminants that may be generated by the occupants, such as carbon dioxide, by dispersing odours and by regulating the ambient humidity. In order to allow for simplification in the modelling, it was assumed that a constant flow of external air, measured in air changes per hour (ACH) was infiltrated into each zone. CIBSE Guide A [89] recommends a minimum flow for hotel bedrooms of 10 L/s/person, which corresponds to 1 ACH for a typical 20 m^2 bedroom at an average occupancy of 1.5 people per room. The infiltration rates for the loft space and the corridor were estimated at 0.5 and 0.2 ACH respectively.

In order to increase occupant comfort in summer and to prevent overheating, it was assumed that the guests would open the windows when the temperature reaches a certain level, allowing the increase in ventilation to cool down the rooms. The amount of heat loss through ventilation will depend on multiple parameters, such as wind speed, window opening size, and temperature differences between inside and outside. In order to simplify the analysis, an additional constant air change rate of 1 ACH was added to the existing infiltration rate if the temperature in the room was above 22ºC. This value is consistent with studies in literature show that the opening of a single window in a dwelling can increase the rate of air changes per hour between 0.8 and 1.3 [90].

5.6. *Heating system setpoints*

The heating setpoints for the rooms and the corridor were defined according to a schedule that can be seen in Table 10, aiming for maximum occupant comfort in the evening hours when the rooms are likely to be occupied and lower setpoints at night to maximise the quality of sleep and during the day when the rooms are likely to be empty. The corridor setpoint was established at a constant temperature of 18ºC. As heating needs during the summer season, between 1st June and 30th August, are considered to be non-significant, the space heating system was turned off. No cooling loads were calculated as it was assumed that adequate cooling should be obtained by the use of natural ventilation.

Season	Time	Setpoint
	0 – 9 h	21 ºC
1 September – 31 May	9 – 18 h	17º C
	18 - 24 h	21º C
1 June – 30 August	0 – 24 h	None

Table 10: Heating setpoints for rooms

Season	Time	Setpoint
1 September – 31 May	0 – 24 h	18 ºC
1 June – 30 August	0 – 24 h	None

Table 11: Heating setpoints for corridor

5.7. *Domestic hot water analysis*

According to literature [85], average consumption per guest in a four-star hotel can be estimated at 80 litres per day. At an average occupancy of 70%, and adding the water used by the offices, whose occupancy is estimated at six people at a rate of 15 litres per day per person and considering the water is heated from an average of 10ºC up to 70ºC, this represents an energy use of 145 kWh per day.

In order to estimate the losses from the tanks, the heat flow to the ambient was estimated using heat transfer analysis in steady state. The two main heat transfer mechanisms present in this particular case are convection and radiation, as conductive heat flow from the tank surface to the surrounding air is considered negligible.

Heat losses due to natural convection were estimated by calculating the Nusselt *(Nu)*, Prandtl *(Pr)* and Grashof *(Gr)* numbers for the system conditions using Equations 3-6. Hot water tanks are simplified as cylinders of 1.4 m in length and 0.7 m in diameter, with a surface temperature of 55ºC and an ambient temperature of 20ºC.

$$Nu = 0.53\ (Gr\ Pr)^{0.25} \ \text{ for } 10^3 < Gr\ Pr < 10^9 \tag{3}$$

$$Gr = \frac{g\ \beta\ (T_s - T_\infty) d^3}{\mu^2} \qquad Pr = \frac{c_p \mu}{k} \qquad Nu = \frac{h\ d}{k} \tag{4-6}$$

Where g is the gravity constant (m/s^2), β the coefficient of cubical expansion (1/K), T_s and T_∞ the temperatures (K) of the surface and the fluid, d the cylinder diameter (m), μ the dynamic viscosity (kg/m s), c_p the specific heat capacity (J/kg K) and k the thermal conductivity of the fluid (W/m K).

Once h, the convection heat transfer coefficient (W/m^2 K) is calculated, the total U-value can be obtained through Equation 7, where r_1 and r_2 correspond to the inner and outer radius of the cylinder, h_1 and h_2 are the convection heat transfer coefficients for the inner and outer surface and k the thermal conductivity of the cylinder. The heat flow can be calculated by multiplying the U-value by the surface area, resulting in a loss of 386 W per tank.

$$\frac{1}{U} = \frac{r_2}{r_1 h_1} + \frac{r_2}{k} ln \frac{r_2}{r_1} + \frac{1}{h_2} \tag{7}$$

Heat flow through radiation heat transfer mechanisms were calculated by the Stefan-Boltzmann law for radiation simplified for a small object in a large enclosure (Equation 8), with the same tank and wall temperatures. Emissivity was estimated at that of stainless steel, resulting in a heat loss of 440 W per tank:

$$Q = \sigma\ A_1\ \varepsilon_1\ (T_1^4 - T_2^4) \tag{8}$$

Where σ is the Stefan-Boltzmann constant (W/ m^2 K^4), A_1 the outside area of the tank (m^2), ε_1 the emissivity of the surface and T_1 and T_2 the temperatures (K) of the tank and room surfaces respectively.

Combined heat losses from the tanks due to convection and radiation can then be estimated at 826 W or 119 kWh per day. The remaining losses, 78 kWh per day, were attributed to piping. These values are in accordance with studies in the literature that suggest that thermal losses can reach 21-40% of the total energy used to heat water [86]. The combined results can be observed in Figure 47.

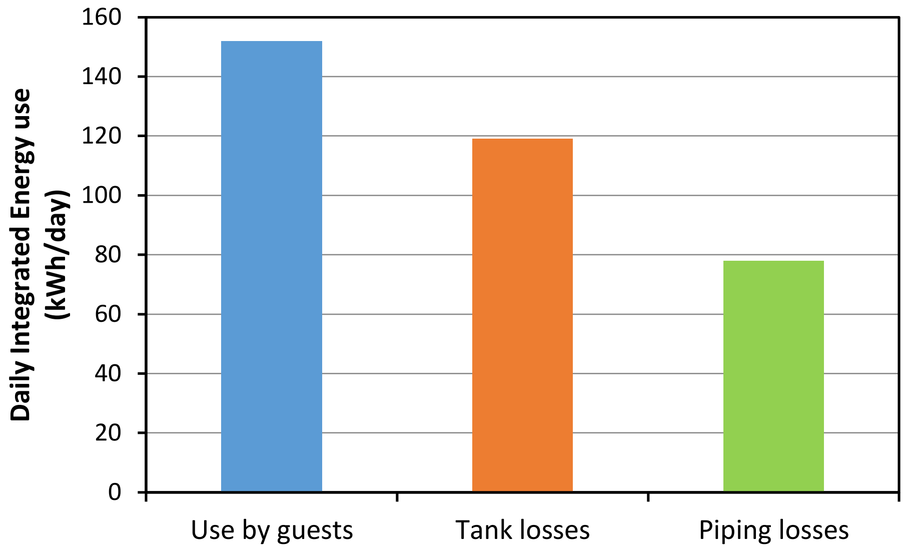


Figure 47: Daily integrated energy use for hot water classified by final use.

As expected, a significant amount of the electricity consumption is being used to heat the building's fabric or being dissipated into the ambient through the roof, hence explaining the lower values than the benchmarks in space heating consumption. When analysing the combined figure for energy consumption for space heating and hot water, the hotel registers 148 kWh/m^2/year, 37% lower than the benchmark.

5.8. Baseline simulation

In order to validate the model's baseline conditions, a first simulation was run. Two possible module positions were tested:

1. Mid-corridor, with one exposed façade.
2. End-corridor, with two exposed façades.

The first resulted in a heating load of 55 kWh/m^2/year and the second yielded 72 kWh/m^2/year. A weighted average was taken to represent the actual proportion of five mid-corridor modules to one end-of-corridor in the building, resulting in 58 kWh/m^2/year.

Some adjustments need to be made to this value before comparisons with the measured data can be carried out. The first one will be the occupancy level in the rooms, as the simulation was run assuming full occupancy. Based on data provided by Visit Britain, the average occupancy for hotels for 2016 was 70%, and 64% during the heating season [91], which also agrees with the information provided by the hotel. According to recent research [92], the correlation factor between occupancy and electricity consumption in a commercial building is 0.74, with specific correlation factors for HVAC of 0.54. These values is also consistent with the study carried out by Taylor et al. on hotels [2] so 0.54 will be adopted as the correlation coefficient to calculate the estimated load at average occupancy, resulting in 47 kWh/m^2/year.

The second adjustment factor accounted for climatic variations between the period which includes the measured data (2016/2017) and the climate file used for the model. For the measured period, there were 1,958 degree days compared to an average of 2,299 in the climate file. Heating degree days are considered to be proportional to the heating load [93], so the corrected modelled heating load for 2016/2017 was calculated to be 40 kWh/m^2/year. The adjusted model's baseline heating load is considered to be in good accordance with the measured values of 37 kWh/m^2/year, with a difference of 8%. Figure 48 provides a sum-up of the obtained results.

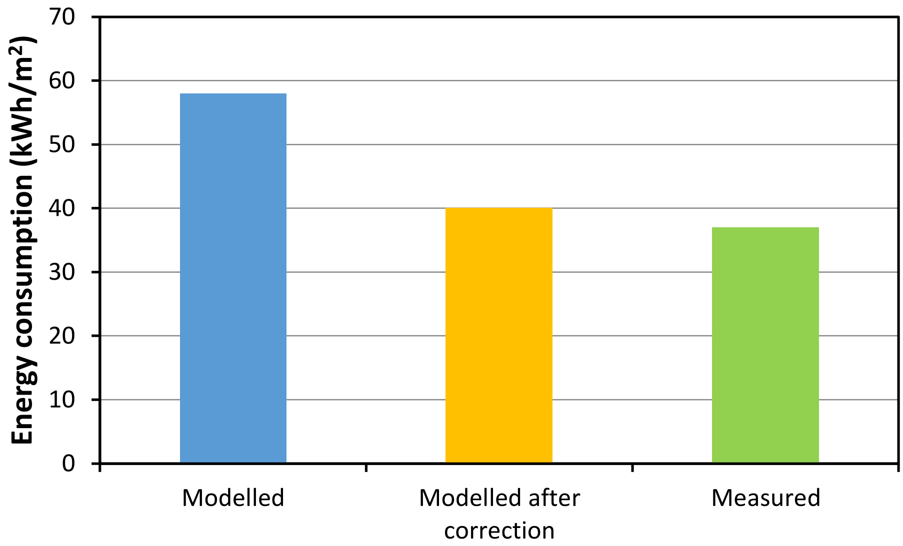


Figure 48: Energy consumption for space heating – modelled and measured

Next, the building's behaviour regarding indoor temperatures and heating loads during typical weeks for winter and summer was observed. The results for zones temperatures for these two seasons are shown in Figures 49 and 50, the winter heating loads in Figure 51.

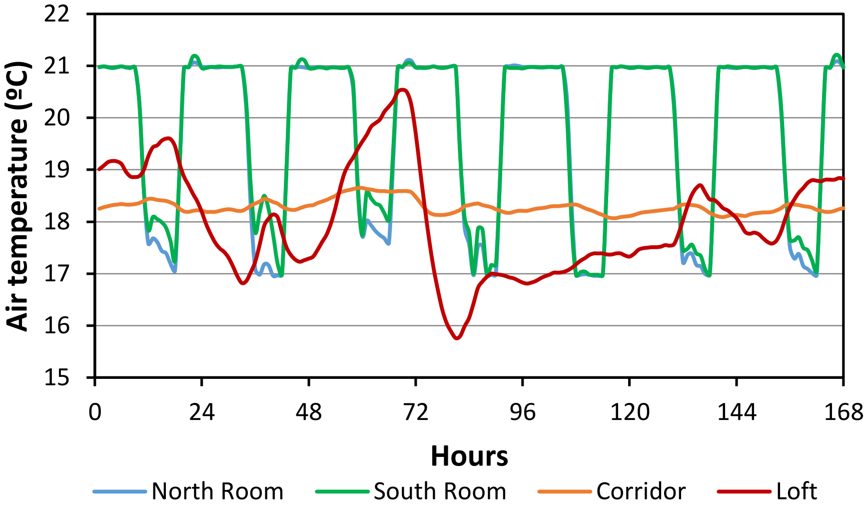


Figure 49: Dry-bulb air temperatures during a typical winter week: baseline simulation

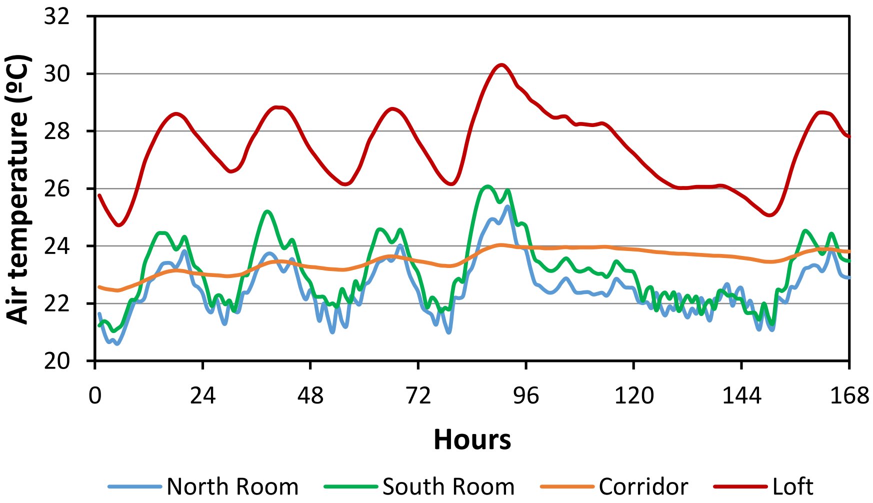


Figure 50: Dry-bulb air temperatures during a typical summer week: baseline simulation

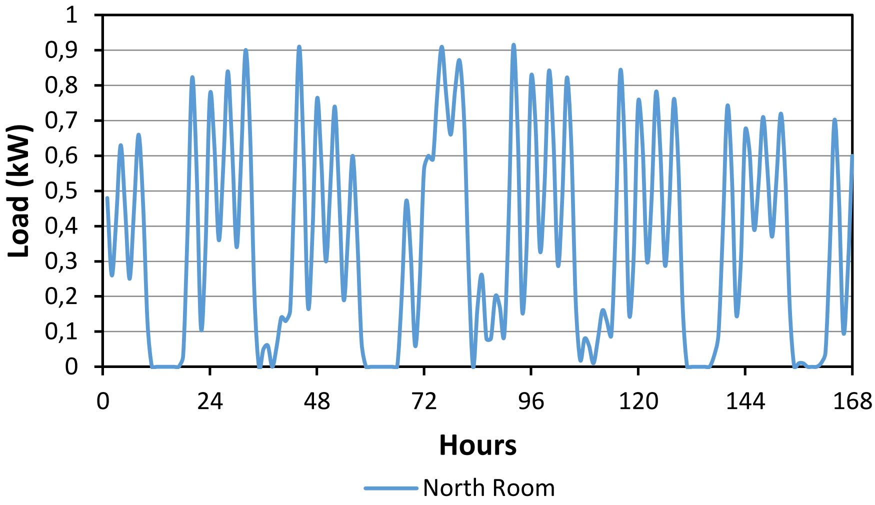


Figure 51: Heating load during a typical winter week: baseline simulation

During winter, the temperature inside both North and South facing rooms is similar, driven mainly by the heating system setpoints, ensuring adequate average comfort levels of -0.4 in the Predicted Mean Vote (PMV) scale. The temperature in the loft space shows a higher variation due to the differences in solar radiation entering through the roof and the heat losses varying with the outside air temperature. The temperature in the corridor remains constant at around 18ºC. Peak heating loads for typical days are between 0.7 and 0.9 kW.

In the summer simulation, the South-oriented rooms show a higher temperature throughout the day as it would be expected due to the higher solar gain, although it does not exceed 26ºC on a typical week, maintaining adequate comfort levels. Opening windows to increase ventilation allows the occupants to decrease the room temperature. The loft space, heated by the solar radiation and the tanks' casual gains, stays warmer than the rest of the building at an average of 28ºC, which could be confirmed during the field visit.

6. Implementation of a fabric upgrade

6.1. Introduction

Of the numerous interventions that can be applied to reduce energy consumption in the hospitality sector, a screening of promising strategies was carried out to point out the most promising upgrade strategies. In this section, different upgrades related to the building's fabric will be modelled and assessed, including wall insulation, triple glazing and loft insulation, and its results compared.

6.2. Methodology

The first intervention proposed was to increase the external wall insulation to decrease the heat loss through the building's fabric. This can be done by adding a supplementary layer of insulation on the outside, although this could mean a change in the site's character and atmosphere. The project could also encounter resistance from the management or from the local planning authority. A more plausible alternative would be the filling of the cavity wall with rigid phenolic thermoset insulation board, which has a typical U-value of 0.018 W/m^2 K, and would be invisible to the public.

As there is no accurate information about the thickness of the air gap which would allow the installation of the additional insulation board, simulations were run considering the addition of a 30-mm and 60-mm insulation layer to the cavity wall, which set the U-value of the wall to 0.30 W/m^2 K and 0.20 W/m^2 K respectively. The second intervention was a change in the existing windows to an argon-filled triple glazing (U=0.9 W/m^{2}K) in a PVC frame (U=1.0 W/m^{2}K). The third upgrade was an improvement on the insulation in the loft space, replacing the original 80 mm layer of glass wool with 300 mm insulation, in line with the current building standards. This would set the U-value of the roof at 0.13 W/m^2 K. All the heating loads resulting from the simulations were then corrected to the average occupancy rates of 70% using a correlation factor of 0.52.

As a consequence of the insulation and windows upgrade, a lower infiltration rate is to be expected as well. Data related to decrease in air infiltration after fabric interventions are scarce, especially for non-domestic buildings such as hotels [2]. However, lower infiltration would have to be compensated by higher ventilation to provide the needed fresh air to the occupants, so the combined rate of fresh air intake into the building was estimated to be constant at one air change per hour, increasing to two if the indoor temperature exceeded

22ºC. A batch of simulations was run to observe the effects of the mentioned upgrades in the building's heating load

6.3. *Results*

A decrease in energy consumption for space heating of 45% was observed after all the upgrades are implemented, reducing the annual heat demand to 26 kWh/m^2. This level represents similar values to the maximum specific heat demand required in the EnerPHit standard (25 kWh/m^2). Loft insulation is the greatest individual contributor to energy savings, producing a 22-24% reduction in consumption depending on the insulation level. Cavity wall insulation reduces heat loads by 19-21% when considered on its own, whereas triple-glazed windows and extra insulated frames account for a reduction of 10%. Given the high cost of triple glazing, it is likely that this solution's payback time will be much longer than the rest. The results of these upgrades in terms of energy and carbon dioxide emissions can be seen in Figures 52 and 53.

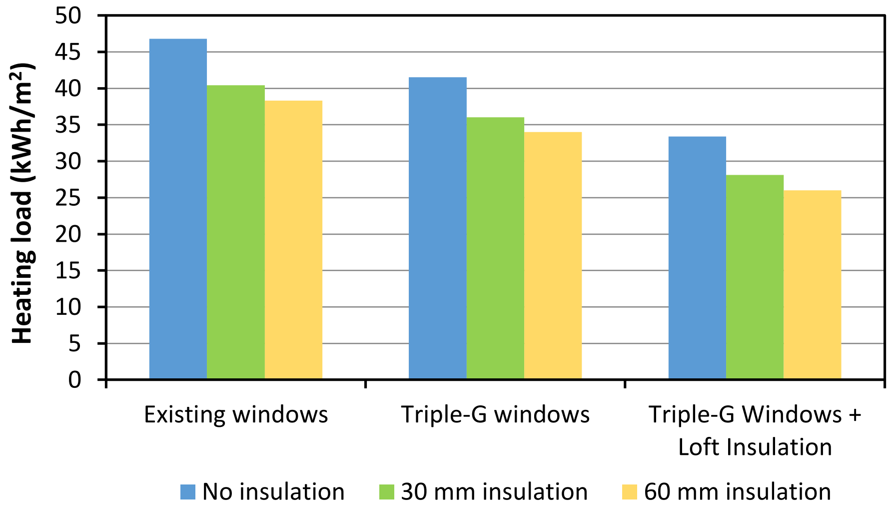


Figure 52: Change in electricity consumption for different upgrade strategies

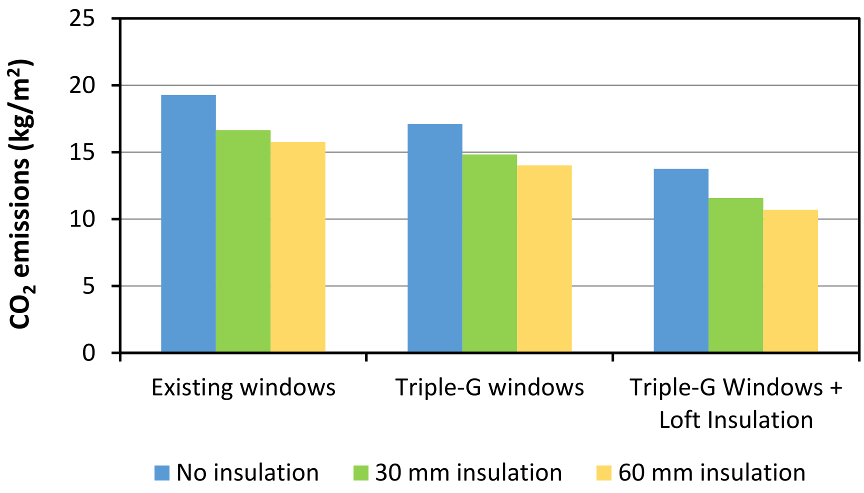


Figure 53: Change in carbon dioxide emissions for different upgrade strategies

As the hot water system remains without any change from its original form, an analysis of the combined savings for space heating and hot water yields savings of 13% in energy consumption and carbon emissions with the maximum proposed level of insulation. In this case, the combined use of hot water and space heating represents 137 kWh/m^2. Therefore, even after the proposed fabric upgrade, the building would not qualify for an EnerPHit certification: its primary energy demand exceeds by far the annual target of 132 kWh/m^2 after the conversion efficiencies for primary energy are factored in.

From an operational perspective, the temperatures in the rooms for a typical winter week do not change significantly after the intervention and are still mostly defined by the setpoints in the heating system, although the temperatures when the rooms are unoccupied have increased by an average of 1.5ºC. The temperature in the loft space has also increased 5ºC as a result of the improvement in the loft insulation as it can be seen in Figure 54. Figure 55 shows that the heating loads have been significantly reduced after the intervention.

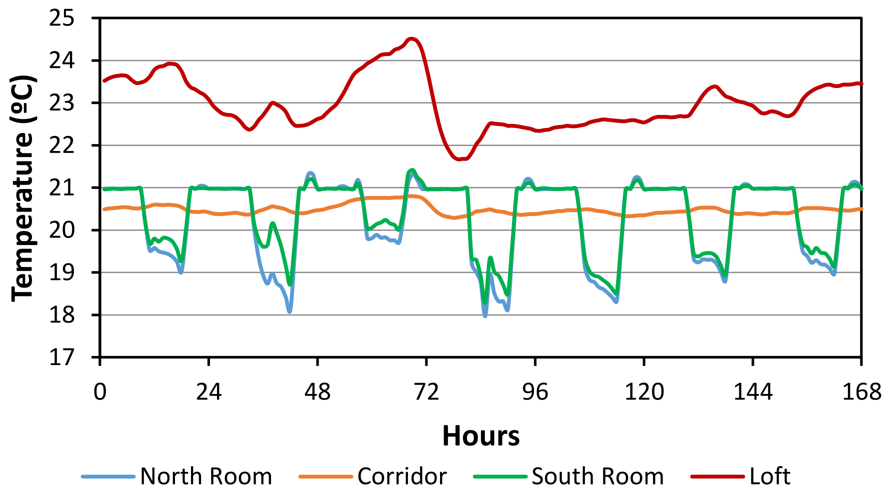


Figure 54: Temperatures during a typical winter week: upgraded fabric simulation

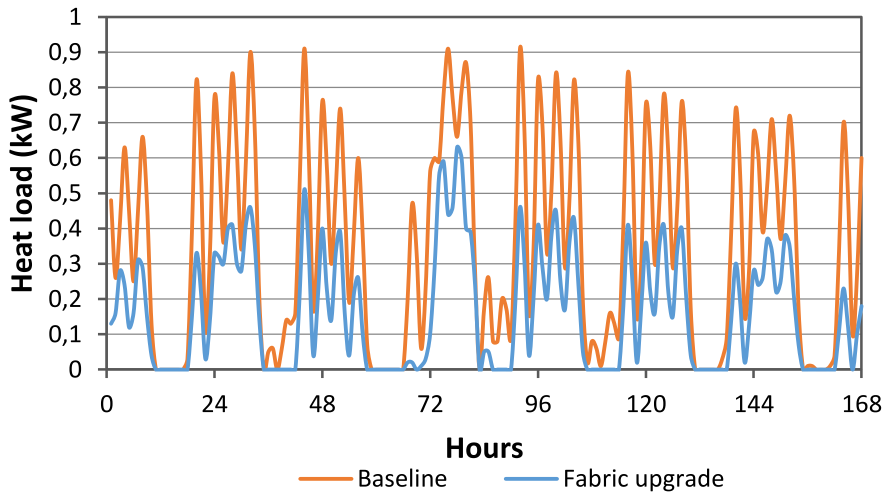


Figure 55: Heating loads during a typical winter week: upgraded fabric simulation

In order to study possible overheating issues, a simulation was conducted for a warm summer week with high solar radiation and higher-than-average temperatures. The results, which can be observed in Figure 56, show that the temperature inside the building can reach 31ºC in the South-facing rooms, which would be clearly above the optimum for the occupants' comfort levels. As a result of the reduction of heat loss through the building's fabric, a higher proportion of the heat released by the hot water tanks in the loft is now trapped inside the building, heating the rooms below them, which are not sufficiently cooled down by natural ventilation.

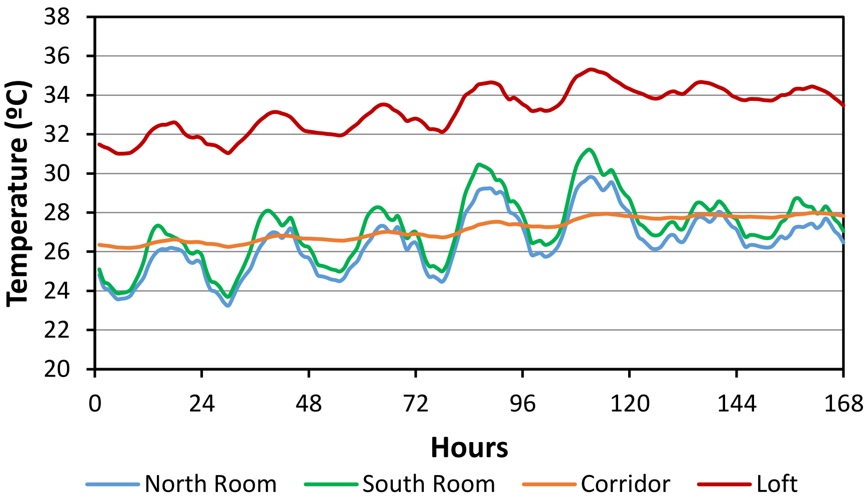


Figure 56: Temperatures during a especially warm summer week after intervention

At this point, completing a life-cycle cost assessment of the different proposed elements in the upgrade strategies would be helpful to allow the building's stakeholders to quantify the impact on the environment of each of the retrofit options. Specifically, the choice of materials used can significantly influence the eco-efficiency of the interventions, not just in terms of greenhouse gas emissions but also in other impacts such as ozone depletion, land acidification and freshwater or marine eutrophication. This type of study is, however, out of the scope of the present work.

6.4. Conclusions

The proposed fabric upgrade strategy brings clear consumption reduction benefits of the space heating demand, of up to 45%, being the loft insulation the main contributor to the savings, followed by the cavity wall insulation and the triple glazed windows. On the other hand, the savings are much more modest when both space heating and hot water demands are assessed together, yielding reductions in energy consumption of just 13%.

Performing insulation upgrades without any action on the hot water system can cause overheating problems during the warmest period of the year due to the heat gains from the uninsulated water tanks in the loft space. If this strategy is implemented at the same time that the domestic hot water system is upgraded, these issues can be minimised.

7. Insulation of the hot water tanks and pipes

7.1. Introduction

A preliminary analysis of the building's consumption shows that a great proportion of the energy used to heat the water for the guests' use is being dissipated through uninsulated hot water tanks and pipes. Part of this heat is lost through the building's fabric, but another part is absorbed by it, thus reducing the use of the space heating system. Any change that will reduce energy losses in the domestic hot water system will then necessarily influence the performance of the heating system. This section analyses the impact of insulation of the hot water tanks in a jacket and the improvement of the pipes' insulation on the overall performance of the building.

7.2. Methodology

The tank losses were estimated using steady-state equations similar to those used in Section 5.7, adding a layer to the cylinder in order to represent the insulation. This is assumed to be 80 mm thick and to have a thermal conductivity value of 0.04 W/m K. With the recalculated Gr, Pr and Nu numbers, the new overall heat transfer coefficient U can be obtained, and hence the new heat loss, which is estimated at 180 W per tank or 22% of the original.

The assessment of energy loss reduction from the improvement of the pipe insulation is particularly challenging. As suggested by literature for domestic buildings, adding insulation to uninsulated metal piping can reduce thermal losses by 24-35% [94]. However, in this case study the hot water pipes are already partially insulated, so a value of 15% reduction was chosen, representing half of the total possible saving from the totally uninsulated case. Simulations were then run with the calculated reduced heat gain value in the loft space.

7.3. Results

When the tanks are insulated, a significant decrease in energy demand for hot water and a simultaneous increase for space heating purposes can be observed. In the case of the original fabric, the hot water consumption decreases by 33 kWh/m^2. Simultaneously, the space heating system registers an increase in demand of 25 kWh/m^2. The simulation shows that approximately three quarters of the original amount of energy lost by the hot water tanks was being used to reduce the heating load. This fact can be explained through the relatively high

U-value of the surface connecting the loft space to the bedroom floors (1.3 W/m^2 K) compared to the roof (0.4 W/m^2 K), which drives most of the released heat towards the rest of the building.

This strategy shows combined savings of 5% in terms of electricity use and carbon dioxide emissions for space heating and hot water. The results can be observed in Figure 57.

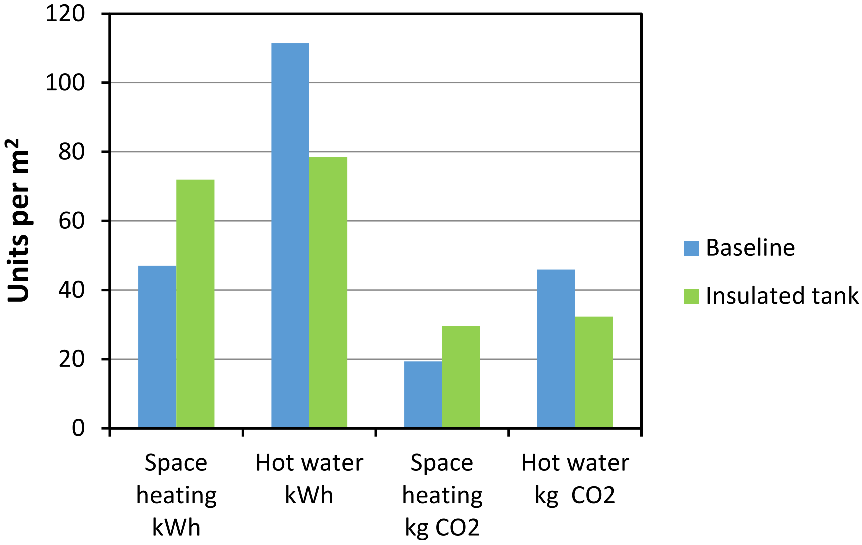


Figure 57: Energy use and CO_2 emissions with insulated tanks and the original fabric

When the simulation is conducted combining this strategy with a fabric upgrade, savings of 20% in energy consumption and emissions can be achieved, as shown in Figure 58.

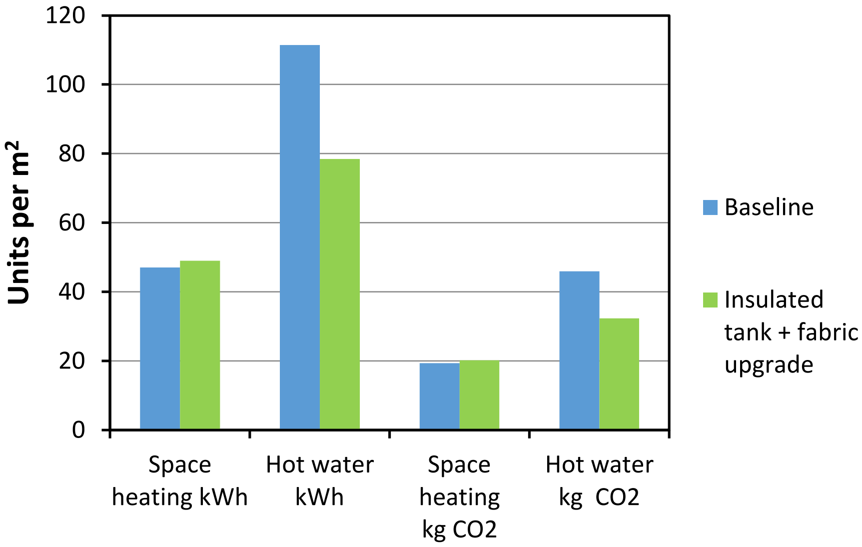


Figure 58: Energy use and CO_2 emissions with insulated tanks and the new fabric

However, it is possible that the model underestimates the real heat losses through the roof, due to the fact that it considers the insulation to be perfectly installed. In real-life circumstances, the insulation material may have gaps due to poor installation or wear and tear, which can result in a higher U-value than the intended, increasing the heat loss to the exterior. The infiltration rate through the roof, which is estimated at 0.5 ACH in the model, is another uncertainty that could alter the result: an increased leakage of outside air to the loft space would significantly increase the heat loss. Both of these factors would reduce the proportion of the heat gain due to the hot water tanks that is retained by the building, therefore increasing the effectiveness of this intervention.

7.4. Conclusions

The strategy of tank insulation can deliver significant energy consumption reductions to the hot water system, up to 30%. However, the benefits of this strategy are compensated by increases in the space heating demand, resulting in an equivalent saving of only 5% if space heating and hot water demands are analysed together. When implemented with a fabric upgrade, the combined savings can reach 20% of the original value. However, as heat losses through the roof may be underestimated by the model, the savings in energy consumption may be higher than those predicted.

8. Implementation of a new gas boiler

8.1. Introduction

Although electric heaters are 100% efficient, the mix of technologies used to produce that electricity and their conversion efficiencies greatly influence the sustainability of the unit of heat delivered. For the UK generation mix in 2016, this means that every kWh of electricity consumed generates 412 g of CO_2, whereas the same amount of energy being provided by gas the figure is 184 g. This section analyses the replacement of the existing electric space and water heating systems by a gas boiler.

8.2. Methodology

Similarly to Section 7, simulations were run, both with the original and renovated building fabrics, eliminating the heat gain from the hot water tanks and recording the new space heating demand. In order to estimate it the total energy consumption, a 90% seasonal efficiency was assumed for the new system, above the requirement of Part L in the Building Regulations for new natural gas boilers to be installed in existing buildings, which is set at 84% [95]. Regarding hot water consumption, it was assumed that the amount used by guests remains constant, while piping heat losses are reduced to 25% of the total through the installation of state-of-the-art insulated pipes [86].

8.3. Results

When the uninsulated tanks are replaced by the new system, a similar effect to the one found in Section 7 can be observed: there is a significant increase in the demand for space heating for the bedrooms and a simultaneous decrease in the demand for hot water. The total energy demand decreases by 8% compared to the baseline, but the actual energy consumption of the building increases by 3% as the efficiency of the gas system is factored in. The CO_2 emissions decrease significantly by 54% due to the lower carbon content of the fuel. The modelled space heating demand increases from 47 to 81 kWh/m^2 with the original building fabric. Figure 59 shows the results of the simulations

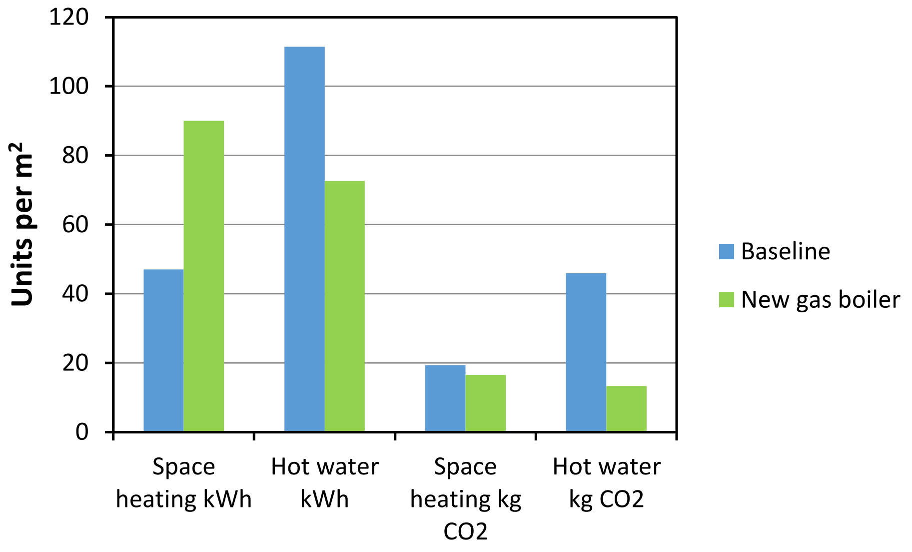


Figure 59: Energy use and CO_2 emissions with a new gas system and the original fabric.

If the heating system is combined with an upgrade in the building's fabric, a decrease of 13% in the total energy consumption could be expected compared to the baseline, with associated emissions reduction of 61%. The results for this part of the analysis can be seen in Figure 60.

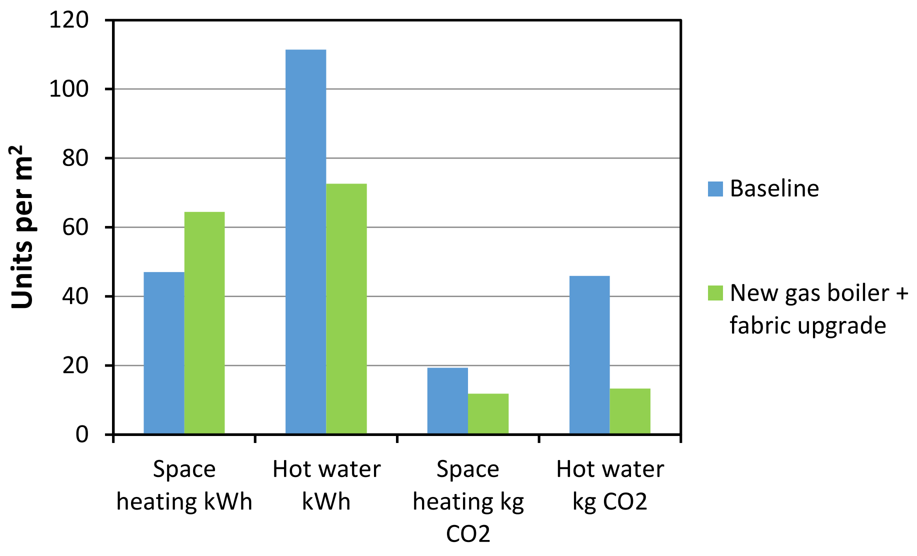


Figure 60: Energy use and CO_2 emissions with a new gas system and the upgraded fabric.

From an operational point of view, the newly insulated building with the gas-fired system would also have more adequate comfort levels in summer time, avoiding the overheating issues detected in Section 7. As it can be seen in Figure 61, the temperature on the hottest day of the year would be below 25ºC at 23h.

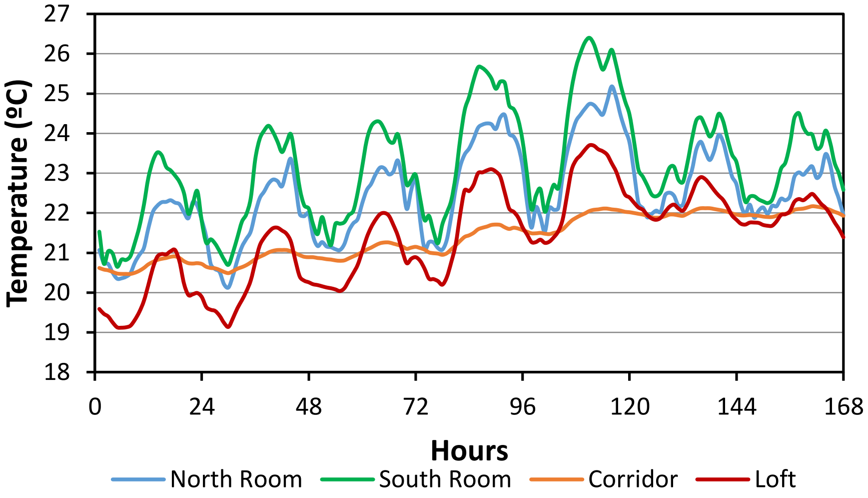


Figure 61: Summer temperature simulation with new gas-fired hot water system

8.4. Conclusions

The implementation of a new gas boiler shows a clear decrease in energy demand for hot water use. At the same time, an increase in demand in the space heating system is recorded with the original fabric, due to the elimination of the heat gains produced by the uninsulated hot water tanks. Although the total energy consumption increases by 3%, there are significant CO_2 savings to be expected from this strategy: it can yield emissions reductions of 54%. It is also expected that the cost per unit of energy for gas will be significantly lower than for electricity, producing also financial benefits in its operational phase. If combined with a fabric upgrade, the carbon dioxide savings could reach 61%.

9. Implementation of an air-to-air heat pump and a new gas boiler

9.1. Introduction

Heat pumps can be an efficient, low-carbon source of heat, especially if the electricity to run them can be provided by renewable, low-carbon technologies. As the national network continues phasing out carbon-intensive facilities such as coal-fired power plants in favour of more carbon-benign sources, the environmental advantages of heat pumps will only increase.

An analysis was carried out by to observe the impact of replacing the hotel's current electric space heating system by an air-to-air heat pump. As it would not logical to keep the inefficient, heat-dissipating uninsulated tanks in the roof space, it is assumed that domestic hot water would be supplied by a new gas-fired system, analogous to the one previously described in Section 8.

9.2. Methodology

The total heat demand was calculated in a similar way as in Section 8. As the coefficient of performance of heat pumps, and thus the electricity consumption, varies with the source temperature –outside air in this case- a series of data with includes the heating load and outside air temperature for every hour of the year was obtained by means of a simulation.

As a case study, the Daikin air-to-air VRVIII inverter heat pump was chosen, with a RXYQ-P9 outdoor unit with 25kW nominal heating power. For an indoor air supply temperature of 20ºC, the COP values for different operating temperatures between -10 and +15ºC were obtained from the manufacturer's technical specifications [96]. A linear regression was subsequently applied to the data as per Figure 62, in order to transform the discrete data to a continuous function and thus enabling the calculation of the COP for any source temperature.

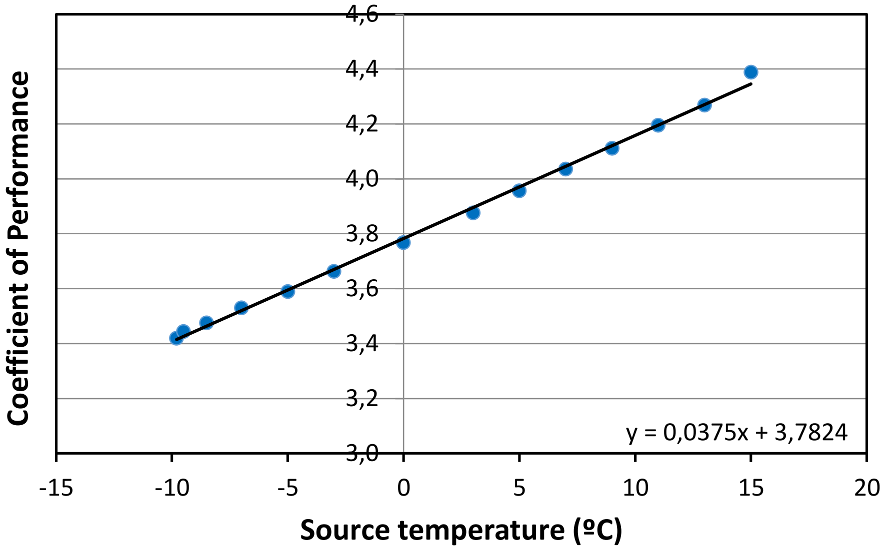


Figure 62: Air-to-air heat pump COP as a function of source temperature [96].

Using the outdoor air temperatures from the climate file in the model, the COP for every hour of the year was calculated. Next, the hourly heat pump loads were calculated by dividing the hourly space heating loads by the previously calculated COP. Finally, the result was added up and adjusted for occupancy. The data from the hot water system were estimated in an analogous way to Section 8.

9.3. Results

The simulations show that the peak load needed to cover the demand for space heating for the two bedroom floors with the studied air-to-air heat pump is 27 kW, calculated assuming full occupancy. After the implementation of the new system, the electricity use for space heating decreases by 57%. The heat pump's average COP of 3.95 is responsible for this reduction, although the heating load actually increases when the hot water tanks are replaced. The CO_2 emissions decrease in the same proportion as the fuel displaced is grid electricity. When considering the space heating and hot water combined, the reduction in consumption is 41% and 67% less CO_2 emissions. The results can be observed in Figure 63.

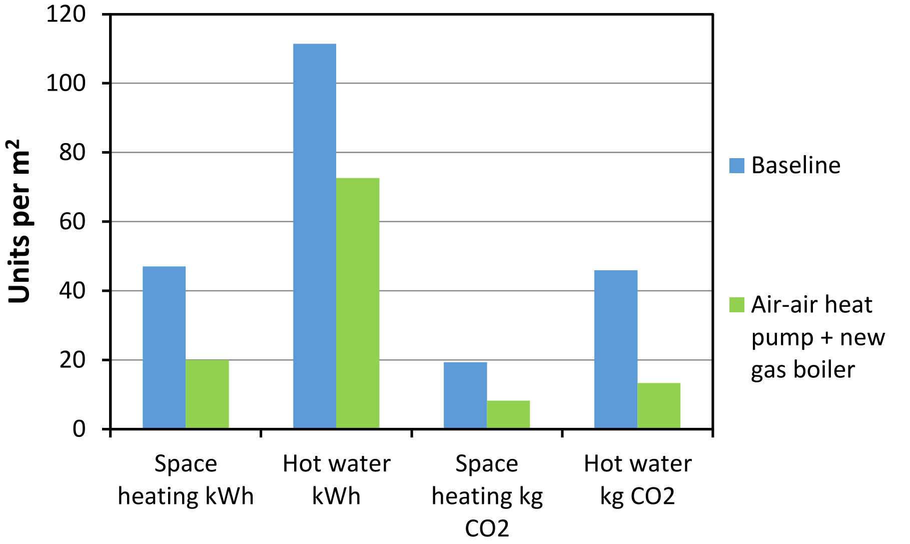


Figure 63: Energy use and CO_2 emissions for an air source heat pump with original fabric

In the case of the installation with the fabric upgrades described in Section 6, the calculated peak load was 21 kW. The electricity used for space heating decreases by 69%. The heat pump COP remains at 3.95, a similar level to the previous case. A joint analysis of space heating and hot water shows a reduction of 45% in energy consumption and a decrease of 70% in CO_2 emissions compared to the baseline. The results can be seen graphically in Figure 64.

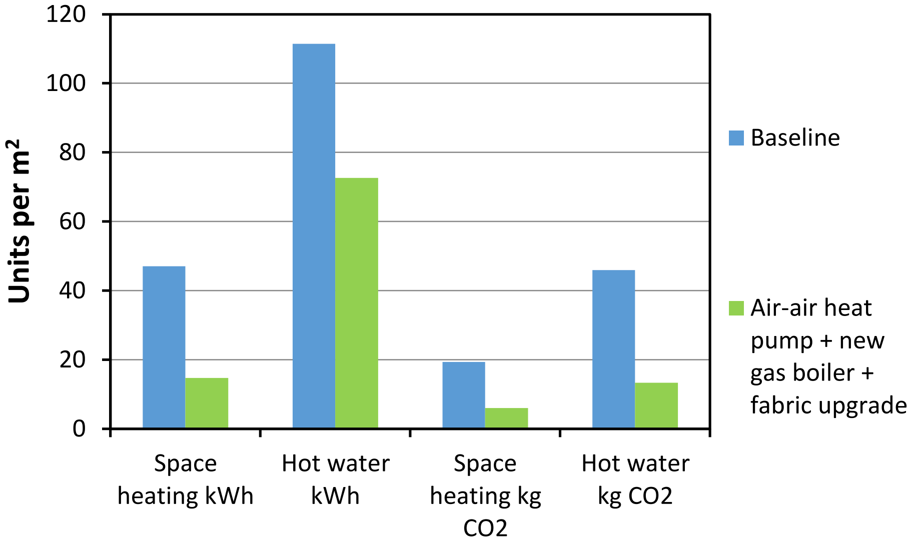


Figure 64: Energy use and CO_2 emissions for an air source heat pump with upgraded fabric

9.4. Conclusions

The implementation of an air source heat pump for space heating in combination with a new gas-fired domestic hot water system can decrease the energy used by the building by 41%, with a reduction in CO_2 emissions of 67%. The electricity consumption for space heating shows a reduction of 57% after the implementation of the heat pump. The heat load actually increases due to the elimination of the heat gains in the loft space due to the uninsulated tanks. If this strategy is combined with a building fabric upgrade, the reductions can increase to 45% in energy terms and 70% in emissions compared to the baseline.

10. Implementation of a water-to-water heat pump

10.1. Introduction

Although a solution like the one studied in Chapter 9 significantly reduces energy use and emissions to the atmosphere, it still relies on natural gas for the provision of domestic hot water. Therefore, the study of a system that provides both space heating and hot water by means of a heat pump, with no on-site emissions was the following natural step.

The source from where the heat will be extracted can be either air, water or the ground. In this case, a water source heat pump was chosen due to the fact that there is a reservoir near the property where this could be installed, from which water could be pumped to the heat exchanger before being discharged back to the water body with a difference in temperature of 3 to 4ºC. This is also a replicable solution for other hospitality facilities as many other hotels are situated near water bodies: rivers, lakes or the sea.

Water-source heat pump technology has been successfully installed in places such as the World Heritage Site of New Lanark in Scotland, where a 90 kW machine provides the space heating and hot water needs for visitor attraction and an event facility, extracting the heat from the tail race of a local hydro power plant. On a greater scale, heat pumps are currently in use in district heating schemes such as Drammen in Norway (14 MW), using the water from the fjord as a heat source.

10.2. Methodology

For this case study, the DAIKIN WRA 180 system was used, which is a 44kW water-to-water heat pump which can provide both heating and cooling. As the peak load for space heating and hot water for the two bedroom floors is 88 kW for the original fabric and 79 kW after the fabric upgrade, two such units would be needed. It was assumed that in this new system both the radiators and the hot water would be provided at a temperature of 54ºC.

The COP data for the chosen water output temperature and different source water temperatures was obtained from manufacturer's technical sheet [97] and a linear regression was applied to convert the discrete data into a continuous function as in Figure 65.

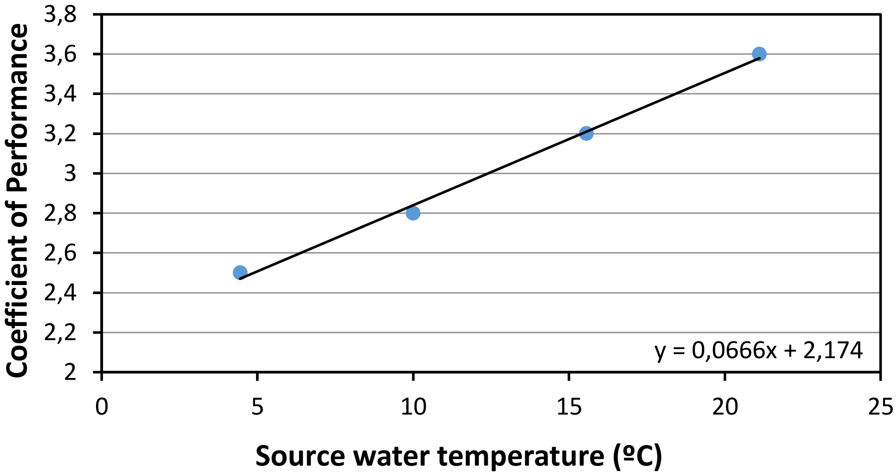


Figure 65: Water to water heat pump COP as a function of water temperature [97].

As the COP is heavily dependent on the temperature of the water body that acts as a heat source, an investigation was carried out to determine the yearly profile of the water temperature in the reservoir. No data were available for this specific location, so data from Llyn Padarn (North Wales) from a period from 2012 to 2015 were used. The temperatures throughout the year, which can be seen in Figure 66, are measured at a depth of one metre.

It is worth noting that before such a strategy is implemented, on-site actual measurements would be necessary to determine if the water body's temperature profile is any different from the suggested one, as well as an estimation of its depth and total volume. This would be needed not only to study the influence on the heat pump's performance but also to assess the possibility of the reservoir water freezing during the winter time.

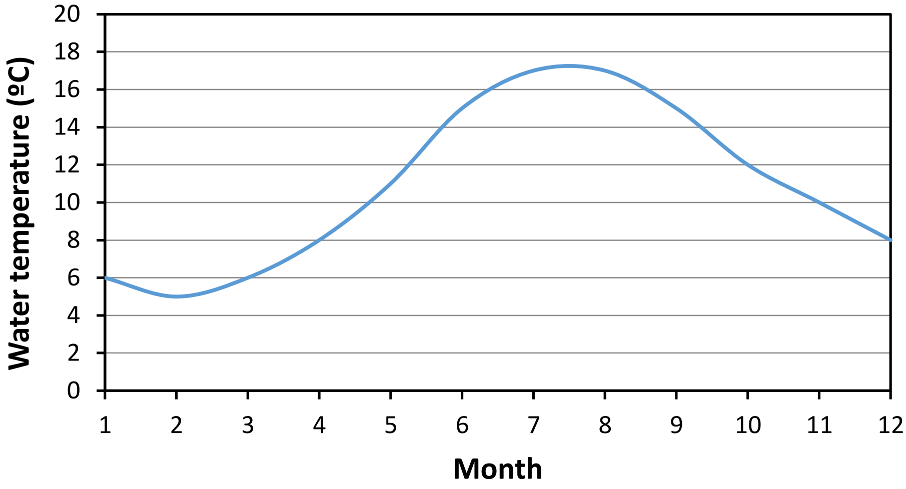


Figure 66: Llyn Padarn average water temperature 2012-2015 [98].

The first step of the methodology was the calculation of the heating loads, which was conducted in an analogous way to Chapter 9. The approach to estimate the hot water demand consists of two steps: the first is to estimate an average daily consumption, which is dependent on the room occupancy. This was calculated in Section 4.3 resulting in 207 kWh per day when the hotel is full and 145 kWh per day at average occupancy. Losses in the system are estimated in an analogous way to Section 8 at 25% of the total. The following step was to create a daily profile. In order to do this, a hot water demand profile from Rankin and Rousseau [99] was adapted as per Figure 67, which shows a typical distribution of hot water consumption by guests in a hotel.

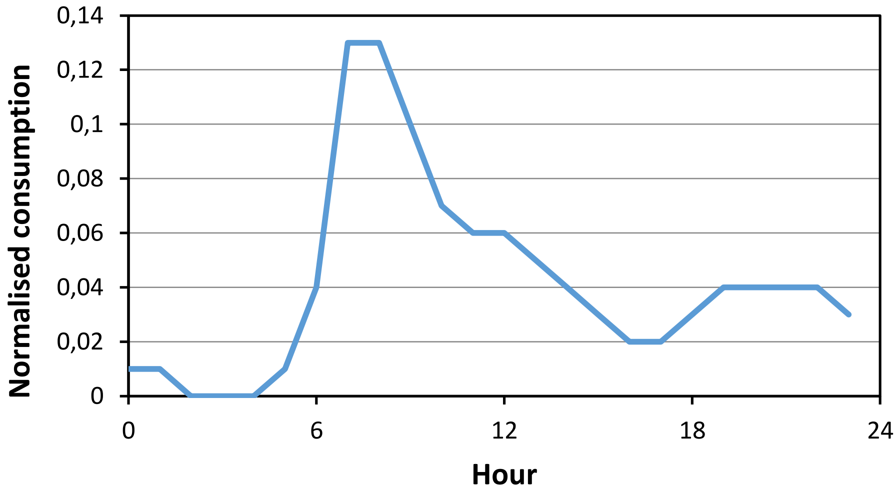


Figure 67: Typical hot water demand profile in a hotel. Adapted from [99].

The load due to domestic hot water for every hour of the year can be then calculated multiplying the average consumption per day by the normalised consumption. As the inlet temperature of the water mains does not remain constant throughout the year, an additional factor correcting the difference in expected consumption for each month relative to the yearly average was introduced. It was assumed that the temperature of the inlet water is the same as the temperature measured in the lake.

Then, the expected COP of the heat pump was calculated for every hour of the year using the regressions mentioned before. It is worth mentioning that this is a simplified method, as it assumes steady state conditions, which are rarely the case in real operation. The performance of the system will also vary with other parameters such as the load on the heat pump, return temperature from the radiators and hot water tanks and the temperature at which the heat is delivered. The control algorithms which decide the switching on and off of the system also will play an important part in the system's performance.

As a next step, the electric loads for space heating and hot water were calculated and corrected for the average occupancy. Finally, the CO_2 emissions were assessed using the habitual conversion factors.

10.3. Results

For the original building fabric, the simulations conducted show that the strategy of implementing a water source heat pump to supply both hot water and space heating can reduce the hotel's electricity consumption and CO_2 emissions by 68%. The average calculated COP was 2.7. The results can be observed in Figure 68.

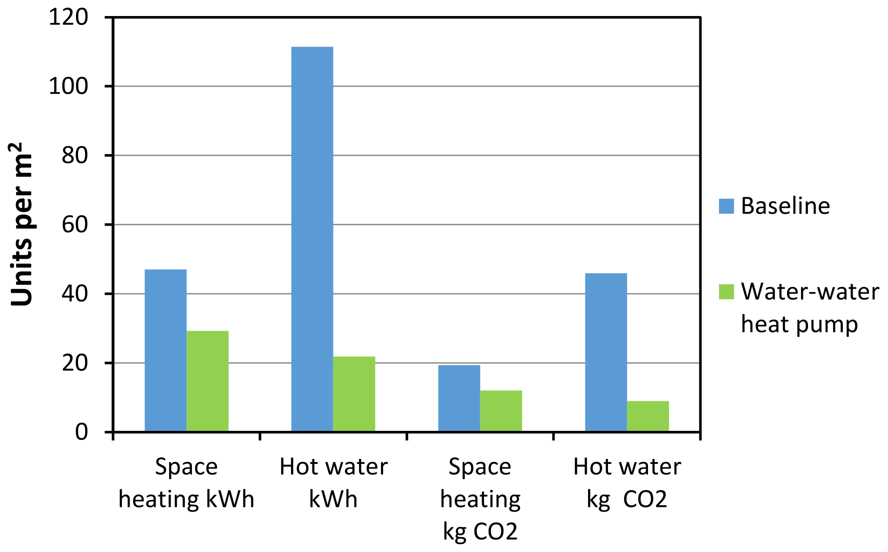


Figure 68: Energy use and CO_2 emissions with a water-to-water heat pump with original fabric

For the upgraded fabric, the reduction in energy use and emissions reaches 73%, with an average heat pump COP of 2.8, marginally higher than in the previous case due to the reduced usage for space heating in winter when the water source is colder. Figure 69 shows the set of results.

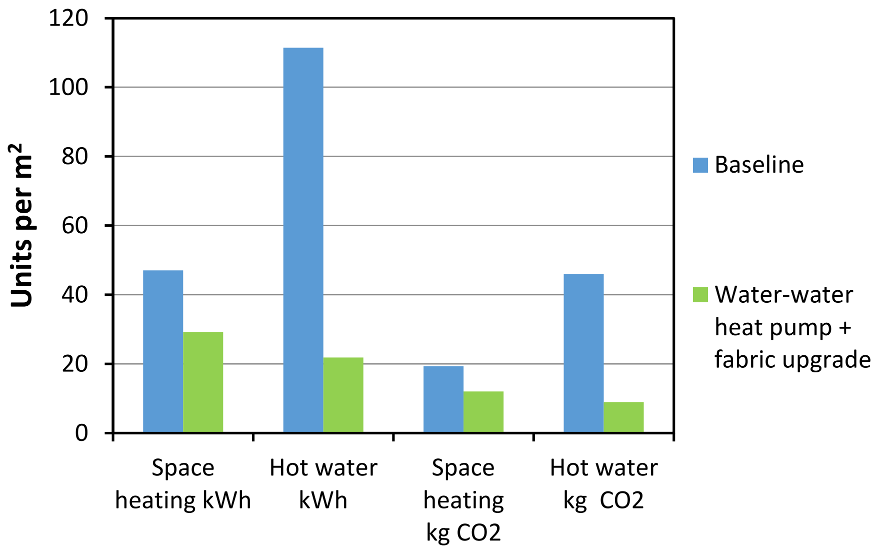


Figure 69: Energy use and CO_2 emissions with a water-to-water heat pump with upgraded fabric

An additional advantage of such type of systems is that they can also provide "free" cooling: the cold water outlet from the heat pump evaporator can be used, by means of a heat exchanger, to decrease the cooling load in other parts of the building, such as the conference centre or the refrigerators of the catering facilities.

The performance of this system in terms of CO_2 emissions could further be enhanced through the implementation of a thermal store. Taking advantage of the time of the day, normally during the night, when there is a higher production of renewable energy and/or lower grid use, the heat pump could work to produce heat that then could be stored in well insulated tanks, to be used when necessary during the day. The hotel could also benefit from a financial perspective if an electricity tariff that relates emissions to cost is developed. The efficiency of the heat pump could also be increased if the heat for space heating purposes could be delivered at a lower temperature, for example 35ºC, by the means of an underfloor heating system. The assessment of the influence of these two strategies is unfortunately out of the scope of this document and it is recommended for further work.

10.4. Conclusions

A water source heat pump is a viable solution to provide low-carbon heat for both space heating and hot water use, with no local emissions, producing up to 2.9 units of heat per unit of electricity used. The conducted simulations show that such a system could provide savings of 68% from the baseline in both energy consumption and emissions, growing up to 73% if combined with a fabric upgrade. The environmental benefit of water source heat pumps is maximised in a situation with a low-carbon electricity grid, where the generation mix is composed mostly of renewable sources. A thermal store can be used to further enhance renewable electricity usage.

11. Summary of findings: strategy comparison

11.1. *Results with current grid*

The different proposed strategies yield various results in terms of energy and carbon savings. In order to allow a more convenient comparison, a value of 100 was assigned to the energy use and emissions for the baseline scenario, before any of the interventions takes place. The values for the rest of the strategies were calculated as a percentage of this reference and can be observed in Figure 70.

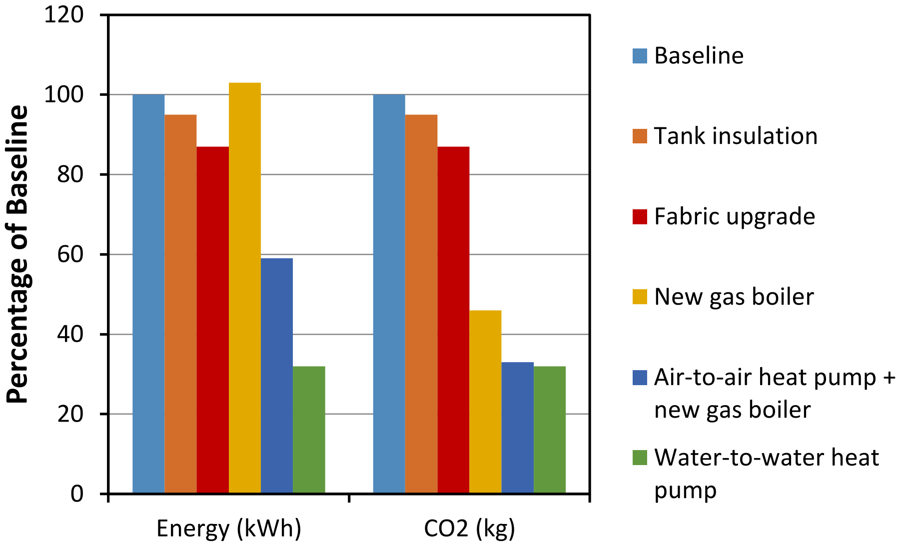


Figure 70: Energy and carbon comparison for different efficiency strategies: current electricity mix

It can be observed that the interventions which yield a higher decrease in energy use and emissions are the water-to-water heat pump and the combination of an air-to-air heat pump with a gas boiler. A new gas boiler for space heating would be the following best strategy in reducing carbon emissions. Although the actual energy use would increase, the lower price of natural gas compared to electricity, estimated at one fourth of the latter for the United Kingdom, would also see significant cost savings. A fabric upgrade without acting on the hot water systems would produce limited savings, whereas a tank insulation would yield more limited consumption reduction. However, as the cost of the intervention is considered to be economic, payback times will be predictably short.

11.2. *Results with future low-carbon grid*

The previous analyses have been carried out with the last officially published values for carbon dioxide emission factors for grid electricity published by the UK government (2016). However, any energy efficiency upgrade is forecast to last for several years in the future, when the electricity mix may be different. As the share of renewable generation grows and coal power plants are phased out, the emission factor is forecast to be lower than the current one in years to come.

A sensitivity analysis on the results was prepared, based on a future with a significant higher amount of low-carbon generation, resulting in an emission factor for grid electricity of 200 g CO_2/kWh. This results in significant decreases in emissions savings compared to the baseline for the upgrades that rely on natural gas. A new gas boiler would then only reduce the emissions by 6% compared to 54% in the previous case, although from a cost perspective the total running costs are still likely to be lower due to the predictably lower fuel price. Installing a water-to-water heat pump would be significantly more advantageous in terms of emissions than an air-to-air heat pump with a gas boiler under this future situation, when under the current scenario the two yield similar results. The results can be observed graphically in Figure 71.

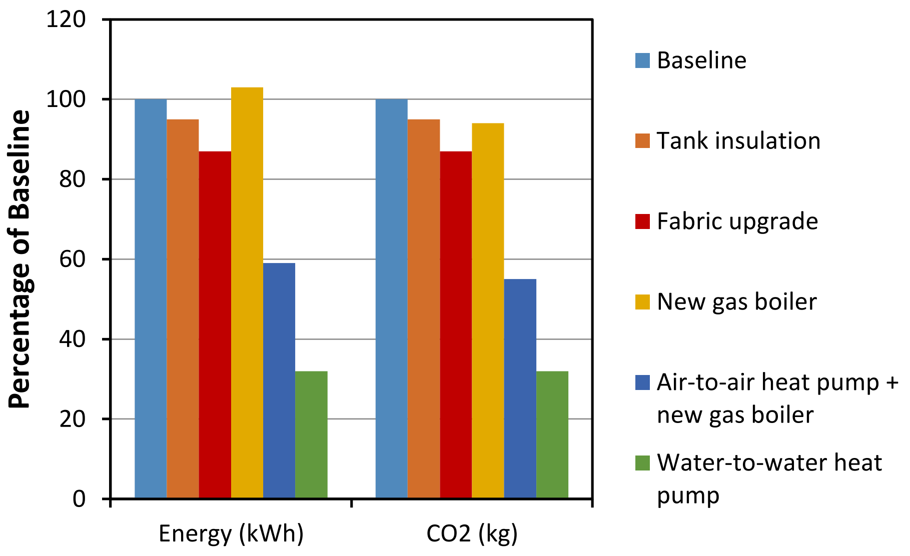


Figure 71: Energy and carbon comparison for different efficiency strategies: lower carbon electricity mix.

12. Conclusion

Dynamic simulation has been used to assess the most energy efficient upgrade strategy for a hotel in a UK climate, based on real data from a hotel whose energy consumption is monitored in real time. Measured energy use values were found to be very different than the published benchmarks for the hospitality sector, showing a much lower space heating demand (37 kWh/m^2/year) along a much higher demand for hot water purposes than expected (111 kWh/m^2/year).

The model built to represent the part of the hotel under study, after the necessary corrections for occupancy and weather, showed a good representation of the real site's energy consumption, the difference between the two being smaller than 8%, which can be attributed to the fact that the model was developed with a set of assumptions regarding construction materials, heating schedules and setpoints, casual gains and tank and pipe heat loss calculations.

Demand-side strategies such as a fabric upgrade and an insulation of the hot water tanks were tested on this model, along with supply-side strategies such as a new gas boiler, air-to-air and water-to-water heat pumps. A strong interaction between the hot water and space heating systems was observed, resulting in significant increases in space heating demand when energy efficiency measures were applied on the hot water system. Therefore, any package of upgrade measures should be carefully planned taking into account the mentioned interactions.

The simulation results showed that the installation of a water-to-water heat pump, which would extract the heat from a nearby reservoir for space heating and hot water, would be the best strategy both from an energy efficiency and CO_2 emissions reduction point of view, especially taking into account the expected lower carbon content of the UK grid electricity in the years to come. Such strategy could reduce up to 73% the current consumption if combined with a fabric upgrade. An air-to-air heat pump for space heating combined with a gas boiler for hot water would be the second best strategy, with up to 70% reduction. The installation of a gas boiler to replace the current electric systems would produce significant carbon emission savings with the current electricity mix in the grid, although in a future low-carbon mix these benefits could be significantly reduced. Fabric upgrade or hot water tank insulation strategies are likely to produce more moderate energy savings, although they may become an attractive and financially viable solution offering short payback periods, especially in the case of loft and tank insulation.

13. Limitations and further work

The current investigation used a number of assumptions in order to reproduce the energy behaviour of the building and its response to different strategies, including heating setpoints and schedules, construction materials and casual gains. All of these assumptions carry an uncertainty that has to be taken into consideration.

Through different simulations it was verified that infiltration and ventilation rates have one of the highest levels of influence regarding space heating energy demand. Although in reality these rates will vary with wind speed and temperature, among other factors, constant infiltration and ventilation rates were assumed, which can influence the results of the upgrade strategies.

Heat losses from hot water tanks were calculated in steady state conditions assuming stable boundary conditions and there is a degree of uncertainty in the assumptions of heat losses arising from hot water pipes. Any change on these values will affect the results in any of the strategies analised.

The model was built as a “stand alone” system, with no registered thermal influence from the rest of the building. A significant difference in operational temperature between the bedroom floors and the rest of the building resulting in a heat flux to or from the model could modify the results. Shading from nearby buildings or trees was not considered in the solar gains calculations.

This project focused only on thermal demand of the bedroom floors of the hotel. An inclusion of the rest of the facilities such as gym, swimming pool, conference rooms and kitchens to the analysis could give a more rounded idea of the impact of the different strategies on the hotel’s total energy needs. An economic analysis to evaluate the cost-efectiveness of the upgrade strategies would also set a more global picture to the hotel management in order to take an informed decision.

In a future electricity grid with more stochastic generation due to renewable sources, the possibility of increasing demand response from big consumers such as hotels would be a good strategy to increase renewable penetration. The installation of a heat pump combined with hot water storage could allow shifting the consumption to a time of the day when there is more electricity production from renewable sources and hence the CO_2 factor of the grid is lower. An exploration of the potential emissions savings with this measure would be worth to see how further they can be reduced.

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