An Investigation of the Effects of Air Infiltration and Thermal Transmittance on the Design of a Single Low Energy Building for the UK Climate

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Abstract

Reducing energy consumption in the UK is necessary, both in terms of meeting the regulations set by the EPBD and in order to mitigate the effects of climate change. This thesis examines the potential for achieving buildings with net zero energy performance in the UK, which can help to reduce energy consumption.

The thesis uses a literature review method to determine: building end use energy and the methods by which thermal energy can be lost, retained and even gained (through passive solar design) in a building; the importance of minimising thermal transmittance and air infiltration, without causing damage to the building fabric; and passive solar design techniques that can be used to assist in achieving net zero energy performance and the importance of balancing the reduction of thermal energy demand with the comfort of the buildings' occupants.

Nine buildings from the USA have been identified as low-, nearly zero- or net zero energy buildings and have been critically analysed to identify and determine the effectiveness of the low energy design and operation techniques that have been used to achieve net zero energy performance. In regards to the buildings that failed to meet net zero energy performance, the reasons for this have been identified.

A single, low energy building for the UK climate that has the potential for achieving net zero energy performance is designed using thermal energy simulation software. A base case building energy model is created, followed by a parametric study of low energy design techniques and a study to investigate the optimum modifications for achieving very low thermal energy demand.

The findings from the investigations of the thesis are then brought together into a coherent argument. A standard for the design and operation of a single type of commercial building that will be able to function with the same annual thermal energy demand regardless of location in the UK is proposed.

It becomes apparent that air infiltration and thermal transmittance of construction elements are the parameters to target to achieve buildings with very low energy consumption. The simulation data suggests that infiltration is responsible for the largest net heat loss and that glazing was responsible for the largest heat gain and heat loss although provided a relatively low net heat loss.
It also suggests that roofs provide an overall heat loss that is greater than that from walls, despite a lower thermal transmittance value and a lower overall area.

The simulations culminate in a model that predicts thermal energy demand of just 7.4 to 7.7kWh/m2/year is achieved across the 10 locations, which corresponds to an average reduction in thermal energy demand of 85% compared to the base case model.

Declaration

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Dedications and Acknowledgements

I wish to dedicate this thesis to those closest to me but especially my wonderful parents, Alan and Linda Freeman, for their financial and moral support and my girlfriend, Leila Newton, for teaching me to believe in myself and helping me to retain my sanity through the toughest times.

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1 Introduction

1.1 Problem statement

Climate change and the Energy Performance of Buildings Directive (EPBD) are drivers for change in the construction industry in the UK. Although the UK climate is temperate and temperatures are relatively mild in comparison with other European countries, the standards for thermal transmittance and air tightness of buildings in the UK are not strict enough to feasibly construct a stock of net zero energy buildings that comply with the minimum fabric parameters set out in the England and Wales Building Regulations Part L.

This thesis proposes a radical change to office buildings in the UK whereby the required fabric parameters are improved far beyond the levels set by England and Wales Building Regulations Part L2A [1]. A building is proposed as a standard design for net zero energy commercial buildings in the UK and, as such, is expected to be constructed, and perform at net zero energy, in any location in the UK.

1.2 Hypothesis

A single design of a low energy building can function at the same thermal energy performance level at any geographical location. Thermal transmittance of construction elements and air tightness will have the most effect on reducing the energy consumption of the building and hence in reducing the diversity of energy consumption levels for the same building sited at different locations within the UK.

1.3 Objectives

This programme of research uses a literature review based approach and thermal simulation software to achieve the objective of answering the following questions:

- To what extent does reducing the building's thermal transmittance value reduce energy consumption?
- To what extent does reducing the building's air permeability reduce energy consumption?
- To what extent does reducing the building's thermal transmittance and air permeability reduce the range in energy consumption for the building in each location?
- To what extent do temperature controls reduce the building's energy consumption?

1.4 Methodology

The thesis uses a literature review method to determine the likely energy end uses within buildings, to determine how the building fabric can affect energy consumption and to select and evaluate a number of case studies that demonstrate effective measures taken to reduce energy consumption.

Thermal energy simulation software is then used to perform a parametric study in order to determine the most effective modifications that can be made to the building fabric to reduce energy consumption and the range of energy consumptions. The most effective measures are then optimally combined to give a practical design for a net zero energy building that functions at the same energy performance regardless of location in the UK.

1.5 Thesis layout

Chapter 2 discusses why reducing energy consumption in the UK is necessary, both in terms of meeting the regulatory requirements set out within the EPBD [2] and in order to mitigate the effects of climate change. It also examines the definition of a net zero energy building and the potential for achieving buildings with net zero energy performance.

Chapter 3 examines building end use energy and the methods by which thermal energy can be lost, retained and even gained (through passive solar design) in a building. The chapter investigates the importance of minimising thermal transmittance and air infiltration, without causing damage to the building fabric. It also examines passive solar design techniques that can be used to assist in achieving net zero energy performance and the importance of balancing the reduction of thermal energy demand with the comfort of the buildings' occupants.

Chapter 4 analyses actual low-, nearly zero- and net zero energy buildings to determine the effectiveness of the various techniques used to achieve very low energy consumption. Nine buildings from the USA have been identified as low-, nearly zero- or net zero energy buildings and have been critically analysed to identify the low energy design and operation techniques that have been used to achieve net zero energy performance. In regards to the buildings that failed to meet net zero energy performance, the reasons for this have been identified.

Chapter 5 uses the findings of chapter 4, in conjunction with building energy modelling software, to design a single, low energy building for the UK climate that has the potential for achieving net zero energy performance. A base case building energy model is created, followed by a parametric study of low energy design techniques and a study to investigate the optimum modifications for achieving very low thermal energy demand.

Chapter 6 is a concluding chapter, in which the findings from the investigations of the thesis are brought together into a coherent argument. It proposes a standard for the design and operation of a single type of commercial building that will be able to function with the same annual thermal energy demand regardless of location in the UK. It also identifies limitations in the research and areas for further research.

2 Why reduce energy consumption?

2.1 Drivers for change

2.1.1 Climate Change

Climate change and global warming are two terms that are commonly viewed as synonymous. However, they are in fact different. Climate change is a naturally occurring process that results in long term changes in climate [3]. Global warming is the increase in atmospheric temperature [3] either by the Earth's natural cycle or through human impact in the form of burning fossil fuels and the subsequent release of carbon dioxide (CO_2), and other harmful gases, into the atmosphere. Global warming is a product of climate change, which results in increased global temperatures.

Ordinarily, the Earth will experience temperature, and thus climate, fluctuations over a long period of time. Glacial periods, for example, tend to follow the Milankovitch Cycle [4], occurring once every 100,000 years when the Earth is furthest away from the Sun. This is because the Earth follows an elliptical orbit around the Sun and the distance between the bodies is constantly changing. In addition, research by Sharma [5] suggests that the Earth's climate are linked with the Sun's magnetic activity, warmer periods being experienced in times of high activity and cooler periods at time of lower activity. The period follows the same pattern as the Milankovitch Cycle of approximately 100,000 years and coincides with glacial periods. Just as glacial periods follow a pattern, so do global warming periods. Data shows that natural warming periods will cause an increase in temperature of 5℃ over a period of approximately 5000 years, meaning that, on average, a temperature rise of 0.08℃ would be experienced over a human lifetime.

Recent data suggests that the rise in temperature during the 20th century is unprecedented and can mainly be attributed to human activity from the Industrial Revolution onwards. Throughout the 20th century alone, average global temperatures rose by 0.74℃ [6]. Considering that previous temperature fluctuations occurred over thousands of years and the recent temperature rise has only taken approximately 150 years to reach a similar change [7], it is evident that the Earth's natural cycle is not the main cause. It is now widely agreed that the recent temperature rise is mainly attributable to the burning of fossil fuels and deforestation of large areas of woodland; both of which contribute to rising CO_2 levels, a more substantial Greenhouse Effect and, subsequently, higher temperatures.

Research has predicted that future temperatures over the next century could rise to between 0.5℃ and 4℃, depending on the strategies adopted for mitigating the effects of climate change [8]. Figure 2.1 shows various scenarios that have been modelled by the Intergovernmental Panel on Climate Change (IPCC), all of which demonstrate a rise in global temperatures regardless of the strategy adopted [8]. Most notable is the orange line, depicting a scenario where greenhouse gas emissions stayed at the levels experienced in 2000. The concern of this scenario is that global temperatures will still increase, although at a much lower rate than if extensive fossil fuel consumption were to continue. This is because the Earth's oceans have a large thermal inertia, absorbing and releasing heat slowly. The evidence suggests that a critical point, whereby global temperatures can be stabilised at a manageable level, is about to pass or may have already passed.

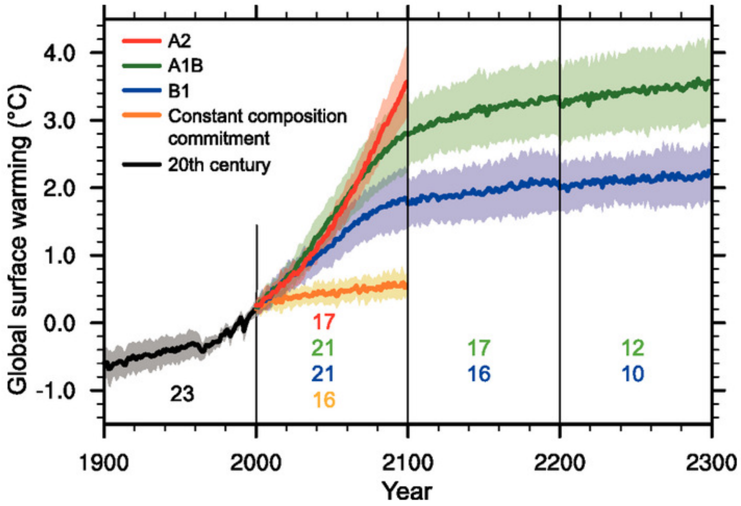


Figure 2.1: Predictions of future global temperature increase [8].

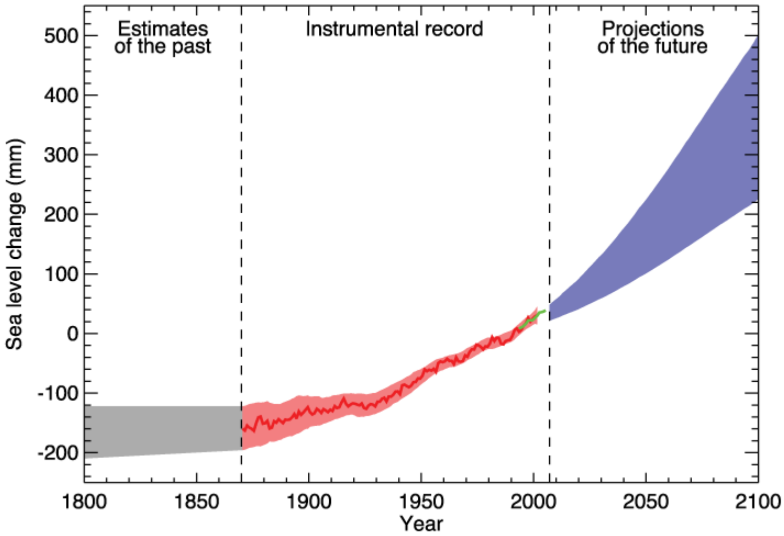


Figure 2.2: Predictions of future global sea level change [5].

Climate change, if not controlled, is predicted to have a substantial effect on global weather patterns [8]. It is expected that increased global temperatures will lead to, among others, more severe storms, an increase in flooding, an increase in precipitation in the higher latitude regions, severe droughts due to long periods of dryness, and will cause sea levels to rise beyond a controllable measure for much of the world's coastal and low-lying regions. Figure 2.2 suggests that sea levels could increase by as much as 500mm in the next century.

It is imperative that, although the effects of climate change can already be felt, the most extreme effects are mitigated and an action plan for reducing energy consumption, and thus greenhouse gas emissions, is mandated.

2.2 Energy Performance in Buildings Directive

The Energy Performance of Buildings Directive (EPBD) 2010 [2] is an updated version of the previous directive in 2002, which mandates that all new commercial buildings within the EU shall perform at nearly zero energy by the end of 2020 and that all new public authority buildings perform at the same target by the end of 2018. The EU has also set a target of 20% of the energy generated in Europe to be supplied from renewable energy sources by 2020 but, thus far, many of the EU member states are far from meeting their individual targets [9]. This could be due to the expense of installing large renewable energy sources to replace traditional fossil fuel electricity plants. Considering that renewable energy systems contribute a small proportion of the final energy demand in European countries (particularly in the UK) it can be deduced that much of the energy used in buildings is from fossil fuel sources. As of 2008, the contribution of energy from renewable sources amounted 2.2% of the final energy consumption of the UK [9].

One solution to meeting both of the targets set by the EU is to use a decentralised energy generation strategy, the most decentralised being renewable energy systems installed at the end use site. Net zero energy buildings (nZEB) provide a suitable platform for both decentralised and renewable energy generation.

In Europe, buildings account for approximately 40% of the total primary energy consumption [2], while buildings in the UK account for 45% of the national energy consumption [10] and commercial buildings, in particular, are responsible for 36% of building energy consumption. The majority of end use energy consumption within buildings is for space heating, with indicative values in the UK ranging from 48% for an air conditioned office to 60% for a naturally ventilated office [10]. Other European countries have similar energy consumption values.

In order to reduce CO_2 emissions, and thus have an effect on mitigating climate change, further investment will be required in renewable energy systems (RES), with specific investment in developing a stock of nZEBs.

2.3 Net zero energy buildings

Much research has been undertaken in the field of net zero energy buildings with a specific focus on the methods of successfully achieving net zero energy performance. While the individual methods may differ in some details, the consensus is that buildings should firstly be designed to minimise energy consumption as far as feasibly possible, then high efficiency building services should be installed to meet this reduced energy consumption and only then should renewable energy systems be specified to power the building services.

Goncalves [11] examines the evolution of building energy reduction from the first energy crises in the 1960s and 1970s to the present day. Today's building designers are faced with the new challenge of net zero energy and positive energy buildings. The author suggests a strategy to achieve these targets:

1) Minimise heat losses through a higher performance building fabric;
2) Use solar gains for passive heating and cooling;
3) Provide natural ventilation;
4) Provide natural lighting;
5) Install more efficient HVAC systems, and finally;
6) Use renewable energy to provide power.

The critical message here is that in order to achieve the net zero energy target the building design must be highly energy efficient and only then should renewable energy systems be installed.

Crawley *et al [12]*provide definitions of net zero energy buildings (site, source, emissions and cost) but summarises that in each definition, the key theme is to reduce energy consumption before providing energy generation. They state that all nZEBs must reduce demand side energy by providing buildings with insulation, passive solar heating, natural daylight, evaporative cooling, highly efficient HVAC and only then provide the renewable energy technology. They also state that while a building may be designed as an nZEB, annual weather fluctuations may result in the target not being met. Building energy performance is susceptible to weather, occupancy and degradation of fabric and HVAC plant.

Kolokotsa *et al* [13]state that the objectives for achieving the nZEB are to minimise building energy consumption through improved building fabric, innovative shading devices and incorporation of high efficiency HVAC and then to supply the building with energy from renewable energy systems while managing the energy use through sensors and monitoring.

Griffiths *et al* [14] studied 4820 buildings in the US, which are representative of the US building stock. The buildings were modelled and simulated with improved thermal envelope, lighting systems, plug loads and HVAC, coupled with on-site renewable energy systems to try to achieve the target of net zero energy. The study demonstrated that 62% of commercial buildings in the US could achieve nZEB performance with the modifications. The researchers claim that a proportion of the buildings can even become positive energy buildings, helping to offset the energy consumption of non-nZEB buildings.

3 Building Energy Usage

Low energy design is the idea of creating a building that still fulfils the comfort requirements for its occupants but does so in a way that consumes less energy than a conventional building. Low energy design can be applied to all parts of the building envelope, HVAC systems, lighting and equipment. In some cases, a building may only require, or the building operator may only be able to afford, some of the low energy design modifications, although in the context of net zero energy buildings, it would be prudent to incorporate as many low energy design techniques as is possible, in order to reduce consumption before installing renewable energy generation.

In order to achieve net zero energy performance nZEBs will be required to generate sufficient energy through renewable energy systems over the course of a year to in order to offset the amount of energy used from the electricity grid. Renewable energy systems are relatively inefficient at generating electricity when compared to that generated by traditional fossil fuel. In addition, renewable energy generation tends to coincide with diurnal patterns. That is, electricity can only be generated by PV during daylight hours, and wind, which is induced by the Sun's differential heating of the Earth's atmosphere, will often be strongest during the day. This inflexibility, and inefficiency, of generating electricity means that buildings have to be designed efficiently to make the most of the available energy. There are various low energy design strategies used in buildings that will be discussed in this chapter

3.1 Energy end use

Energy supplied to buildings can be divided into four end uses [10]:

1) Space heating,
2) Water heating,
3) Lighting,
4) Other electrical.

The first three uses are self-explanatory although in practice, there is often cross linkage between space and water heating as both can be supplied through one heating system. The last is a combination of any other electrical products in the building, such as office equipment, fans, pumps and controls. Figure 3.1 and Figure 3.2 show the breakdown of end use energy consumption in a naturally ventilated office and an air conditioned office, respectively, in the UK [10].

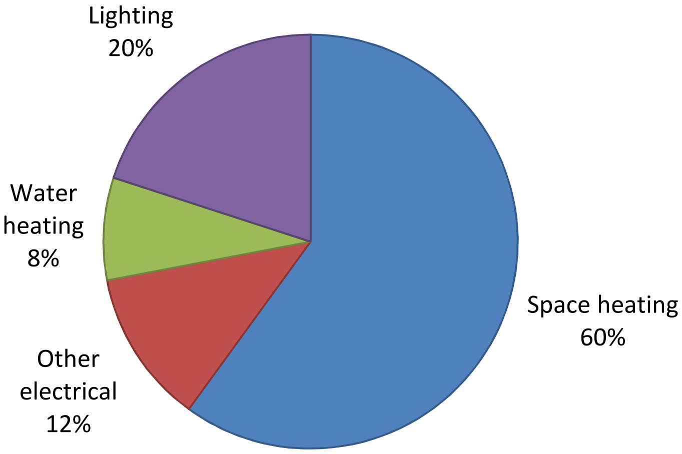


Figure 3.1 Energy end use in a naturally ventilated office [10]

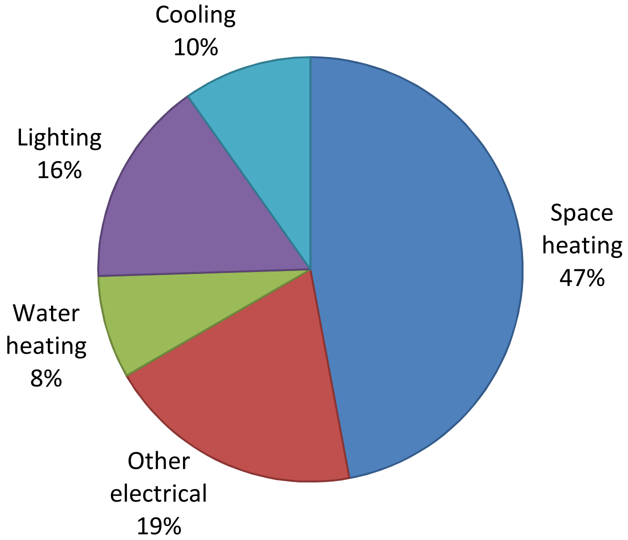


Figure 3.2 Energy end use in an air conditioned office [10]

Figures 3.1 and 3.2 demonstrate that the major energy end use in the UK is for space heating. As such, the primary focus of this thesis will be concerned with reducing the energy consumption for space heating. This section will examine why space heating is the largest energy end user and methods to reduce the energy consumption in buildings through low energy design, specifically targeted at space heating energy reduction.

Low energy design techniques applied to building services and building envelope will have a direct effect on the heating, cooling and ventilation loads in a building, decreasing them and making the building perform more efficiently. Reducing these loads, however, will mean that other energy end uses in the building, such as lighting, hot water and equipment, become more prominent. The aim of this thesis is to study how reducing air permeability and thermal transmittance can assist in buildings achieving net zero energy status.

3.2 Thermal Transmittance

3.2.1 What is thermal transmittance?

Thermal transmittance (U-value) is the flow of heat through the building fabric and is usually associated with heat loss from the building, although, in some important instances, can also be associated with heat gain to the building (for instance, during summer when exterior temperatures may be higher than interior temperatures). It is measured in W/m^2K and is a measure of the speed with which heat is lost through one square metre of the element with 1K temperature difference across its faces [10]. In light of climate change and the EPBD, reducing energy consumption (especially in terms of space heating) in buildings has become a high priority. Buildings in colder climates, such as the UK, should therefore be designed to retain as much heat as possible through the use of low thermally transmitting building envelopes.

3.2.2 Importance of minimising thermal transmittance

Insulation is required to reduce energy consumption but also to provide comfort by insulating against heat transmission across a building envelope and regulating indoor temperatures. There have been many practical experiments conducted to determine the effect of reducing thermal transmittance on the energy performance of buildings.

Cabeza *et al* [15] conducted an experiment to test the effectiveness of three different insulation types on the thermal energy performance of a $2.4m^3$ test cubicle in a Mediterranean climate. The test cubicles were clad either in 50mm polyurethane insulation, 50mm mineral wool insulation or 50mm polystyrene insulation. A control cubicle with no thermal insulation was also monitored to act as a control specimen. The study concluded that thermal insulation reduced the energy demand for space heating but also found that it reduced cooling energy demand. Heating and cooling energy demand were reduced by up to 37% and 64%, respectively with polyurethane insulation found to have the greatest energy demand reduction potential. Polyurethane insulation had the lowest thermal transmittance value of all the insulation products that were tested and this would have minimised the rate of heat transmission through the building fabric.

Papadopoulos [16] claims that enhancing thermal insulation is the best and most cost effective method of constructing a building with;

"....reasonable energy consumption, satisfactory thermal comfort conditions and low operational costs".

Despite this, Papadopoulos highlights the lack of change in insulation requirements in some European countries while others, such as those in Scandinavia, have doubled the requirements since their initial inception [16]. In cold climates, insulation has always been critical to high energy performance. In warm climates, it is emerging that reflective insulation can reduce cooling loads. In temperate climates, thermal insulation must be worth installing and upgrading, especially with rising fuel prices.

Minimising heat loss through thermal transmittance is fundamental to reducing heat loss from the building space in colder climates and reducing heat gains into the building space in warmer climates for new buildings. However, only 2% of the commercial UK building stock is less than 5 years old [17]. This means that refurbishment of buildings could be required in order to improve thermal energy efficiency.

Filippin *et* al [18] modelled a dwelling located in Argentina in order to determine its energy performance and methods for improving it. The building was simulated as it is currently built and then with refurbishments; 50mm expanded polystyrene insulation in the external walls, 75mm expanded polystyrene in the roof double glazing with thermal transmittance of 2.5W/m^{2}K and an increased amount of glazing in the north wall (raising the window to wall ratio from 0.12 to 0.2) were incorporated into the model. The modifications resulted in a 66% decrease in heating energy demand in the winter and also raised the indoor temperature. The same refurbishments were applied for summer with the addition of solar shading over the north facing windows, which resulted in a space cooling energy reduction of 54%. The authors highlight the “outstanding importance” of incorporating thermal insulation into buildings to reduce energy consumption. The findings suggest that energy savings and comfort should be achieved by first applying insulation to the fabric and then by introducing high efficiency HVAC or upgrading existing HVAC.

Ruiz and Romero [19] simulated a typical house in Spain, constructed to building regulations, both in an as built case and with improvements to the building fabric. The original dwelling uses 20.06kWh/m^2/year for heating and 14.69kWh/m^2/year for cooling. The modified building incorporated an additional 20% glazing in the north and south facades, a 300mm horizontal shading device over windows, an additional 20mm expanded polystyrene insulation in the external walls (providing thermal transmittance of U=0.39W/m^{2}K) and a fully south facing orientation. All the modifications resulted in heating and cooling energy consumptions of 17.1 and 13.23kWh/m^2/year, respectively; an overall thermal energy saving of nearly 13%. The largest single contributor was providing an additional 20mm expanded polystyrene insulation as this provided a thermal energy saving of 6%. The report suggests that thermal insulation is the most important of all the modifications. However an infiltration reduction was not factored into the modifications and, as such, the effect of reducing the infiltration rate on the thermal energy performance of the building has not been observed. It could be argued that Ruiz and Romero should have simulated a reduction in infiltration rate before drawing conclusions as to the most effective method of increasing thermal energy performance. It seems that this has been completely overlooked as a refurbishment issue, whereas increasing the amount of north facing glazing was deemed an option that may reduce energy consumption.

Manz and Menti [20] state that while advancements in opaque building elements have resulted in low thermal transmittance values, glazing elements are not yet approaching the same levels and, as such, their performance is found lacking. Despite their extensive use in buildings to provide light and heat, they are elements with low thermal resistance. The study examines how different types of glazing impact on the energy demand of buildings in various European climates.

Manz and Menti [20] state that optimal glazing is that which has a low thermal transmittance value but a high solar heat gain coefficient. In this scenario, the glazing allows radiation to enter into the space and provide heat and light (high solar heat gain coefficient) but limits the loss of heat through conduction across the glazing (low thermal transmittance). The authors claim, though, that this is difficult to achieve by simply increasing the amount of panes of glass. Increasing the number of panes will, of course, reduce thermal transmittance by trapping more air layers but will reduce the solar heat gain by reflecting radiation off of an increasing number of panes of glass.

The authors [20] found that in all locations, triple glazing with krypton filled cavities and two low-emissivity coatings resulted in a net heat gain when placed in south facades. Double glazing with an argon filled cavity and one low-emissivity coating resulted in net heat gain in five of the eight locations and these were the southernmost locations. It was found that double glazing with an air filled cavity and single glazing resulted in a net heat loss in nearly all locations and orientations. North facing glazing fared worst of the orientations in all locations and with all types of glazing. Heat gains were greatest in southern locations and lowest in the north

The Manz and Menti study [20] shows that south facing glazing is most beneficial for passive solar buildings. It also demonstrates the importance of the solar heat gain coefficient in addition to the thermal transmittance value of glazing. The findings suggest that basing a regulation for glazing on thermal transmittance alone is unwise as there are two major methods for heat gain and loss. The authors claim that solar energy gains are important for saving heating energy in cold and temperate climates but also highlight that extensive glazing can result in overheating and may even increase the total energy load due to increased cooling.

3.2.3 Building fabric and thermal transmittance

Thermal transmittance is affected by the material properties. Thermal transmittance varies with building materials and elements within the building fabric. Roof, floor and external wall constructions tend to have lower thermal transmittance values than glazing because of the relatively easy practicality of installing insulation materials to roofs, floors and external walls. This section will examine typical construction elements in office buildings in the UK and give an overview of typical thermal transmittance values and those that can be achieved with best practice.

3.2.3.1 Insulation for walls, roofs and floors

The UK climate results in most buildings predominantly require heating from around October to March without any substantial requirement for cooling in the summer months in most buildings. As such roofs, floors and external walls in UK construction are designed to have low thermal transmittance values, which are achieved through the use of insulation materials. As thermal transmittance values decrease further, the requirement for space heating reduces; casual internal heat gains can be sufficient to provide the necessary space heating requirement, thus highly thermal resistant insulation can provide substantial heating energy and cost reductions. This sub-section describes the methods by which thermal transmittance reduces heat loss and discusses a number of thermal insulation materials as a knowledge of these materials will help inform the design of a low energy building model in Chapter 5.

Insulation works by using a low density membrane that traps pockets of gas to limit conduction and, to some extent, convection heat losses. In some instances, reflective layers are also used to limit radiation heat losses. Gases have very low thermal transmittances due to their molecular structure; the molecular particles are spaced far apart opposed to a dense, solid material like steel. The relatively large spacing between each particle results in a slow heat transfer across a given volume of gas. This property of gases makes them ideal for resisting the flow of heat. The aim, therefore, of insulation is to resist the flow of heat by entraining gas particles, the most common of which is air. Commonly used insulation materials include wool fibre, rock wool, polystyrene (both expanded and extruded) and polyurethane; the calculation method for determining the thermal transmittance value of construction elements is given in BS EN ISO 6946:2007 [21].

Insulation is used in roofs, floors and walls to reduce the rate of heat loss from inside a building space or, to a lesser extent in the UK, to reduce the rate of heat transfer from the external environment to the building space. Insulation has low thermal transmittance values to achieve this aim and can be fixed to the building envelope elements, thus retaining the structural integrity of a building. Insulation uses the low density properties of trapped gases and, in certain circumstances, vacuums to reduce the rate of conduction heat losses; the specific methods and their effectiveness are detailed below. Regardless of the insulating material, the aim of insulation is to reduce the rate of heat transmission across the building envelope.

Mineral wool

Wool based products (mineral wool) are formed by heating the raw material and forming it into thin fibres. They are then formed into a matrix to trap air in the voids between fibres. Stone and glass are common raw materials for creating mineral wool insulation. In each case, the raw material is heated to temperatures of between 1400 and 1500℃ and then either spun out from a disk (stone) or extruded through rotating nozzles (glass) to form fibres; a dense and scattered pattern of fibres encourages the entraining of air. High density mineral wool can be produced so that the insulation can withstand loads in addition to reducing heat loss. Mineral wool is able to be modified on site without reducing the thermal resistance and typical thermal conductivity ranges from 0.03 to 0.04W/mK [22].

Polystyrene

Polystyrene insulation is formed by using expansion gases to create gas voids in the material that will reduce the rate of heat transfer across the medium. Polystyrene insulation is created using one of two processes; expansion or extrusion. Expanded polystyrene (EPS) is formed by creating small balls using an expanding gas and bonding the balls together to form a board. Extruded polystyrene

(XPS) is formed by adding an expansion gas to the polystyrene under pressure and extruding it through a nozzle, whereby the pressure is equalised by the material expanding and creating voids for gas. Both EPS and XPS have similar thermal conductivities of between 0.03 and 0.04W/mK and both are capable of being modified on site without compromising thermal resistance [22].

Polyurethane

Polyurethane is formed by mixing isocyanates and polyols and the associated reaction that is caused. The reaction causes the material to expand, leaving voids for gases. Polyurethane can be formed into rigid boards to be placed adjacent to construction elements or can be extruded on site to fill gaps in construction. The boards can also be modified on site without reducing thermal resistance. Polyurethane insulation can have thermal conductivities of as little as half of those for polystyrene or mineral wool with typical values ranging from 0.02 to 0.03W/mK [22].

Vacuum insulation

Vacuum insulation is formed from a core of fumed silica that has been sandwiched between thin aluminium and polymer films. The core is depressurized to a pressure of between 0.1 to 20mbar [23] and covered in a thin, airtight film to prevent the loss of pressure. The vacuum formed within the central core is less dense than the entrained gases in conventional insulation, resulting in low thermal conductivity values that are as little as 10% of those found in conventional insulation. Typical thermal conductivity of vacuum insulation panels (VIPs) is of the order of 0.004W/mK. This low thermal conductivity means that the same thermal transmittance as mineral wool, polystyrene and polyurethane insulation can be achieved with VIPs at much lower thicknesses, resulting in reduced transport costs and more of the internal building area available for occupant use. The major disadvantage of VIPs is that they cannot be modified on site as the vacuum is critical to their performance and, if perforated, the vacuum is lost, which can increase thermal conductivity to 0.2W/mK [22]. This would mean that the very expensive vacuum insulation panel would result in having a thermal conductivity of that of polyurethane at a much lower thickness and a much higher cost in addition to causing major, unanticipated heat loss problems .

3.2.3.2 Thermal mass

Increasing the thicknesses and densities of building elements will also have a positive effect on the heat retained in the building space. Increasing the thickness of construction elements will increase their thermal resistivity, but increasing the density and thickness of the elements will create a thermally massive building. Thermal mass is used in buildings to retain the energy inside the envelope. Thermally massive envelopes will have a high thermal inertia, meaning that, although initially taking longer to heat to the required temperatures, the heat will be lost less readily, resulting in a building that stays at a stable temperature. The temperature may only decrease by a few degrees overnight meaning the heating system will require less energy input the following morning. Thermally massive designs will only work those buildings that require very little change in indoor temperatures and do not need to dissipate heat quickly throughout the day.

3.2.3.3 Glazing

The most thermally transmitting elements of a building are usually the windows. Glass has a (comparably) very high thermal transmittance, with typical U-values of 4.8, 2.8 and 2.1 W/m^{2}K for single, double and triple glazing respectively [10]. Although the same rules apply to glass as all other construction elements, that as the thickness increases so does the thermal resistance, increasing the thickness of glass is expensive and inefficient. To counteract this problem, double and, sometimes, triple glazing is used, as well as low emissivity coatings and various gases to fill the voids between panes.

Glass is a dense material and, as such, transmits heat very easily. An extra pane of glass in the window not only increases the thickness (and, in turn, the thermal resistance), it also adds a layer of intentionally trapped air between the panes. The air acts as an insulating layer, just as in traditional wall and roof insulation, and resists the flow of heat across the glazing, helping to lower the rate of heat loss from the building. In addition, each layer of glass and surrounding air assists in reradiating heat back inside the building space. The resistance to heat loss increases with increasing thickness of air layers between panes of glass up to thicknesses of approximately 16mm [10]. Beyond this the space is sufficiently wide enough to initiate convection currents, the heat losses from which counteract the increased resistance to conduction heat losses resulting from the increased volume of air.

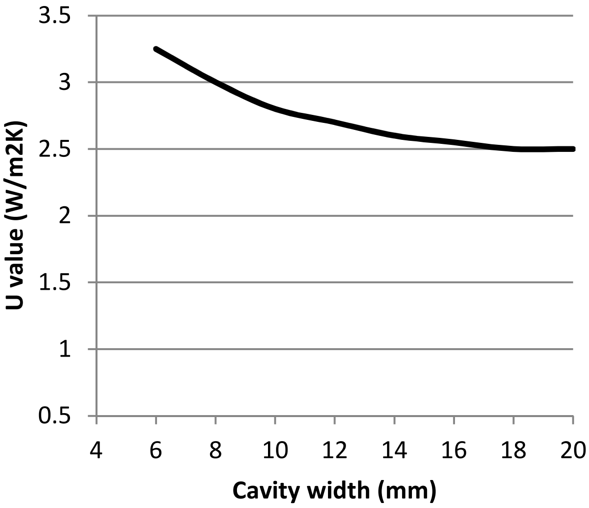


Figure 3.3 The effect on thermal transmittance of increasing the gap between panes of glass (reproduced from [10])

Windows pose a dilemma for zero energy building designers. They are required to allow access for daylight into the building, thus reducing the lighting load, but, due to the materials used, they are large contributors to heat loss in the winter and overheating in the summer, both of which result in extra load being placed on the heating and cooling services. There are then three possible design alternatives:

1. Minimise the area of glazing on the building envelope;
2. Reduce the thermal transmittance of the glazing elements;
3. A strategic combination of the above.

Minimising the area of glazing on the building envelope will have the positive effect of reducing the amount of heat lost from the interior space but will also give the negative effect of lower daylight ingress, thus resulting in a higher energy requirement for artificial lighting. Reducing the thermal transmittance of the glazing elements will also reduce the amount of heat lost from the interior space of the building but will mean that the cost for glazing will increase dramatically as high performance windows will be required. However, the area of glazing can be reduced on north facades (in the northern hemisphere) as the north facade never receives direct sunlight and heat and light gains are less than those experienced on the south facade; this issue is discussed in more detail in 1.5.2.3. Coupling this strategy with high performance glazing will mean that the total cost can be reduced while light and heat can still enter the building effectively.

It is also interesting to note that using argon rather than air as the insulating gas also decreases the thermal transmittance [10]. This is because the thermal conductivity of argon is less than air, reducing conduction heat losses and argon is denser, meaning that convection heat losses are reduced as the convection currents occurring in relatively large gaps between panes are slow in comparison to those experienced in the same gaps filled with air. Low emissivity coatings are used to limit the amount of heat being transmitted from inside the building to the external environment and have an effect on limiting the heat from solar radiation into the building. The coatings reduce heat loss by trapping heat in the building that has been re-radiated from equipment and occupants.

Despite using all of the techniques mentioned above, windows are still large contributors to heat loss from a building. A triple glazed window in a PVC-U frame with an emissivity of 0.05 and 16mm, argon filled gaps has a thermal transmittance value of 1.3W/m^{2}K [1]. This is much higher than the maximum allowable thermal transmittance value of U=0.35W/m^{2}K for walls under Part L2A of the Building Regulations 2010 [1] and, as such, makes the location and area of glazing a critical aspect of the building design.

There are however, concerted efforts to reduce thermal transmittance of windows using vacuum technology. Vacuum glazing uses similar technology to the vacuum insulation panels that were described above. Instead of using a traditional layer of gas between panes of glass, the space is depressurised, which reduces the density of the gas layer and, in turn, the conduction and convection heat losses. In order for the glazing to maintain structural integrity, small supports are placed in the vacuum layer so that the glass doesn’t deform or crack under the pressure differential. This also has the effect of forming thermal bridges across the glazing that reduce the overall thermal resistance of the window but vacuum technology is still able to produce glazing that has much better thermal performance than comparable traditional glazing; thermal transmittance values of as low as 1W/m^{2}K and 0.2W/m^{2}K have been reported for double and triple glazed vacuum windows, respectively [24, 25].

3.2.3.4 Limiting thermal transmittance values

England and Wales Building Regulations Part L2A 2010 [1]

Limiting values are imposed on the thermal transmittances of construction elements in new UK commercial buildings by the Building Regulations Part L2A 2010 [1]. The details are given in the table below. Although these are set out in order for buildings to comply with limits on the carbon dioxide emissions, they are rarely sufficiently low enough for designing low energy buildings.

Element	Maximum U-value (W/m^{2}K)
Roof	0.25
Wall	0.35
Floor	0.25
Windows, roof windows, rooflights, curtain walling and pedestrian doors	2.2
Vehicle access and similar large doors	1.5
High usage entrance doors	3.5
Roof ventilators	3.5

Table 3.1: Maximum thermal transmittance values for building fabric elements constructed to England and Wales Building Regulations Part L2A [1]

Passivhaus standard

The Passivhaus standard [26], on the other hand, does not impose limits on the thermal transmittance of building envelope elements; rather it imposes maximum limits on the energy demand for heating and cooling, the air infiltration rate (when tested at a pressure difference of 50Pa) and the primary energy demand while still imposing criteria for achieving comfortable thermal conditions. The limits are as follows:

Criteria	Maximum allowable limit
Specific space heating demand OR Heating load	15kWh/m^2/year 10W/m^2
Specific space cooling demand	15kWh/m^2/year
Annual overheating hours (indoor temperature over 25℃)	10%
Airtightness test result (n50)	0.6ACH
Total specific primary energy demand	120kWh/m^2/year

Table 3.2: Maximum thermal energy demand, overheating hours and infiltration value for buildings constructed to Passivhaus standard [26]

The targets set for the Passivhaus standard give more scope to the designer for how to achieve the standard as there are no limits on thermal transmittance values. The Passivhaus standard is more conducive to achieving nearly-zero and net-zero energy buildings.

3.2.4 Super insulation: effects and risks

Super insulation is the process of providing high amounts of thermal insulation and a highly airtight building envelope such that almost all of a building's heating demand can be met by casual and solar heat gains [10]. This can be achieved by using very thick insulation (250-500mm) in roofs, floors and walls, by using low thermal transmittance glazing and by sealing the building envelope. Although the objective is to achieve low thermal energy consumption, super insulating a building can cause more harm than good.

Super insulation can cause problems with damage to brick work and poor air quality in buildings. Insulating the entire cavity of a cavity wall, for instance, will reduce the thermal transmittance value but will provide a path for moisture transfer to the inner leaf and into the building space. Moisture left in the outer brick leaf will be much colder than the air inside the building, which could result in the moisture freezing and causing spalling to brick work. In addition, the moisture inside the building, coupled with very low air change rates can lead to mould growth and poor indoor air quality [10].

Batty *et al* [27]state that as energy demand is increasing and fuel is becoming more expensive, homeowners and designers are creating dwellings that have high levels of insulation and are less leaky. However, the authors also claim that these modifications can manifest problems in the building structure. The authors argue that increasing the air tightness and thermal insulation of buildings is causing higher amounts of condensation. They describe this as a ***'....penny-pinching attitude.....'*** without ***'....thoughtful building design.....'*** which, in the long term can have detrimental effects on the building fabric and structure through growth of mould and spalling of brick work by moisture being trapped in the outer leaf. They argue that insulating cavities in traditional brick walls has the effect of decreasing the external leaf temperature, which could freeze trapped moisture and result in spalling brickwork.

3.3 Air Infiltration

The vast majority of buildings will experience air infiltration as it is very difficult and, in some cases, unwise to completely seal a building envelope. There are many different ways of air infiltrating into and escaping from a building envelope but there are also many ways of reducing the infiltration rate.

3.3.1 Infiltration versus ventilation

Air infiltration is the unwanted air entering a building envelope through cracks, leaks and openings in the fabric. This differs from ventilation, which is the intentional supply of air to a building to provide comfortable conditions.

The criteria for building design is to seal buildings so that unwanted air is unable to enter through the building fabric but to provide a strategy to allow fresh air to enter and to remove odours and pollutants; to quote Perera et al,

“***build tight and ventilate right”*** [28].

3.3.2 Importance of minimising air infiltration

Air that enters the building from the external environment will require conditioning (heating, cooling and possible humidity control) for most of the year in order to provide a comfortable temperature and humidity. In the winter, heating dominates, while in the summer, cooling does. In the transition between the heating and cooling season, the incoming air may not require any form of conditioning, although this is usually only for a relatively short period in the annual cycle.

Heating, cooling and humidity control requires an energy input, even if there is a passive heating or cooling strategy. In the case of a passive heating or cooling strategy it is arguably more important to reduce air infiltration as the sun provides the heat for the building, which is uncontrollable, meaning that the temperature cannot simply be increased when it drops below a comfort level. Any air that unintentionally enters or escapes through the building fabric will result in a loss of energy for three reasons:

- The air has been heated or cooled and has subsequently left the building fabric, meaning that the energy has been wasted.
- The escaped air will be replaced by further incoming air, which will require heating or cooling to provide comfortable temperatures.
- The escaping air, if the flow rate is high enough, can cause uncomfortable conditions in the form of draughts, resulting in the occupants increasing the temperature of the heating system.

Evidence from studies into air infiltration in buildings highlights its importance in reducing space heating energy consumption. Jokisalo *et al* [29] claim that air infiltration is responsible for 15-30% of the space heating requirements in Finnish detached houses and found that the space heating requirement increases linearly with the air change rate (at 50Pa). Emmerich *et al* [30] found that in a TRNSYS modelling study of three different building types (office, retail and apartment) in five US locations, heating and cooling energy savings range from 3-36% for best practice air infiltration compared to buildings without an air barrier. In a study of the US building stock, Cummins *et al* [31] found that repairs to duct leaks in 19 commercial buildings resulted in an average reduction of air infiltration rate of 12.5% (maximum reduction=74.1%) and an average reduction in energy demand of 14.7% (maximum reduction=36%). Nabinger and Persily [32] found that by retrofitting a manufactured home through sealing ductwork, sealing building services access and applying a ‘building wrap’ to the house, whole building infiltration rates reduced by approximately one third and space heating energy consumption reduced by 10%. Liddament and Orme [33] claim that (as of

1998) air infiltration in 13 major industrialised countries was responsible for almost half of the losses from heating equipment and for 36% of the space conditioning energy of buildings. They also claim that if incoming air were to match the minimum required ventilation rate of 7.5l/s/person, stated in ASHRAE Standard 62, air change related energy consumption could be reduced by up to 75% (of the 1998 values) [33].

It is, thus, important to retain as much of the incoming air as possible, while still providing an adequate amount of incoming air to remove odours, harmful gases and pollutants. It can be seen that escaping air results in wasted energy, so minimising the air infiltration rate will result in energy savings. As a result, UK Building Regulations Part L2A [1] imposes limiting values on air tightness in order to reduce energy consumption, which will be used as a benchmark during the building simulation. Air permeability is the measure that is used in UK Building Regulations Part L2A and is defined as:

"The physical property used to measure air tightness of the building fabric. It is defined as air leakage rate per hour per square metre of envelope area at the test reference pressure differential across the building envelope of 50Pa. The envelope area of the building, or measured part of the building, is the total area of all floors, walls and ceilings bordering the internal volume subject to the test." **[1]**

The maximum allowable air permeability of a commercial building to the aforementioned Building Regulations is $10m^3/m^2/hr$ at a test pressure of 50Pa.

3.3.3 Modes of ventilation

Ventilation can be mechanical or natural. Mechanical ventilation uses building services to regulate the amount of incoming and outgoing air. This allows the ventilation rate to be easily controlled and adjusted when necessary. Mechanical ventilation uses additional energy and due to the aims of this thesis, mechanical ventilation will not be discussed in great detail. However, this section will explore the area of natural ventilation due to its use in low energy buildings. Natural ventilation can be driven by two functions; temperature and wind.

Temperature driven natural ventilation is known as the stack effect and functions as follows; air enters into a building from a low level through intentional openings and cracks in the building fabric, it is then heated through casual and solar heat gains and through the heat input from the building services, it rises and escapes through openings at the top of a building and, in its place, fresh air is drawn in. Wind driven natural ventilation functions through the pressure from wind impacting on the building envelope and forcing air through intentional openings and cracks in the fabric.

Wind driven ventilation can be single sided, whereby the air enters and leaves through the same facade or by cross ventilation, whereby the air enters through the openings on one facade and leaves through the openings on the opposite facade. Single sided ventilation works well in buildings where there are individual rooms and where the width of these rooms are approximately 2.5 times larger than their height, which allows for adequate mixing of the fresh and stagnant air. If the room width is any larger then there is the risk that slow moving air deep inside the room will not escape and will retain heat and pollutants. Cross ventilation, however, works well in buildings with relatively narrow, but open, floor plans (width of approximately 5 times the height), which stimulates adequate mixing of fresh and stagnant air without the airflow rate slowing to below the required ventilation levels [34].

Natural ventilation at night time can also help to reduce the high internal temperatures that can occur in passive solar buildings during the summer. The strategy is to open an adequate amount of intentional openings in the building during the night to purge the building with cooler air. This will reduce internal air temperatures to a point such that, through solar and casual heat gains, the maximum daytime temperature during the following day should not exceed comfortable limits.

Natural ventilation is a much cheaper alternative than mechanical ventilation, both in monetary and energy usage terms, yet it is adequate for providing comfortable thermal conditions in buildings in the UK. Its effectiveness, however, relies on the behaviour of occupants in a building, their understanding of when and how to achieve comfortable conditions through natural ventilation and the suitability of its use, especially in urban areas where there may be high pollution.

3.3.4 Modes of air infiltration

3.3.4.1 Occupants and intentional openings

Windows and doors, whilst providing a means for occupants and ventilation air to enter and leave a building, can contribute to a large amount of energy consumption. It is difficult to control occupant behaviour, and even more difficult to please every occupant with a building's heating and cooling regime (refer section 3.5 for more information on thermal comfort). As such, occupants in buildings with opening windows will tend to open windows and doors to suit their individual temperature requirements. In doing so, air can enter and leave the envelope through relatively large openings. If windows and doors are left open or are opened wider than is necessarily required to achieve comfort conditions, energy may be wasted by heat escaping from a building or by heat entering into a building. Window opening behaviour is strongly related to external temperature; occupants will open windows when it is too warm and close them when it becomes cold [35].. CIBSE states that naturally ventilated buildings can typically expect to have 2-5% of windows open for most of the year, resulting in ventilation rates of 0.5-1.0 ach [36].

Occupant behaviour is difficult to control and opening windows can result in increased energy consumption if not managed adequately. Raja *et al* [37]conducted field studies of 16 buildings in the UK to determine the controls used to achieve comfort conditions in naturally ventilated buildings. The study found that window opening and blind adjustments were the most frequently used controls when the indoor air temperatures rose above 20℃. The authors claim that the availability and proper use of controls are critical to improving building energy performance and occupant satisfaction.

Andresen *et al* [38] modelled a 7m x 4m room (the ceiling height was not given in the literature) with a single occupant and six controls that could be manipulated (table fan, window opening, blinds, heating, clothing insulation and metabolic rate). Two behaviours were simulated; energy expensive and energy efficient. For each of the simulated behaviours the aim was to keep the PMV in the ranges A) ±0.2, B) ±0.5 and C) ±0.7. The study found that the PMV range was attainable in all simulations but it was found that being energy expensive and aim to achieve tight comfort conditions resulted in energy consumption 3.3 times greater than being energy efficient with a wide range of comfort conditions. More importantly, the research found that behaviour was responsible for an increase in energy consumption of 324% while the controls were responsible for an increase in energy consumption of 117%. The results suggest that energy consumption can be reduced most effectively by educating occupants on efficiently achieving comfortable thermal conditions. This research demonstrates that achieving high energy performance is largely significantly affected by occupant behaviour in the building.

3.3.4.2 Ducts

Ductwork may be required in buildings to effectively supply fresh air and remove stale air from the interior space. Ductwork for ventilation and distribution of conditioned air is susceptible to leaks, primarily caused through poor workmanship [39] and poor sealing between joints in the ductwork [40]. Poor sealing of joints will lead to a loss in pressure in ducts resulting in the intake and exhaust fans working harder to draw in more air to raise the pressure. In doing so, excess air is brought into the building space. In addition, where ductwork meets the building envelope, poor sealing will lead to infiltration of outside air. In a study of 70 small commercial buildings in Florida, it was found that 48 of the buildings experienced duct leakage, averaging a leakage rate of 579m^3/hour (at a pressure of 25Pa). The duct leakage was found to be three times greater than that experienced in the residential sector and the main causes of the problem were poor workmanship and designs [39]. A more recent duct leakage study [40] found that a main proponent to minimising duct leakage is to install ductwork with pre fitted rubber seals. In countries where this is common practice (Nordic countries), duct leakage has become a less critical variable in reducing the energy consumption in buildings. However, the authors agree with the preceding study, stating that on site modifications to ductwork reduce the efficiency of the duct system and cause more leaks, thus highlighting that poor workmanship and failures in the design stage almost inevitably contribute to duct leakage.

3.3.4.3 Building envelope

Unintentional openings in the building envelope can occur from poor workmanship and material degradation. The materials used to construct the building envelope will also have a major effect on the infiltration rate. Typical construction materials for office buildings in the UK include masonry, sheet metal, precast concrete and structural insulated panels. Masonry is limited to being constructed on site with individual labourers undertaking the work. This method is prone to infiltration through the porosity of the materials used, poor workmanship and cracks in mortar joints through the settling of buildings. Sheet metal, precast concrete and structural insulated panel facades are also assembled on site but each of these materials are manufactured in quality controlled environments where defects can be detected and repaired more easily. The main issue for air infiltration with these materials are where the individual panels are bonded to form a continuous facade. The joints are still prone to damage during settling of the building and the assembly can still be affected through poor workmanship.

Kalamees [41] notes that typical air infiltration paths occur at junctions between construction elements (ceiling/floor and external wall) and penetrations of services through the air barrier (electrical sockets, air ducts, plumbing pipes). Although the aforementioned study was conducted in houses, the houses were detached and, as such, give a similar representation of small, detached commercial buildings. Kalamees found that high air leakage was associated with the type of construction (prefabricated buildings were more airtight than buildings constructed on site) and the quality of workmanship (houses built by professional builders or with professional supervision were more airtight than those without). A more recent study of airtightness in relation to building envelope carried out by Pan [42] found that the construction materials affect the rate of air infiltration. 170 Finnish detached houses were tested for air leakage using the fan pressurisation test; timber frame and log buildings had average air change rates at 50Pa of 3.9 and 5.8ACH respectively, while houses built using prefabricated concrete sandwich elements and shuttering concrete block experienced average air change rates of 2.6 and 1.6ACH respectively. Pan's findings concur with the above study; 287 UK houses built to UK Building Regulations Part L1A were tested and it was found that precast concrete panel construction gave the lowest air permeability (2.21$m^3/h/m^2$) with the highest air permeability occurring in masonry construction (6.64$m^3/h/m^2$) [42]. Pan concludes that this is mainly due to the quality control achieved through prefabrication, which cannot be replicated on site.

3.3.4.4 Differential pressure between inside and outside

The stack effect is caused by pressure differences between indoor and outdoor environments and is a process by which infiltration can occur. Buildings tend to be heated, either by heating systems or internal gains, and this heated air will rise, leaving behind low pressure, cooler air below. The low pressure is sufficient to draw in air through cracks in the building fabric. While the stack effect can be used for ventilation purposes in naturally ventilated buildings, it is difficult to control and can result in infiltration of unwanted air, especially in the heating season when air temperatures indoors are much higher than those outdoors. In mechanically ventilated buildings, the stack effect will almost always result in infiltration as the fresh air supply has already been accounted for in the ventilation strategy.

3.3.5 Air infiltration testing

Buildings can undergo air leakage tests, the data from which can be processed to give a value for the air infiltration rate; the fan pressurisation (or blower door) method is common in the UK and will be discussed in this section.

The air permeability of a building in the UK is tested in accordance with BS EN 13829:2001 Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurisation method [43]. The code shall be consulted for a comprehensive view of the method while the main points will be discussed below.

The code gives two options for testing the building. Method A is a test of the building in use in either the heating or cooling season and Method B is a test of the building envelope. The difference between the tests is that Method A requires the intentional openings to be closed, while Method B requires all intentional *adjustable* openings to be closed and the remaining openings to be sealed. Therefore, in both methods, all of the external windows and doors will be shut but the air inlets and exhausts are sealed for Method B. In each method, the internal doors shall be wedged open to allow equal pressurisation throughout the building and all mechanical ventilation systems shall be turned off. Readings are taken for zero flow-, zero flow positive- and zero flow negative- pressure differences at the beginning and end of the test. If any of these readings is above 5Pa (indicating strong winds) the test will be declared invalid. The building is then pressurised, by either a single fan or a series of fans, to the desired pressure difference between the interior and exterior environment. Clause 5.3.4 states that houses and small buildings should be tested to maximum pressure difference of at least 50Pa although a pressure difference of 100Pa may give more accurate results. The code continues to state that for large buildings, a pressure difference of at least 50Pa may not be achievable due to the size of pressurisation equipment and of the building space. In this case, a pressure difference of at least 25Pa should be achieved; achieving a maximum of less than 25Pa means that the test is invalid.

The air permeability and air leakage index can be calculated from the results. It is important to recognise the difference between the two parameters – air permeability and air leakage index. The test determines the amount of air entering and escaping from the building fabric, the difference in parameters being that air permeability takes account of the floor, while the air leakage index does not. It is, arguably, very important to measure the amount of air escaping from the floor, as it is part of the building fabric and, as such, just as susceptible to defects as any other part of the fabric.

3.3.6 Envelope sealing and draught proofing

Reducing the air infiltration rate is one of the critical functions for achieving energy savings concerning space heating. As such, low energy buildings should be designed to be as airtight as possible, while still providing the required amount of ventilation air. A widely used method is to seal the envelope with an airtight membrane to avoid air escaping through porous materials and voids in the building fabric. It is important to design the building envelope so that there are no gaps in the airtight membrane, for example, where the sheets of the air barrier material overlap each other and where building services penetrate through the air barrier. The air barrier is an essential aspect of the building fabric for reducing air infiltration rates. It is widely agreed that typical building materials are either porous (masonry and concrete) or will have gaps between joints (prefabricated panels), allowing air exchange through the fabric. Specific areas that are most susceptible to air infiltration are joints in the facade, electrical sockets, penetrations of plumbing and wiring through the building fabric and joints between construction elements, such as where ceiling meet external walls. Thus, it is essential that in these types of construction the envelope is sealed to minimise the infiltration rate. The reader is referred to Good Practice Guide 224: Improving Airtightness of Dwellings [45] for further information supporting the benefits of reducing air infiltration rates.

3.4 Passive Solar Design

The envelope is the part of a building that will affect thermal transmittance and air permeability. Reducing thermal transmittance is achieved by increasing the thermal resistance of the building elements. Reducing the air permeability is achieved by creating a tighter building envelope. The techniques used to reduce heat loss through the building envelope are discussed in this section. For a comprehensive guide to designing passive solar buildings, the reader is referred to “Planning for Renewable Energy: A Companion Guide to PPS22” [46].

3.4.1 Shading

In low energy, passive solar buildings it is important to utilise solar gains during the heating season but to limit them in the cooling season to avoid overheating and glare. Shading provides the ideal solution for this problem [10].

Blinds can be used, either internally or externally to control the amount of light and heat entering a building. Internal blinds are protected from outdoor weather conditions and can reduce the amount of light entry when the sun us at a low angle and the amount of heat transmission during the summer. As they are located indoors, heat can still be transmitted into a building space, albeit at a slow rate. External blinds have the benefit of limiting the amount of light and heat actually entering the building, reducing heat gains more effectively than internal blinds. As they are located outside, they are susceptible to weather damage so must be of a more robust construction and, consequently, a higher cost is associated.

Louvres and light shelves are designed to be installed on the facade of a building, letting in some daylight to provide natural lighting, but blocking out some of the solar radiation, thus reducing the heat gains [10, 47]. They are most useful on facades that experience solar radiation ingress when the Sun is at a low angle; east and west facing facades are most common but south facing facades can experience the benefit of louvres in the winter when the Sun is at a low angle for most of the day. The major benefit of louvres is that they need no occupant interaction and, if designed correctly, will effectively block intense, high angle summer radiation but will allow less intense, lower angle winter radiation through, helping to heat a building in winter and reduce heat gains in summer.

3.4.2 Building Orientation

The Sun not only provides daylight but can also provide a usable form of heat. The heat gain is strongly affected by the orientation of the building [10]. In the northern hemisphere, sunlight covers the south face of a building, leaving the north face in shade; the opposite is true for the southern hemisphere. In both cases, the Sun rises in the east and sets in the west, meaning that the east face of a building experiences solar gain in the morning, and the west face will receive gains in the evening. The resultant effect is that in the morning, the east face of a building will be heated and lit by solar gains, the south face will receive heat and daylight throughout most of the day, the west face will be heated and lit in the late afternoon and evening, while the north face receives no direct sunlight or heat, only that reradiated from other sources. It would be sensible, therefore, to locate most of the glazing on the south face of the building to provide heat and light throughout the majority of the working day. East facing glazing will provide access for solar radiation, thus helping to heat the building in the morning. Glazing should also be installed on west faces but to a lesser extent than the south or east faces. The building will be heated throughout the day, whether by traditional heating systems, free solar heating, occupant and equipment gains or a combination of the three, resulting in high internal temperatures by the end of the day. This coincides with the sun at a low angle in the west; excessive glazing on the west face will increase the internal temperature even further and may require additional energy in the form of cooling.

3.4.3 Window to wall ratio

Window to wall ratio (WWR) is the proportion of a facade that is formed with glazing elements as opposed to wall elements. WWR is expressed in decimal form or as a percentage of the area of wall that is comprised of windows. The amount of windows in a facade will have an impact on the amount of daylight and solar heat gains the building can take advantage of but will also have an impact on the heat loss from the interior space. Increasing WWR will result in high amounts of daylight and solar heat gains but it will also mean that the amount of heat lost from a building will also be increased as thermal transmittance of glazing is almost always greater than that of solid walls.

However, this is only one aspect of the problem facing low energy building designers. Where to place windows will also have an effect on how effectively a building is able to use solar energy to reduce its energy demand. In the northern hemisphere, windows on the south facade receive the majority of natural light and solar heat gains through the day. On the other hand, windows on the north facade only receive benefit from diffuse radiation during the day; radiation that has been reflected from other surfaces and, as such, has already dissipated some of its energy. Windows on the east facade are able to take advantage of solar heat gains at the beginning of the day, assisting in warming the building to comfort temperatures before occupants arrive. Windows located on the west facade allow solar gains through in the afternoon, which, in conjunction with casual and solar heat gains during the day, may result in a building overheating [10, 48]. For a building to effectively take advantage of passive solar gains, the WWR should be highest on the south facade, lowest on the north facade and, depending on the heating and cooling strategy, the WWR on the east and west facades should lie somewhere in between [49].

In a study on the design of a net zero energy house in the UK, Wang *et al* [49] found that the optimum WWR for south facades was 0.4 and for all other facades was 0.1. The study found that rooms with west facing facades typically have the highest heat gain from solar radiation and require the most cooling. South facing facades experienced the lowest cooling demand when WWR=0.1 but lowest heating demand when WWR=0.4. Heating demand, however, was approximately 100 times greater than cooling demand resulting in a justification for WWR of 0.4 for south facing facades. The study demonstrates the heat gains from solar radiation through windows due to their high thermal transmittance and how manipulating the location and amount of glazing can assist in reducing energy consumption.

3.4.4 Intelligent zoning

The orientation will have an impact on the use of the rooms inside the building; and intelligent design, with regards to zoning, can maximise the solar gains for the best use in the building. Equipment and occupants in commercial buildings will emit heat, providing another source of heat in addition to solar gain and heating systems. If uncontrolled, this can lead to overheating, the use of cooling equipment, and additional energy usage. A balance is required between comfort and practicality. A commercial building will require occupants and equipment necessary for its operation and, as such, these critical elements cannot be sacrificed. Therefore each room should be located in an area of the building where the by-products of the activities taking place can be utilised to reduce energy consumption.

The north side of a building will usually be cooler than the south side, providing an ideal place for locating equipment that emits large amounts of heat. IT equipment, central HVAC systems and changing facilities, including showers, are all ideally suited for cooler areas of buildings as the heat released can assist in offsetting the heating load that would normally be required to maintain comfortable temperatures. South facing rooms are ideal for human occupancy. The sunlight available on the south facing side provides heat and light to these rooms, meaning that the heating and lighting loads can be reduced significantly by harnessing these gains [10].

3.5 Comfort

Buildings tend to be occupied by humans and the human body is very sensitive to changes in the environment, such as temperature, humidity and air velocity. In order to keep occupants satisfied, the building should be designed with controls to maintain comfortable conditions. However, for many buildings, comfortable conditions are usually achieved through energy intensive building services. Most buildings will have a method of heating, cooling and ventilating the interior space, with some buildings in hot and humid climates having air conditioning equipment as well.

3.5.1 Thermal comfort

In the UK, the Workplace (Health, Safety and Welfare) Regulations 1992 state that a reasonable temperature must be maintained in workplaces; reasonable is defined as a minimum of 16°C in an office or 13°C if there is physical work [50]. CIBSE makes recommendations for best practice temperatures in the workplace, with the aim to achieve a 90% occupant satisfaction rate. CIBSE recommend that general office space in the UK is maintained at an operative temperature of 21-23°C during winter and 22-24°C during summer [51].

3.5.2 Predicted mean vote (PMV) and predicted percentage dissatisfied (PPD)

PMV is the average thermal sensation response of a large group of people using the ASHRAE thermal sensation scale (Table 3.3). The equation for calculating PMV was developed by Fanger by conducting a series of experiments [52]. Subjects would be exposed to varying:

- Air temperature;
- Mean radiant temperature;
- Air velocity;
- Air humidity;
- Clothing resistance; and
- Activity level.

They would then report their thermal sensation using the ASHRAE thermal sensation scale. The results were correlated and Fanger developed the following equation to predict the thermal sensation for a variety of thermal conditions:

$$PMV = (0.303\, e^{-0.036M} + 0.028)\, L$$ [52]

where M is the metabolic heat rate and L is the thermal load on the body. Fanger found that optimum comfort conditions were realised in very narrow ranges of skin temperature and sweat evaporation rate.

Thermal sensation	Corresponding value
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Table 3.3: ASHRAE thermal sensation scale [53]

Predicted percentage dissatisfied is a method of representing how many people would be comfortable under specific thermal conditions and is related to the PMV such that a PMV of ±0.5 corresponds to a PPD of 10% [51]. The design brief for a building may require the thermal comfort level to be maintained within a certain range of PMV values; the narrower the range (and thus higher the level of thermal comfort), the greater sophistication will be required for the HVAC systems.

3.5.3 Adaptive thermal comfort

The adaptive theory to thermal comfort [54] claims that occupants will adapt to their environment to maintain thermal comfort levels. This may be achieved by controlling their metabolic rate through level of activity (more movement when temperatures are low and less movement when temperatures are high), changing the amount and type of clothing, opening and closing windows to control temperature and 'freshness' levels, operating heating and cooling equipment and moving around the building to take advantage of sunlight or shade. Nicol and Humphreys summarise the adaptive theory to thermal comfort;

" if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" [55].

Proponents of the adaptive theory claim that occupants can be satisfied with a wider range of internal temperatures than those stated in section 1.2.1. For example, de Dear and Brager [56] found from a study of thermal comfort field experiments that there is a difference between comfort temperatures experienced in mechanically cooled and naturally ventilated offices. The study found that the thermal sensation votes of occupants of a naturally ventilated building were almost identical for indoor temperatures of 22°C and 27°C whereas most occupants in a mechanically cooled building found that 27°C was too warm. The authors suggest that occupants of naturally ventilated buildings are more forgiving of the wide range of temperatures that will be experienced, while occupants of mechanically cooled buildings become accustomed to the narrower band of comfort temperatures and, as such, different thermal sensations are experienced by the two sets of occupants.

Nicol and Humphreys [55] claim that occupants should have the opportunity to alter their indoor conditions otherwise discomfort is likely to occur if there are no controls or if these controls are ineffective. They suggest that in a building with no occupant control (one in which the occupants cannot change their clothing, activity or air movement) the comfort temperature band can be as low as ±2℃ but is much wider where occupants can adapt to their conditions; Humphreys' previous research shows that an annual comfort temperature range of 10℃ is achievable [57]. The measured mean indoor temperature closely correlates with the comfort temperature in naturally ventilated buildings and the comfort temperature of a free-running building and the mean outdoor temperature follow a linear relationship, with the comfort temperature increasing with increasing mean outdoor temperature [58]. However, in heated or cooled buildings, the comfort temperature is in a narrower range and the relationship between comfort temperature and mean outdoor temperature is weaker [58].

3.5.4 Ventilation

Buildings require a ventilation strategy to provide an adequate level of supply air to occupants, to remove odours, to avoid the accumulation of harmful gases and to prevent condensation inside the building fabric [59]. The ventilation rate required for supplying clean air is usually much lower than that for removing unwanted gases and odours, thus it is the latter variable that tends to dominate when calculating ventilation rates in a building. The amount of fresh air required to provide oxygen is 0.2l/s per person, whereas to give a feeling of freshness requires 10l/s per person [51]. CIBSE suggests an air supply rate of 8l/s per person for general office spaces in the UK [59].

3.5.5 Humidity

Buildings may also need to control relative humidity as this can cause more discomfort than inadequate temperatures. Relative humidity (RH) is the ratio of the amount of water vapour currently in the air to the amount of water vapour required for total saturation. In buildings, it is recommended to maintain the RH between 40% and 70%. A RH less than 30% will cause the air to feel very dry, causing discomfort especially in the eyes and mouth, and can also lead to electric shocks through a build-up of static electricity. A RH greater than 80% will cause occupants to feel sticky through condensation on the skin. Condensation may also occur on the interior surfaces and furniture, which can result in mould growth, leading to illness [10, 51].

3.5.6 Achieving thermal comfort in practice

In order to fulfil the criteria for comfort, some form of heating, cooling and ventilation strategy is required. This strategy may consist of mechanical systems with control over the temperature, air intake and humidity or a natural system that relies on passive heating and cooling, wind driven ventilation and no humidity control. In either condition it is of the utmost importance to avoid unnecessary air leakage and heat loss through the building envelope as these will result in excess energy use and possibly over-sizing of mechanical plant and the additional costs that ensue.

Low energy buildings should, ideally, be designed so that they do not require the additional energy input involved in mechanical heating and cooling, instead relying on internal and solar gains to achieve the heating requirement and making use of natural ventilation for achieving the cooling requirement. If natural methods of heating and cooling a building can be used to achieve comfort conditions effectively, these methods should be adopted. From the research by de Dear and Brager [56] and Humphreys [57, 58], it is evident that free running buildings provide more comfortable conditions for occupants at higher internal temperatures than heated or cooled buildings. The evidence demonstrates that eliminating the requirement for HVAC systems – and the inherent energy demand – can assist in achieving adequate thermal comfort. It therefore seems sensible to adopt a natural heating and cooling strategy, the results of which could reduce energy demand and increase thermal comfort. In addition to using sunlight for heating and wind driven ventilation to provide cooling, the occupants should be given opportunities to control their environment and should be briefed on the aims of the building's energy reduction agenda. Nicol and Humphreys [55] claim that occupants require control over their environment in order to achieve thermal comfort. Be that as it may, occupants of low and net zero energy buildings must be vigilant to reduce unwanted air movements into and out of the building and unnecessary overheating by adequately controlling window openings and shading as these will contribute to additional energy demand and uncomfortable thermal conditions.

3.6 Summary

This chapter has investigated the end uses of energy within commercial buildings and has discovered that a large proportion of this energy is due to heating and cooling building spaces. It then examined the methods that thermal energy usage can be reduced through the building fabric, orientation of the structure, and low energy design techniques. The chapter also discussed the methods by which heat is lost from a building space and came to the conclusion that this was from thermal transmittance across the building fabric and through air infiltration. The findings from this chapter will help to give an understanding of building energy end uses, building construction and methods of heat loss. This will be useful when analysing the case study building in the following chapter.

4 Low, nearly zero and net zero energy building case studies

4.1 Introduction

The previous chapter investigated the importance of reducing thermal transmittance and air infiltration on the energy performance of buildings and then investigated the techniques and products available to designers for achieving high performance building envelopes. This chapter studies nine well documented low, nearly zero and net zero energy buildings to determine if there is a consensus amongst the design of building envelopes towards achieving low energy demand and the specific techniques and products that each of these buildings incorporates. The following buildings were selected primarily due to the extensive research that has been undertaken and documented. They were chosen as they are all commercial buildings, which gives a good reflection of the building processes that are to be encountered and makes the studies relevant to the theme of this research. In addition, they are all buildings that either had the aim of achieving net zero energy performance or showcased good low energy design practice that could help to inform the design decisions in this thesis. Although none of the buildings are from the UK, the extent of the information provided about the nine selected buildings meant that the case studies could be presented and analysed in much more detail. The information obtained for the case studies consists of technical reports and information from the High Performance Buildings Database [60]. The buildings are as follows:

- Adam Joseph Lewis Centre for Environmental Studies at Oberlin College [48, 61];
- NREL Research Support Facility [47];
- The Science House in Minnesota [62-64];
- Solar XXI Office Building [65-67];
- Chesapeake Bay Foundation’s Philip Merrill Centre [68, 69]
- Cambria Department of Environmental Protection (DEP) Building [70, 71]
- NREL Thermal Test Facility[68, 69, 72, 73]
- BigHorn Home Improvement Centre [74-77]
- Zion National Park Visitor’s Centre [78-81]

The case studies have been separated into three distinct categories: those that have achieved net zero energy performance; those that have achieved nearly zero energy performance and those that intended to achieve a significant improvement in energy performance when compared to a similar building designed to minimum standards. The rationale of separating the case studies into successes and failures is to determine the attributes of successful net zero energy buildings, which can then be incorporated into a low energy building design and to determine the attributes of buildings that fail to achieve net zero energy performance and to learn from these failures in order to achieve success in designing a low energy building that operates at the same annual thermal energy demand in any location in the UK.

The first three case studies have achieved net zero energy performance and are:

1. Adam Joseph Lewis Centre for Environmental Studies at Oberlin College
2. NREL Research Support Facility
3. The Science House in Minnesota

The fourth case study is a nearly zero energy building that aimed to achieve net zero energy performance:

4. Solar XXI Office Building

The final five case studies are those that were not aiming for net zero energy performance but still showcase good low energy practice:

5. Chesapeake Bay Foundation’s Philip Merrill Centre
6. Cambria Department of Environmental Protection (DEP) Building
7. NREL Thermal Test Facility
8. BigHorn Home Improvement Centre
9. Zion National Park Visitor’s Centre

The data items collected for each building consist of:

- Thermal energy consumption
- Size
- Building type
- Renewable energy system and capacity
- Thermal transmittance of external building envelope elements
- Infiltration rate
- Building orientation
- Clerestory windows
- Solar shading
- Window to wall ratio
- Natural ventilation
- Natural daylighting
- Thermal mass

These data items have been collected, analysed and compared between buildings in order to judge the most effective design and operation elements for reducing thermal energy consumption. The data was collected through researching published articles about the design and performance of each building. Not all data was available for each building. The data that was available allowed for comparisons of design criteria to be made in order to ascertain the most effective parameters for reducing end use thermal energy consumption.

4.2 Adam Joseph Lewis Centre for Environmental Studies at Oberlin College, Ohio

Figure 4.1: Photograph of Adam Joseph Lewis Centre for Environmental Studies at Oberlin College [82]

Location: Oberlin, Ohio, USA
Size: 1260m^2
Building type: Two story educational building with classrooms, offices and an auditorium
Climate: 3254 heating degree days and 619 cooling degree days (base 18℃) [83]
Occupancy: 80 people for 60 hours per week

Energy Performance Aim

The Adam Joseph Lewis Centre was designed and constructed with the aim of maximising energy efficiency and meeting as much of the thermal, lighting and equipment energy use through renewable energy resources as possible. The designers aimed for the building to be a net energy exporter[48].

Building form

The building has been constructed on an east-west axis [48] with a narrow construction to allow sunlight to efficiently penetrate into the rooms. The south facade has a large WWR of 0.57 [48] to take advantage of the solar gains for heating and daylighting, while the north facade has a lower WWR of 0.37 [48] as the only solar gains are from diffuse radiation. The west facade has the lowest WWR of just 0.14 [48] to reduce the amount of heat entering the building in the late afternoon and evening. The east facade has a WWR of 0.48 [48], which will help the building to heat up to comfort temperatures before occupants arrive in the morning.

The classrooms are located in the south facing section of the building as they have the highest use and can take advantage of the solar gains. On the other hand, the mechanical plant rooms and kitchen, which do not require as much heating, are located in the northern zones of the building [48]. The offices on the first floor are located at the north of the building but have clerestory windows to allow diffuse radiation to enter to provide natural light [48]. The auditorium is primarily used for presentations [48], which usually require projection equipment and dark conditions. As such, the auditorium has been designed without any windows. The atrium is connected to all internal corridors without any partitions, meaning that all circulation areas are provided with heat from the solar gains in the atrium.

Building envelope

Floor

Perimeter footings have 50mm rigid insulation, 400mm concrete footing and another 50mm rigid insulation giving thermal transmittance of U=0.26W/m^{2}K [48].

Atrium slab has 50mm rigid insulation, 250mm concrete slab and 17mm slate giving thermal transmittance of U=0.5W/m^{2}K [48].

Non atrium slab has 50mm rigid insulation, 150mm concrete slab giving thermal transmittance of U=0.52W/m^{2}K [48].

First floor has 50mm rigid insulation, 150mm concrete slab, 300mm air gap, decking and carpet giving thermal transmittance of U=0.48W/m^{2}K [48].

Roof

Curved roof has standing steel seam, felt paper, sheathing, 25mm air gap, 125mm rigid polystyrene insulation and wood decking giving thermal transmittance of U=0.21W/m^{2}K [48].

Flat roofs have stone ballast, 100-200mm XPS, 100mm concrete with metal decking giving a range of thermal transmittances of U=0.14-0.28W/m^{2}K [48].

Walls

North facing and underground walls have 50mm of rigid polystyrene insulation and 400mm concrete masonry providing thermal transmittance of U=0.48W/m^{2}K [48].

Auditorium walls are made of 100mm brick, 25mm air gap, 75mm polystyrene insulation and 300mm of concrete masonry providing thermal transmittance of U=0.29W/m^{2}K [48].

All other walls are made as the auditorium walls but with 200mm concrete masonry rather than 300mm and provide thermal transmittance of U=0.30W/m^{2}K [48].

Windows
South facing curtain wall with, triple glazed and argon filled tinted glass with thermal transmittance of 2.0W/m^{2}K and SHGC of 0.26. All other windows are double glazed, tinted and have thermal transmittance of U=2.5W/m^{2}K and SHGC of 0.46 [48].

Natural daylight

To the south of the building is a large, south facing, curtain wall glass facade [48], which allows natural daylight to enter and reduces the lighting energy consumption. There are clerestory windows on the north facade [48] to allow diffuse radiation to enter the rooms on the north side of the building. The roof overhangs the south and east faces of the building [48] to allow diffuse radiation in while blocking the high angle sunlight to prevent overheating. Also, the east facing side of the atrium has adjustable blinds [48] to reduce the intensity of the low angle sunlight. The ground floor classrooms have light coloured ceilings [48] to effectively distribute daylight. The first floor classrooms, however, have dark wooden ceilings [48], which hinder the distribution of light, especially as the rooms use uplighting. The lighting energy load could be reduced by incorporating light coloured ceilings in these rooms.

The building lighting is controlled both manually and through automatic sensors; automatic sensors activate lights when occupants are detected and the lighting level can be controlled manually [48]. The building operators noticed that corridor lights were activated even when daylight levels were sufficient and that there was some misuse of lighting controls. Since June 2001, the lighting has been changed to sense light levels as well as occupancy and has resulted in a much lower lighting load [48].

Solar passive heating

The atrium facade is made of curtain wall glass to allow solar radiation to pass through and heat the building. The floor slab in this area is thermally massive, retaining high amounts of heat and reducing fluctuations in the indoor temperature. The roof, exterior walls and floors are made of thick construction elements (the exterior walls and floors range from 300-500mm in thickness) to minimise the diurnal fluctuations in temperature and to help reradiate heat. This subsequently reduces the heating and cooling loads. There are internal blinds on the east facing side of the atrium to reduce the intensity of the low angle solar radiation to prevent overheating of this space. The building operators found that while the atrium allows sufficient daylight entry, the large area of glazing has resulted in higher heating and cooling loads [48]. This could be improved through using low emissivity coatings on the glazing or by using more insulated glazing units.

Passive ventilation

A natural ventilation system [48], relying on the stack effect, is used in the atrium to provide fresh air and remove unwanted odours and gases. The lower windows in the atrium open from the bottom to allow cold, dense air to enter, which is subsequently heated through solar passive heating. The heated air rises to the top of the atrium, where it leaves through window openings. As the heated air leaves, it draws colder air in from the lower windows to replace the lost volume of air. This method of ventilation is only used outside of the heating season, when the removal of warm air will be beneficial for the comfort of the occupants.

Energy Generation

Energy is generated on site by two arrays of monocrystalline photovoltaic panels [48]. The first array is a 60kWp installation located on the curved roof of the building and the second, later, 100kWp array is located on the car park roof canopy. The entire PV system provides enough electricity for the operation of the building over the year and is able to provide surplus electricity to the grid in times of over production. This system allows the building to gain the status of a net site and net source zero energy building. All of the services are entirely electrical so that the PV array can provide energy for everything in the building. This also allows the building to continue functioning as normal when fossil fuel supplies are depleted.

Energy Consumption

The Adam Joseph Lewis Centre for Environmental Studies operates at a total energy demand of 101.7kWh/m^2/year, and the thermal component of this is 67.5kWh/m^2/year [61].

4.3 NREL Research Support Facility

Figure 4.2: Photograph of NREL Research Support Facility [84]

Location: Boulder, Colorado, USA
Size: 20300m^2
Building type: Research, Office, Multi-storey (4 floors)
Climate: 3442 HDD and 541 CDD (Base 18℃) [83]
Occupancy: 800 occupants, 40 hours per week

Energy Performance Aim

The energy performance aim of the NREL Research Support Facility was to achieve net zero energy performance in a large scale, cost effective and replicable office building [47].

Building form

The building is situated on an east-west axis and has a relatively narrow floor plan; the building has an aspect ratio of 13 [47]. It is split into two wings that are connected by circulation space and common areas [47]. The floor plan is only 20 [47] metres deep meaning that occupants are no more than 10 metres from a window, which assists in a natural ventilation and daylighting strategy. The north wing is taller than the south wing so that the north part of the building still has access to direct sunlight and isn't overly shaded by the south portion. The building has been designed in a "lazy H" form [47] (the gap between the wings is smaller at the east side than the west side). This allows natural daylight to penetrate the unoccupied space in between the wings, providing daylight and heat gains to both portions of the building. While the designers have opted for two wings, thus increasing the surface area and, subsequently, the cost of construction, the building benefits from the high combined amount of south facing facade, which will reduce the building's heating and lighting energy requirements.

Building envelope

Floor

The floor construction details are not available in the literature although it may be assumed that the maximum allowable thermal transmittance of U=0.55W/m^{2}K was taken [85].

Roof

The roof has a thermal transmittance value of U=0.17W/m^{2}K and still retains the property of high thermal mass by incorporating 125mm concrete [47].

Walls

External walls are comprised of 75mm concrete on the exterior, 75mm rigid foam insulation and 150mm concrete on the interior. The result is a thermal transmittance value of approximately U=0.4W/m^{2}K [47]. This is rather high for a net zero energy building but the concrete walls provide a very high thermal mass, which regulates the temperature.

Windows

Within the office areas, there are three types of windows [47]; a lower, opening window, an upper, opening window (north) and an upper, sealed window (south). The lower window is a triple glazed unit with a low emissivity coating, a solar heat gain coefficient of 0.22 and thermal transmittance of U=1.9W/m^{2}K [47]. The upper windows are double glazed units with a low emissivity coating a solar heat gain coefficient of 0.38 and thermal transmittance of U=2.5W/m^{2}K [47]. The frames in all types of window are thermally insulated [47] to reduce the heat loss through them.

The building has a window to wall ratio of 28% on the south facade and 26% on the north facade [47]. While it is unusual to have such close matching WWRs on south and north facades (the south will experience much more solar gain than the north), the building has been designed with an aggressive natural daylight strategy, the details of which are discussed below.

Natural daylight

The east-west orientation and high aspect ratio (narrow floor plan) enhances daylight access for most occupants. The windows on the north and south facades, as stated, are comprised of two separate units. The lower, opening windows have large shading elements along each side and along the top of the glazing [47]. This limits solar heat gains by limiting the amount of direct solar radiation entering the building but still provides access for diffuse radiation. This is particularly useful for occupants situated at desks close to windows as the glare element of natural daylight has been reduced. The top windows on the south facade are sealed and are purely for natural daylight entry [47]. They incorporate a unique louvre blind system [47] that reflects incoming light upwards to the ceiling, allowing it to penetrate further into the building to provide the lighting requirements for all occupants situated at workstations. The north facing windows have no shading devices [47] so that they can take advantage of any diffuse radiation. The natural daylight strategy is so aggressive that all of the furniture and interior walls, floors and ceilings are light coloured with [47] the aim of reflecting light throughout the space.

Passive ventilation

The narrow floor plan of the Research Support Facility is conducive to passive, wind induced ventilation and the relatively tall ceilings are employed for stack induced ventilation. Lower windows are operable at all times but temperature sensors in the building alert occupants as to when they should open and close windows to maintain comfortable conditions [47]. During mild and warm weather, wind can flow in through open lower windows. The heat in the building warms the air and causes it rise and escape from the open, upper windows on the north facade. The escaping air draws cooler, outdoor air in through the lower windows, resulting in a ventilation path. The office space has been designed to have low level desks and short dividers [47] so that there are few restrictions to the air flow path.

An underground, concrete labyrinth is connected to the building and provides night time cooling and ventilation in the warm summer months [47]. The concrete provides thermal mass and, as it is located beneath the building, the air temperature fluctuates only slightly throughout annual and diurnal cycles.

Passive solar heating

The windows on the south and north facade provide daylight and solar gains but the most intensive sunlight often comes from ingress through east and west facing glazing; the sun is at its lowest angle and can cause glare and excessive heat gains. Thermochromic windows are located on the east facade [86]. The glazing tints as the temperature increases; daylight and heat can enter the building in the early morning but are limited when the radiation becomes too intense. Electrochromic windows [86], located on the west facade, tint instantly when an electric current runs through the glazing. This is particularly useful to limit heat gains in the late afternoon when the building has already been heated through solar and internal heat gains. On the other hand, during the heating season, the windows can be left as transparent units, allowing radiation to enter and support the heating strategy.

The construction elements have been designed to have high thermal mass [47]in order to regulate the temperature of the building through all seasons. One explanation for the relatively high thermal transmittance of the walls is that the designers were concerned with the risk of overheating. As the building is highly glazed and has a large occupancy density, the solar and internal gains, coupled with the HVAC systems, are sufficient to provide comfort conditions; any more insulation may result in the internal temperatures becoming too high, causing a higher cooling energy demand.

Energy consumption

The NREL Research Support Facility has an end use energy intensity of approximately 110kWh/m^2/year [47] and it is able to meet this demand through two photovoltaic systems with a combined capacity of almost 1.7MW [47]. Of the total energy consumption 29.7kWh/m^2/year [47]is used for heating and cooling.

4.4 The Science House in Minnesota

Figure 4.3: Photograph of The Science House in Minnesota [87]

Size: 142m^2

Location: St Paul, Minnesota, USA

Climate: 4079 HDD and 572 CDD (Base 18°C) [83]

Occupancy: Typically occupied by two people for 14 hours per week each and 795 visitors per week (approximately 0.12 hours per person per week)

Type: Education, experimental, classrooms, office.

Energy Performance Aim

The aim of the Science House was to create a habitable building in a cold climate that could be designed and constructed at low cost and achieve net zero energy performance [63].

Building form

The Science House is built on an east-west axis, with a large south facing façade that optimises the daylighting and passive solar heating strategy. The majority of the south façade is glazed to allow entry of solar radiation to provide heat and light, while the other faces are minimally glazed to avoid glare and heat loss (from the north façade) and overheating (from the west and east facades). In addition to minimising heat loss by limiting the glazing area on the north façade, the Science House has been built into a slope so that the temperature across the north face is regulated by the ground. This means that the building avoids losing heat in the winter as the ground temperature is warmer than the air and avoids overheating in the summer as the ground temperature will be cooler than the air. The floor area is relatively small for a net zero energy building at only 142m^2; this means less of a requirement for heating and cooling as the space is small, but also means that the options for building integrated photovoltaic energy are limited by the size of the envelope. The Science House is a single storey building with a mezzanine floor on the north side.

Building Envelope

There is limited information about the construction elements but some values of thermal transmittance and materials have been provided. The envelope has been designed to have a low overall thermal transmittance value and uses an insulation product (Icynene [62]) that reduces air infiltration in addition to insulating the building from heat loss. The U values of the construction elements are as follows:

Floor thermal transmittance U=0.5 W/m^{2}K [62]
Wall thermal transmittance U=0.2 W/m^{2}K [62]
Roof thermal transmittance U=0.14 W/m^{2}K [62]

The windows, comprising a large area of the building envelope have been specified to have low thermal transmittance with a U value of 1.82 W/m^{2}K and a solar heat gain coefficient of 0.25 [62], thus reducing the entry of the heat component of solar radiation.

Passive solar heating

The building has a largely glazed south façade, which encourages the ingress of solar radiation to supply a proportion of the heating energy demand, while the risks of overheating are limited by the low SHGC. The clerestory windows help to warm the air in the north space to provide a reduced temperature gradient throughout the entire space. The lower section of the north wall is buried in the ground and is of mass concrete construction, providing thermal mass for the building. Heating is critical to the comfort of occupants and performance of the building as it is located in the cold climate of Minnesota. On a typical sunny winter day, the PV panels generated 35kWh yet the energy use in the building was just 29 kWh [62]; this, despite the outside temperature in winter ranging from -17C to a maximum of -6C, resulted in indoor temperatures of 18-20C [62]. This is evidence that the passive solar heating design is able to function in a cold climate and that surplus PV energy generation is achievable regardless of the low angle sun in winter.

Passive ventilation

The Science House incorporates a design for passive ventilation to minimise the energy required in comparison to a mechanically ventilated strategy. Operable clerestory windows on the south façade allow fresh air to enter through a wind driven strategy while a large tower is located at the north side of the building to allow room air to escape. The tower is taller than the rest of the building, assisting the escape of unwanted heated air and drawing cooler fresh air in through the clerestory windows to replace it.

Natural daylight

The natural daylight strategy is designed to reduce the amount of energy used for electric lighting at all times of the year but without compromising on comfort. Nearly all of the south façade is glazed but a 1.2m, overhanging solar shading element has been incorporated into the design to achieve the correct lighting levels. In summer, the shading element blocks most of the direct sunlight from entering but still allows diffuse radiation to pass through the glazing. In winter, the low angle sunlight is optimally harnessed as it is able to penetrate from beneath the overhanging shades. The clerestory windows at the top of the south façade assist in daylight entry to the furthest reaches of the north wall, thus providing adequate lighting levels to all of the floor area despite the relatively large depth of the internal building space.

Energy consumption

The Science house in Minnesota is a net zero energy building due to its total on site renewable energy generation of between 7900kWh and 9000kWh annually [63]; the photovoltaic system has a peak capacity of 8.8kW [64]. The intelligent use of a high performance building fabric and passive systems result in a heating and cooling energy demand of 32kWh/m^2/year [64].

4.5 Solar XXI Office Building

Figure 4.4: Photograph of Solar XXI [88]

Size: 1500m^2
Location: Lisbon, Portugal
Building type: Commercial/Office
Climate: 959HDD, 693CDD (Base 18℃) [83]
Occupancy: 50 occupants for approximately 40 hours per week

Energy Performance Aim

The aim of the Solar XXI building was to achieve net zero energy performance in a commercial building. However, despite the efforts of the designers, the building has marginally failed to achieve this aim [66].

Building form

Solar XXI is a two storey, near zero energy, office building in Lisbon [66]. The building is oriented on an east-west axis with office space located to the south and laboratories, auditoriums and lavatories located to the north [66]. The designers have located the most occupied rooms in the space of the building that receives the greatest solar gain and have placed the rooms that do not require natural light and heat gains to the north of the building.

Building envelope

Floor

The floor is insulated with 100mm expanded polystyrene insulation, giving thermal transmittance of $U=0.55W/m^2K$ [66].

Roof

The roof is insulated with 50mm expanded polystyrene and 50mm extruded polystyrene insulation applied externally, giving thermal transmittance of $U=0.26W/m^2K$ [66].

Walls

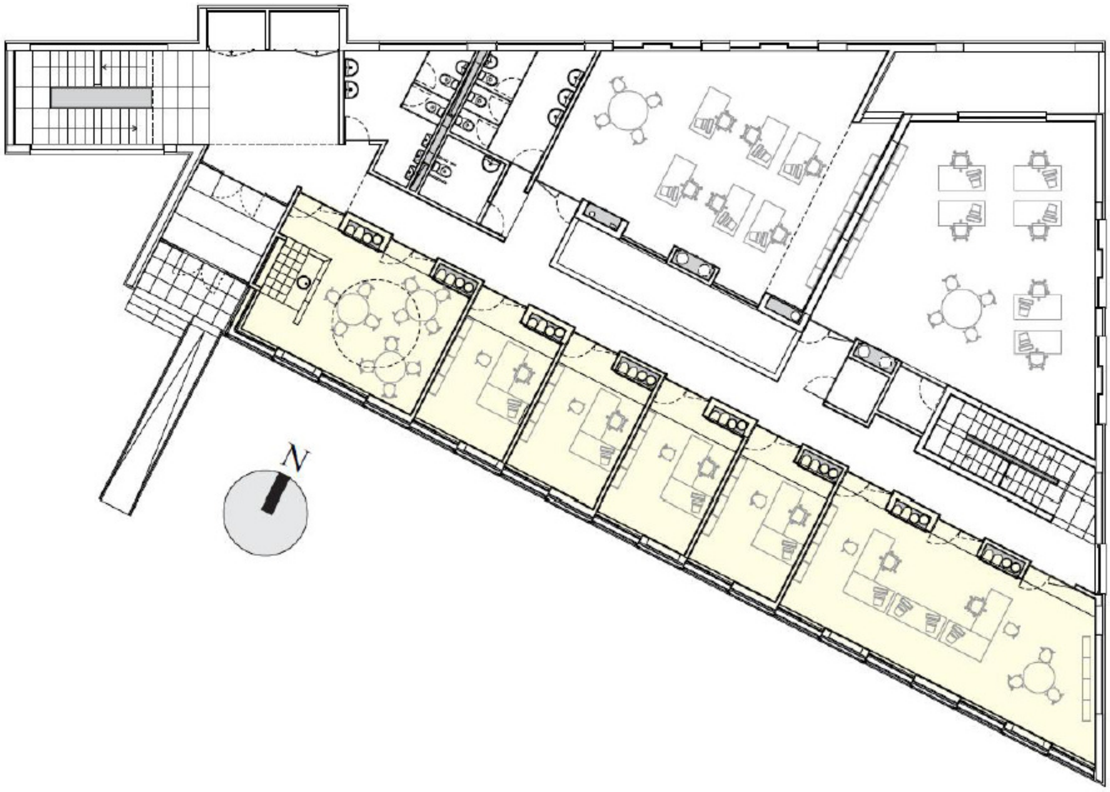
External walls are comprised of hollow bricks with 60mm of expanded polystyrene insulation situated externally. The resulting thermal transmittance is $U=0.45W/m^2K$ [66].

Windows

Double glazing, transparent windows with internal blinds are used and give a thermal transmittance value of $U=3.5W/m^2K$ [65].

Natural daylight

The offices of Solar XXI are located in the south of the building and have large windows to allow natural daylight to enter [65, 66]. The offices are relatively shallow so that the furthest points from the windows still benefit from natural daylight.



4.5: Plan of the Solar XXI Office Building [66]

The building has a centrally located light well that allows natural daylight to penetrate through the structure's three floors [65, 66]. The light well incorporates a south facing canopy allowing direct daylight access during the winter months but only diffuse radiation during the summer months [65, 66], thus limiting the glare aspect of natural light. The light well, located in the brightly finished central core, provides access to natural daylight even for the ground floor rooms at the north side of the building.

Solar passive heating

The south facing offices with large windows take advantage of the heat provided directly from solar gains and the central light well provides heat for the circulation areas of the building. Solar panels are located on the south facade of Solar XXI and cover an area equal to the glazing. The designers were also able to utilise the solar gains from the PV system to provide heat to the offices. Behind each PV panel is a hollow section of wall with two vents located at the top (one on the inside of the facade and the other on the outside) and one at the bottom. Cold air enters the lower vents naturally and is heated by the energy transferred from the rear of the PV panels to the building fabric. This warms the air, causing it to rise to the upper vents. During winter, the upper internal vent is opened and the external vent is closed, which forces warm air into the occupied space and provides comfort temperatures. During summer, the external vent is opened and the internal vent closed, forcing the heated air outside and maintaining comfort temperatures indoors. This process also has the benefit of cooling the rear of the PV panels, thus increasing their overall efficiency.

Passive ventilation

The central light well has another use besides providing light to the interior rooms; it also stimulates natural ventilation through the stack effect [65, 66]. The light well incorporates opening windows at the top to allow heated air to escape. As the light well is three floors high, a temperature gradient will be formed along its height with lower temperatures at the ground floor and higher temperatures at the top. The result is warm air leaving the building from the open windows and the lost volume of air is replaced with cool air drawn in through openings in the fabric. In addition, the air leaving the building from the upper vents behind the PV panels [65, 66] will also have the effect of drawing in air from outside and will stimulate natural ventilation.

A passive cooling strategy has been employed in the building by using buried concrete pipes that link the building to the external environment [65, 66]. Fans are used to draw in air through the pipes and the high thermal mass of the concrete and the location of the pipes below ground help to pre-cool the incoming air, thus reducing the energy demand for mechanical cooling.

Shading

External venetian blinds are located on the south facade of the building, with internal blinds on the other facades and a south facing canopy over the light well, all of which provide shading [65, 66].

The venetian blinds are manually operated [66] and, thus, rely on occupants to control the solar radiation access to the rooms. This means that that the occupants can manoeuvre the blinds for their own comfort but must be vigilant when controlling the room temperature by manipulating the blinds first and, if required, the heating and cooling systems next.

The canopy over the light well allows low angle sunlight to enter the building through the central core in the winter and at the beginning and end of the day [66], when the solar intensity is lower. In the summer and during the bulk of the day, the canopy acts as a shading device to limit the amount of direct radiation entering the building whilst still allowing the entry of diffuse radiation. This limits the heat component of solar gain without a detrimental impact on the light component.

Energy consumption

Solar XXI is a near zero energy building that will benefit from an additional photovoltaic system to achieve net zero energy performance. The current photovoltaic system has a peak capacity of 18kW but a further 12kW array has been specified [65]. Be that as it may, Solar XXI is also an example of the effects that improved building fabric (compared to building regulation minimum standards) and passive design techniques will have on a building’s energy performance. The building, due to its design, is operating at a 64% reduction in energy consumption compared to the same office built to Portuguese Building Code [65] and the site energy intensity for heating is just 4.4kWh/m^2/year [65].

4.6 BigHorn Home Improvement Centre

Figure 4.6: Photograph of BigHorn Home Improvement Centre [89]

Location: Silverthorne, Colorado, USA
Size: 3936m^2
Building type: Retail, office, warehouse
Climate: 6090 HDD, 55CDD (Base 18℃) [83]
Occupancy: 95 occupants on average, 77 hours per week

Energy Performance Aim

This building was not designed with the aim of achieving net zero energy performance, rather it was designed to achieve a 60% reduction in energy costs compared to a similar building constructed and operated to minimum standards [76].

Building form

The BigHorn Home Improvement Centre is split into two adjoining entities, each with different purposes and, as such, comprising different designs. The office and retail spaces are located in the building orientated on a long east-west axis whereas the warehouse is situated in the adjacent, north-south oriented building. The office and retail space, required to accommodate employees and customers, is situated on an east-west axis in order to take advantage of the solar gains for heating and daylighting. The warehouse, on the other hand, is mainly used for storage and as a drive-through timber yard thus, making little sense to provide space heating or any form of passive solar heating due to the expected high infiltration rate. That being said, the warehouse space has been equipped with radiant heaters to maintain a minimum temperature of 2.8℃ [76], although the heat transmission from these tends to stay at ceiling level [76]. Both buildings are single storey with the office located on a mezzanine floor in the retail building. The office and retail building comprises an area of 1709m^2 while the warehouse takes up the additional 2227m^2. Windows are primarily located on the south facade to aid passive solar strategies and are accompanied in the retail and office building by roof mounted skylights running in an east-west direction. Additional north and south facing clerestory windows have been provided in the retail and office building and east and west facing clerestory windows are located in the warehouse [76].

Building envelope

The specific construction details of each building element were not provided in any literature but the resulting thermal transmittance, solar heat gain coefficient and infiltration values have [76] and are as follows:

Floor
The entire floor of the office/retail building has thermal transmittance of U=0.55W/m^{2}K [76].

Roof
The roof of the entire building has thermal transmittance of U=0.15W/m^{2}K [76].

External wall
The first 1.22m of wall elevation has thermal transmittance of U=0.18W/m^{2}K and the remaining height of the wall has thermal transmittance of U=0.24W/m^{2}K [76].

Windows
The windows have thermal transmittance of U=1.4W/m^{2}K, and SHGC=0.44.
Clerestory windows have thermal transmittance of U=1.7W/m^{2}K and SHGC=0.75.
The skylights in the warehouse are translucent and have thermal transmittance of U=0.6W/m^{2}K and SHGC=0.22 [76].

The thermal transmittance values of the construction elements are quite low and this is contributing to increasing the energy performance in such a cold climate. The window to wall ratio is rather low at just 0.092 [76]but the glazing has been used in clerestory windows and skylights (in addition to vertical glazing) which allows a greater proportion of direct sunlight into the building space. The low WWR can be attributed to limiting the heat loss from the building in such a cold climate. Where the windows have been specified, they have low thermal transmittance values and a large proportion is located on the roof or in clerestories to promote the entry of natural daylight. An infiltration value was not specified for the completed building but a value of 0.25ACH [76] was used in the energy modelling phase of the building design. In order to obtain reliable energy performance results for the completed building, the building owner should determine the actual infiltration value as research has shown that infiltration is a large contributor to heat loss in buildings [29, 30, 32, 33].

Daylighting

Daylighting is provided by south facing windows, clerestory windows and skylights [75]. In summer, solar shading above the vertical glazing (in the form of a canopy) limits the level of direct solar radiation entering the building and reduces the risk of overheating and glare. The skylights are translucent glazing elements that diffuse direct solar radiation in order to distribute the incoming daylight over a wider area in the building and to avoid issues with glare. The warehouse daylighting is primarily supplied by skylights, while clerestory windows (facing north and south) and windows located high on the east and west facades supply the retail building with natural daylight. The interior of the building has been decorated in a bright white finish as this assists the reflection of incoming daylight and allows it to penetrate to most spaces in the building. The aggressive natural daylighting strategy has resulted in an 80% saving on lighting energy consumption from the design baseline level [76].

Despite concerted efforts on behalf of the designers and operators of the building to reduce the electricity consumption for artificial lighting, these efforts have been somewhat undermined by the cleaning crew that operate in the evening[76] . The cleaning crew tend to turn the majority of lights on during their work and, as a result, the building energy performance suffers. The designers estimate that if the cleaning was carried out in one zone at a time (and thus only lights in that zone would be operating), the savings in electricity would be of the order of $200 per year [74]. This is a clear example of the need for building occupants to be educated on the energy strategy in order to effectively reduce energy consumption.

Passive ventilation

The building operates with a passive ventilation [76] strategy whereby incoming air enters through open windows on the ground floor, rising to the ceiling by absorbing heat in the building space and exiting from open clerestory windows at the top of the building. This strategy of ventilating and cooling the building space means that no air conditioning or mechanical ventilation is required and, as such, there is no cooling load. Research has shown [55-58]that occupants of naturally ventilated buildings tend to have a wider temperature band at which they are comfortable and this should assist in reducing the energy load, and even demand, for local fans and heaters.

Energy Consumption

The building's energy consumption was measured through simulation of the as built building; the thermal energy consumption is 84.1kWh/m^2/year [75] and the lighting energy consumption is 44.5kWh/m^2/year. This equates to a saving in thermal energy consumption of 69% and an increase in lighting energy consumption of 30% compared to the baseline building's consumption of 317kWh/m^2/year. Although BigHorn Home Improvement Centre is not a net zero energy building (the installed 8.9kW PV system typically generates approximately 2.5% of the total energy consumption [75]) the building is a demonstration of what can be achieved in terms of reduction in energy consumption through thoughtful lighting design. The operation of the lighting, the design of the heating system and the size of the photovoltaic array will require improvements in order to achieve net zero energy performance.

4.7 Chesapeake Bay Foundation’s Philip Merrill Centre

Figure 4.7: Photograph of the Chesapeake Bay Foundation's Philip Merrill Centre [90]

Location: Maryland, USA

Size: 2880m^2

Climate: 2501 HDD, 895 CDD (Base 18℃) [83]

Building type: Office, two-storey

Occupancy: 80-90 occupants

Energy Performance Aim

This building was not designed to be a net zero energy building. It was, however designed with a goal of achieving a Gold or Platinum rating under the U.S. Green Building Council’s (USGBC) Leadership in Energy and Environmental Design (LEED™) certification program [91]. Be that as it may conserving the Chesapeake Bay was the organisation’s first priority, which meant that energy features were not optimised when they conflicted with conservation features [68].

Building form

The CFB Phillip Merrill Centre is a two storey building with parking space beneath the ground floor; the car park is on the ground and the building has been constructed on stilts. The building has been oriented along an east-west axis to take advantage of the solar gains from the south. Such is the extent of the natural daylight strategy that the entire south facade is glazed to allow penetration of daylight.

Building envelope

Floor

While the exterior walls and roof have conservative thermal transmittance values, that of the exterior floor is rather high at U=0.55W/m^{2}K. The exterior floor is constructed of 64mm exterior insulation with a 19mm wooden subfloor and 6mm tiles [68]. The exterior floor is in contact with outdoor air, rather than ground; the result being that outdoor air temperatures fluctuate more than ground temperatures and this may cause greater heat loss in the winter and overheating in the summer. This seems to be an area of the building fabric that would lead to poor energy performance.

Roof

The roof is also constructed with SIPs comprising a thick layer of expanded polystyrene insulation sandwiched between two panels of oriented strand board. The roof has been constructed with 13mm plywood, 190mm XPS foam, another layer of 13mm plywood and 13mm gypsum board on the inside giving a thermal transmittance value of U=0.15W/m^{2}K [68].

Walls

The walls are constructed with structurally insulated panels (SIPs) comprising a thick layer of expanded polystyrene insulation sandwiched between two panels of oriented strand board. The exterior walls have been constructed with 13mm plywood, 140mm XPS foam, another layer of 13mm plywood and 13mm gypsum board on the inside giving a thermal transmittance value of U=0.2W/m^{2}K [68].

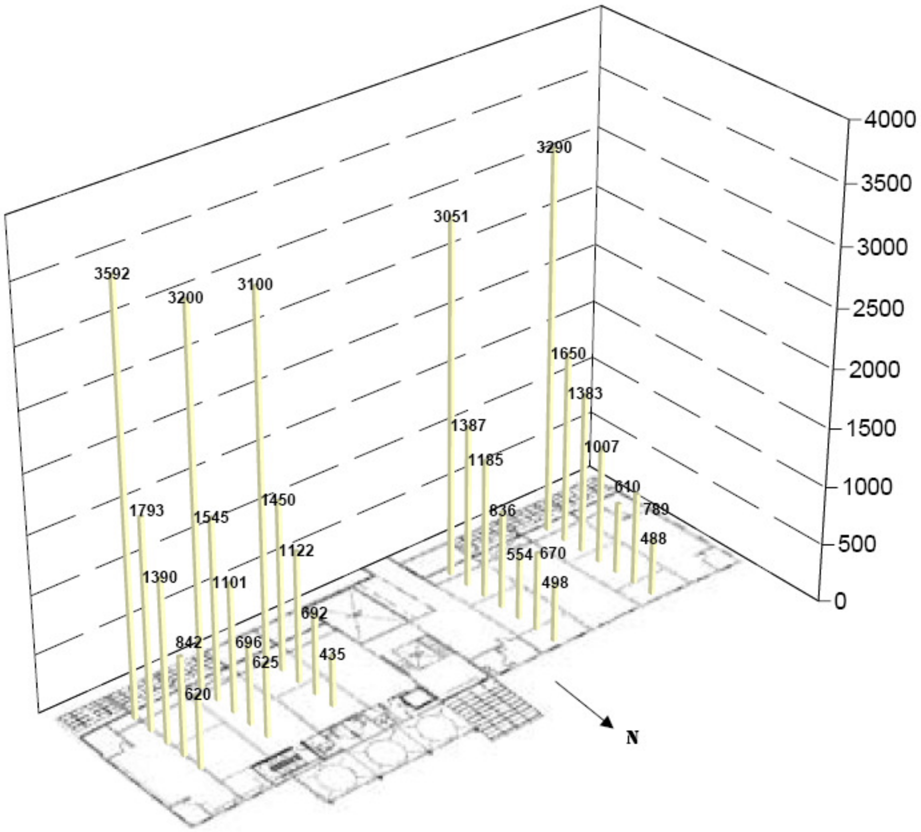
Windows

The glazing, on the other hand, is a high performance element. The double pane, 16mm argon filled windows and accompanying wooden frames result in a thermal transmittance value of just 1.4W/m^{2}K. The low emissivity coating applied to the units also limits the solar heat gain (SHGC=0.47) to manageable levels to provide comfort conditions [68].

Natural daylight

The entire south face of the CBF Philip Merrill Centre has been constructed with glazing to allow as much natural daylight into the office areas of the building. In addition, clerestory windows have been installed in the uppermost section of the top floor to allow daylight to penetrate to the north wall of the office. An open floor plan has been utilised, which would allow a greater distribution and penetration of the entering daylight. In addition, shading elements have been incorporated above the south facing windows to minimise glare effects.

The designers did, however, experience difficulty in attaining satisfactory lighting conditions throughout the office despite the efforts detailed above [68]. The figure below gives an indication of the illuminance values at various distances from the windows in the office. The reason for the unsatisfactory lighting levels can mostly be attributed to the ‘natural’ finish of the interior. The design team strived to keep the building as close to its surroundings as possible and, in doing so, left the interior as bare wood. This relatively dark material absorbs the incoming radiation resulting in dark conditions within the office. The designers have stated that the interior shall now have a bright finish to allow incoming light to be reflected off surfaces and diffused around the office space.



4.8 Handheld photometric measurements of natural daylight at midday in summer in the Chesapeake Bay Foundation's Philip Merrill Centre [68]

Passive ventilation

The building has been designed to have operable windows on both the north and south facades so as to utilise the breeze blowing off of the bay for its passive ventilation strategy [68]. Low windows on the south facade can be opened to allow air to enter the building. As it heats (through the internal gains), it rises and is able to escape from higher windows on the north facade. This ventilation system operates using both wind driven- and stack-effects.

Passive solar heating

Due to its south facing orientation, the building is able to gain heat from incoming solar radiation to offset some of the mechanical heating requirement. The large area of glazing allows direct solar radiation to enter the building when the solar angle is low, while overhanging shading on the roof limits the entry of direct radiation during the summer months (when the solar angle is high and the heating requirement is lessened). The two office spaces, while separated by floors within the building, are connected by a gap in these floors near the south facade. This allows the rising, heated air to enter the second storey rather than just accumulate at the ceiling level of the first storey and results in an effective space heating strategy.

Energy Consumption

This building, while not a net zero energy building, is an example of the reduction in energy usage that can be achieved by designing with passive systems in mind. A passive solar heating system, passive ventilation system, natural daylight strategy and moderately insulated fabric have meant that the CFB Philip Merrill Centre achieves a 25% reduction in total site end use energy intensity compared to a minimum standard building and has a thermal energy end use of 37.5kWh/m^2/year [68, 69]. The thermal energy consumption has only decreased by 11% compared to the baseline model, which could have been improved by increasing the insulation levels in the building, especially those in the floor and walls. The photovoltaic system is the smallest of the systems studied at just 4.2kWp and generates less than 1% of the electrical energy consumed in the building [68].

4.8 Pennsylvania Department of Environmental Protection (DEP Cambria) Office Building

Figure 4.9: Photograph of the Pennsylvania Department of Environmental Protection (DEP Cambria) Office [92]

Location: Pennsylvania, USA
Size: 3205m^2
Building type: Office, laboratory
Climate: 3672 HDD and 325 CDD (Base 18℃) [83]
Occupancy: Approximately 125 people, 50hours/person/week

Energy Performance Aim

The aim of the DEP Cambria office was to significantly reduce energy consumption and operational costs by reducing the required capacity for HVAC equipment, lighting and electrical equipment [70].

Building form

The building is a two storey structure, oriented along a long east-west axis. The windows are primarily located on the south and north facades. North and south facing clerestory windows run along a centre channel in the roof of the building, while there is almost no glazing on the east and west facades. The office is open plan and located in the south space of the building while conference rooms, laboratories and break rooms are located in the north space.

Building envelope

Floor

The floor consists of a concrete floor slab with 50mm insulation extending 1.2m inwards from the perimeter. The resulting thermal transmittance value is U= 0.74W/m^{2}K [70].

Roof

The roof consists of decking and insulation and results in a thermal transmittance value of U=0.17W/m^{2}K [70].

Walls

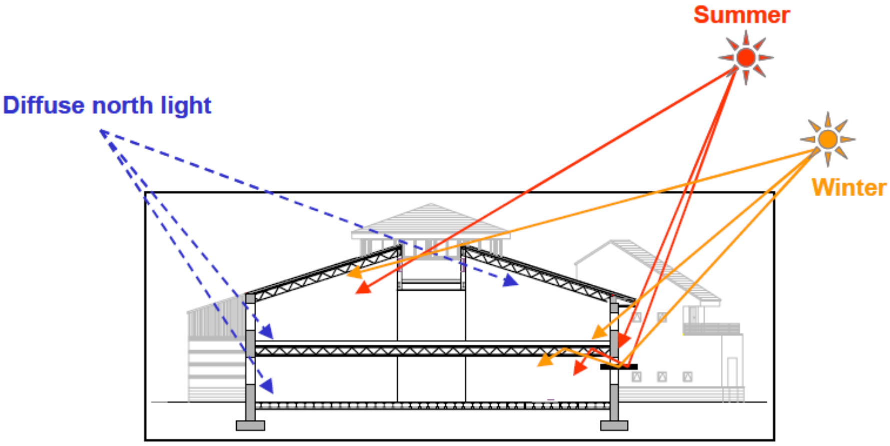
The walls are primarily insulated concrete panels that provide a thermal transmittance value of 0.21W/m^{2}K. These walls are located from the bottom of the building up to the first floor windows. Above this, 150mm steel frame walls with cellulose sprayed cavities and an additional 25mm rigid board exterior insulation are provided and result in the same thermal transmittance of 0.21W/m^{2}K [70].

Windows

Triple pane windows with aluminium frames are used for the entrance glazing while triple glazing in wooden frames are used in all other glazing. The resulting thermal transmittances are U=1.4W/m^{2}K and U=1.5W/m^{2}K respectively [70].

Natural daylight

The natural daylight strategy is so aggressive in this building that the lighting power density is 8.1W/m^2 in the building and just 5.4W/m^2 in the office area [70]. The east-west orientation and prominence of glazing on north and south facades contribute extensively to the natural daylight strategy. In addition, an open plan office space, located on the south side of the building, allows natural daylight to penetrate deep into the space and light coloured finishes, with a reflectance of 75% [70], assist in reflecting light around the office. Light shelves, with a reflectance of 89% [70], also help to reflect incoming light upwards to a reflective ceiling and penetrate further into the space



4.10 Natural daylight strategy of the DEP Cambria building [70]

In order to reduce the risk of overheating and glare, several shading techniques have been used throughout the building. The south facing clerestory windows incorporate photocell activated shading [70]; roller shutters are brought down over the windows when the direct radiation becomes too intense. In addition, fixed horizontal shading is provided over the top of the first floor windows and the light shelves on the ground floor windows help to shade the occupied office area but still allow reflected light to enter through the glazing directly above [70].

The analysis, however, shows that daylighting, despite an aggressive strategy, is not providing the anticipated energy savings [70]. The light shelves on the ground floor do not provide the amount of light anticipated; it emerged that the ceilings and reflectance of the light shelves were too low and there was not enough glazing, all of which combine to result in an inadequate amount of daylight penetration [70]. Similar problems were encountered in the first floor. It was found that incoming daylight did not penetrate beyond the first row of office cubicles as the window area was too small, the windows were not located high enough and the dark, exposed roof trusses hindered the diffusion of light within the office space [70].

Energy consumption

The building has an energy requirement of just 22kWh/m^2/year for heating, cooling and hot water but the total for HVAC and lighting results in a site energy intensity of 108kWh/m^2/year [71]. This is due to the amount of energy required for running fans and pumps and the very high amount required for lighting. It seems that although the building has a very low heating and cooling energy load, the natural daylight design was ill-conceived and results in a much higher energy use than originally predicted. In addition, the 32.2kW photovoltaic system is only providing 1.5%-3.3% (2.0-4.4kWh/m^2/year) of the building’s total energy demand [70]. The lighting strategy, the insulation levels and the photovoltaic system require improvements in order to achieve net zero energy performance.

4.9 NREL Thermal Test Facility

Figure 4.11: Photograph of The NREL Thermal Test Facility [93]

Location: Golden, Colorado, USA
Size: 929m^2
Building type: Office, laboratory
Climate: 6083 HDD and 567 CDD (Base 18°C) [83]
Occupancy: 10 occupants, 50 hours per week

Energy Performance Aim

The aim of the Thermal Test Facility was to reduce the building’s annual energy consumption through the use of energy-efficient and renewable-energy technologies. A specific quantitative goal was not set [72].

Building form

The Thermal Test Facility is a single storey, 7.3m tall building that is constructed in a vertical step design with three south facing walls at different heights [72]. The building faces almost due south and is situated on a long east-west axis [72]. Each of the three south faces is heavily glazed to assist in the building’s natural daylighting strategy. There is a mezzanine level in the centre of the building, accommodating sanitation facilities, storage, a kitchen and mechanical plant [72]. Offices and a conference room are situated in the southern most space of the building (the space with the shortest ceiling height) while the laboratories are situated in the tallest space, at the north [72]. The Thermal Test Facility has been built into the face of South Table Mountain [72], meaning that the north wall acts as a retaining wall and, due to contact with the soil, is able to regulate temperatures inside throughout the year.

Building envelope

Floor

The floor consists of a 150mm concrete slab with insulation around the perimeter and extending 1.2m inwards. This section of the slab has thermal transmittance of $U=0.55W/m^2K$ and the rest of the slab has thermal transmittance $U=3.5W/m^2K$ [72].

Roof

The roof is a metal deck with a 75mm layer of polyisocyanurate insulation, giving thermal transmittance of $U=0.25W/m^2K$ [72].

Exterior walls

The walls are constructed of 150mm steel columns with rigid insulation and 25mm exterior expanded polystyrene insulation. The resulting thermal transmittance is $U=0.25W/m^2K$.

The north wall is constructed of 50mm exterior insulation and 200mm precast concrete. The resulting thermal transmittance is $U=0.55W/m^2K$ and, although not as low as the other walls, this wall is designed for high thermal mass rather than low thermal transmittance [72].

Windows

Vertical windows are double glazed with 6mm grey tinted outer glazing, a 13mm air gap and 6mm clear low-e glazing. Thermally broken aluminium frames were specified but were not installed. The resulting thermal transmittance is $U=2.4W/m^2K$ and SHGC=0.44 [72].

Clerestory windows are specified to the same design as vertical glazing except the outer glazing is clear and, again, thermally broken aluminium frames were specified but not installed. The resulting thermal transmittance is $U=2.6W/m^2K$ and SHGC is 0.65 [72].

Infiltration

The building has had a tracer gas test to measure the air infiltration and it was measured at 0.1ACH [72].

Passive solar heating

The majority of glazing is situated in the south facing windows or in the clerestory windows; $105.4m^2$ is facing south with $5.2m^2$ on each of the east and west facades and only $3.5m^2$ on the north facade [72]. The stair step design allows a greater proportion of light into the building than a typical, entirely vertical frontage; the south facing windows allow direct solar radiation into the building while the roof sections below the windows reflect diffuse radiation into the building. In order to reduce the risk of overheating, the glass has been specified with a solar heat gain coefficient of 0.44 and horizontal solar shading is provided above each window; 0.98m extends outwards above the view glass on the south facade while 0.43m extends outwards above the clerestory windows

[72]. As the clerestory windows are situated much higher than occupancy level and therefore glare is less of an issue, shorter shading devices have been used to allow greater heat transfer.

The high thermal mass of the north wall stores heat from sunlight entry through the clerestory windows and, as such, is able to regulate the indoor temperature by absorbing and emitting heat gradually through a diurnal cycle.

Natural daylighting

Clerestories and south facing glazing contribute towards much of the natural daylight. North windows allow diffuse radiation entry, which, in conjunction with the south facing glazing, provides bidirectional lighting to the interior space. The clerestory windows have a visible transmittance coefficient of 0.72 [72] to enhance the amount of light entering into the building and diffusing over a wide area. All other windows, which are at occupancy level, have a visible transmittance coefficient of 0.38 [72] to minimise glare in these working areas. Shading also helps to minimise this risk. The step design, as well as providing increased solar heat gains, encourages the ingress of diffuse light.

The south wall of the service core has been designed to have a bright finish [72] in order to reflect incoming, direct light from the higher windows towards the offices at the front of the building. Whilst the reflection process works effectively, the office area has been finished in darker colours and has tall office cubicles, which undermine the objective of the light painted service core. Glare also became an issue so internal blinds were installed on clerestory windows and office area view glazing [72].

Despite the failings of the office area, the building is able to achieve 74% lighting energy reductions due to daylighting and occupancy sensors [72].

Energy consumption

The energy efficient initiatives used in this building have resulted in a reduction in HVAC and lighting energy demand of 48% compared to the equivalent building designed to minimum standard [72]. The building operates with a thermal energy intensity of 42kWh/m^2/year [72], however the building does not have a renewable energy generation strategy and, as such, cannot achieve net zero energy performance.

4.10 Zion National Park Visitor's Centre

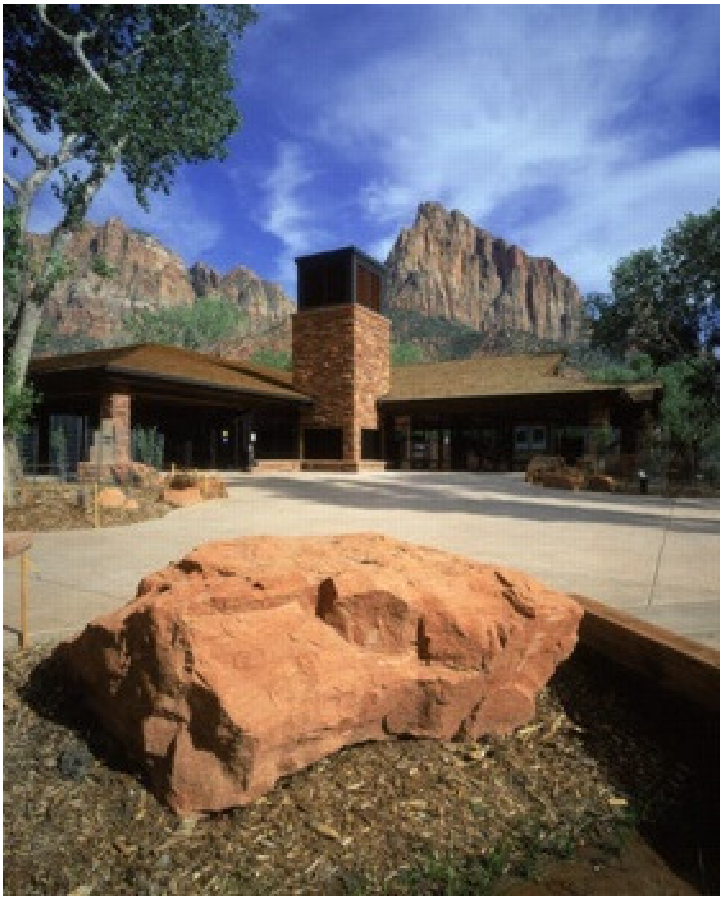


Figure 4.12: Photograph of Zion National Park Visitor's Centre [94]

Location: Utah, USA
Size: 1073m^2
Building type: Low energy visitor centre
Climate: 2095 HDD and 1352 CDD (Base 18℃) [83]
Occupancy: 3000 visitors per hour in summer

Energy Performance Aim

This building had an energy performance design aim of achieving an energy-cost saving goal of 70% compared with a building designed to minimum standards. This was set at the beginning of the design process and used as an energy saving target throughout the process [79].

Building form

The building is a single storey design and has been constructed in a zigzag formation with the majority of windows facing south [79]. It is a timber frame construction with sloped roofs that incorporate clerestory windows [79]. On the south facing sides of the building are trombe walls [79] to assist in the building's passive heating strategy. The summer ventilation strategy utilises two large cooling towers and these are located at the north side of the building so as not to cause any shading over the photovoltaic panels [79]. The complex is comprised of two buildings; a visitor centre (817m^2) and a “comfort zone” (256m^2), which houses the sanitary areas [79].

Building envelope

Floor

The floor is insulated only around the perimeter (1.2m) with 38mm rigid insulation atop a 150mm concrete slab and result in thermal transmittance of 0.74W/m^{2}K [79]. The floor in the rest of the building is a 100mm concrete slab with a U value of 12.5W/m^{2}K [79].

Roof

The roof is comprised of exterior wood shingles, 13mm sheathing and 210mm insulated roof panels. The resulting thermal transmittance is U=0.18W/m^{2}K [79].

Exterior walls (Visitor’s Centre)

The walls are comprised of exterior wood cladding, 13mm insulation board, 150mm metal stud framing with insulating foam, 13mm plywood and 16mm gypsum board. The resulting thermal transmittance is U=0.34W/m^{2}K [79].

Exterior walls (Comfort Station)

The walls are comprised of exterior wood cladding, 38mm rigid insulation and 200mm concrete masonry units with foam insulation inserts. The resulting thermal transmittance is U=0.84W/m^{2}K [79].

Trombe walls

Trombe walls are comprised of 4mm exterior glazing, 65mm air gap and 200mm concrete masonry unit with grout filling. The resulting thermal transmittance value is U=2.44W/m^{2}K [79]. Although this U value is rather high, the trombe wall is used for passive heating purposes and, as such, the thermal transmittance is required to be high to allow heat to be exchanged into the building.

Windows

South and east facing windows are double glazed, low-e coated with thermally broken aluminium frames. The thermal transmittance is U=2.44W/m^{2}K and SHGC=0.44 although they were initially designed to have SHGC=0.55 to enhance the building’s passive solar heating strategy but mistakes were made by the contractor [79].

North and west facing windows are double glazed heat mirrors with thermally broken aluminium frames. The thermal transmittance is U=2.08W/m^{2}K and SHGC=0.37 [79]. The windows are designed to inhibit the transmission of heat into the building from diffuse solar radiation (north facing windows) and from the late afternoon sun (west facing windows).

Passive solar heating

The greatest contributor to the passive solar heating strategy in this building is the trombe walls. They are located on the south facade of the building in order to utilise solar radiation for much of the day. A thin glass pane and black coating on the exterior face of the concrete absorbs solar radiation and transfers heat to the concrete masonry units, which radiates into the building space [79]. The concrete floor slab and concrete masonry units provide thermal mass to the building and, as such, a high level of capacitance, thus retaining heat for longer and slowing the rate of change of indoor temperatures. South facing windows with a high SHGC allow heat and light from solar radiation to enter into the building. Clerestory windows on the south facade also assist in providing heat to the building space.

In addition to passive solar heating, the building incorporated electric powered, radiant heat panels on the ceiling to provide a quicker form of heat so as to avoid discomfort during the building warm up period and when the passive solar heating strategy is not able to meet the heating demand [79]. In actual fact, the building layout was changed late in the design stage with two offices being relocated adjacent to trombe walls, the heat from which is enough to heat the office spaces even in winter [79]. The result, however, is that these offices require additional fans (and consequently, additional energy) to provide cooling during the summer.

Natural daylighting

The south facing windows and high clerestory windows provide daylight penetration into the building but have moderate SHGCs to limit the risk of overheating. There is overhanging shading above the south facing windows but not above the clerestory windows. This is an aspect that the designers wish to improve upon [79] but the lack of shading seems to be a fundamental error in the design of a low energy, passive solar building. In addition, the north walls have an abnormally large amount of glazing for a low energy building. They were designed to promote the entry of diffuse light into the building but even the designers admit that there is too much glazing [79]. While the designers have intended to allow as much light into the building through the glazing, they have failed to recognise possible issues of glare and overheating. In addition, the interior of the building has been left as exposed wood and has not been finished in a light colour. A light interior finish, redistribution of glazing and incorporation of solar shading could further reduce the energy demand of this building.

Passive ventilation and cooling

The building has incorporated two cooling towers to the north, the openings of which are located high above the building [79]. Warm outdoor air enters through the top of the cooling towers and contacts cool water, which cools the air and causes it to fall to the exhaust opening inside the building. This provides cooling to the building occupants. Ventilation is provided by the stack effect, whereby air enters either through the cooling towers or operable windows at occupant level, where it is then warmed inside the building space and rises to escape through operable clerestory windows at the top of the building.

The cooling strategy works for most of the year with occasional periods where the indoor temperature reaches a point that cannot be reduced solely by the cool towers [79]. In this instance, night time natural ventilation is used to cool the building [79], although this will not provide an immediate effect on reducing the indoor temperatures. The designers have suggested that providing solar shading to the cool towers will reduce the amount of water that evaporates and will subsequently increase the efficiency of the cooling strategy [79].

Energy consumption

The annual heating, cooling and hot water energy consumption of the Zion National Park Visitor's Centre is 30.2kWh/m^2/year [79], which translates to a saving in thermal energy consumption compared to a building constructed to minimum standards of 62% [80]. This is achieved through many innovative design features, namely the trombe walls and passive cooling strategies. However, the energy consumption could be further reduced and the PV system could be expanded to achieve net zero energy status. The building's PV system is relatively small at 7.2kWp [80] (producing just 7900kWh per year [79]) but the building has been designed to incorporate a larger PV system in the future. Modifications to the building, including bright interior finishes, solar shading for windows, trombe walls and cool towers as well as reducing the shading by trees over the PV array will help to reduce energy consumption and/or increase energy generation capabilities.

4.11 Low energy building case studies - evaluation

4.11.1 Thermal transmittance

The thermal transmittance values of the building envelope elements vary considerably although some generalisations can be made from the results.

Window thermal transmittances range from 0.6 to 3.5W/m^{2}K with the following distribution: one building has a window thermal transmittance greater than 3.0W/m^{2}K, four buildings with window thermal transmittances of between 2.0 and 3.0W/m^{2}K, five buildings with window thermal transmittances of between 1.0 and 2.0W/m^{2}K and one building with a window thermal transmittance of less than 1.0W/m^{2}K. The consensus here is that the majority of the window thermal transmittances lie between U=1.0 and 3.0W/m^{2}K with a mean value of U=1.95W/m^{2}K and a mode of 1.0-2.0W/m^{2}K

Floor thermal transmittances range from 0.26 to 0.7 with a mean thermal transmittance value of U=0.51W/m^{2}K and a mode of U=0.6W/m^{2}K. External wall thermal transmittance ranges from 0.18 to 0.84W/m^{2}K, although this latter value is for a wall located in an unconditioned sanitary zone. Nevertheless, the mean thermal transmittance is U=0.34W/m^{2}K and the modal value is U=0.2W/m^{2}K. In all cases,roof thermal transmittance is lower than external wall thermal transmittance; the values range from 0.14 to 0.26 with a mean of U=0.18W/m^{2}K and a modal value of U=0.2W/m^{2}K.

Examining these results further yields some more interesting conclusions. The successful nZEBs have low roof thermal transmittance values of 0.1W/m^{2}K (The Science House), 0.2W/m^{2}K (NREL RSF) and 0.14-0.28W/m^{2}K (Adam Joseph Lewis Centre) whereas the buildings that have failed to achieve nZEB performance have roof thermal transmittance values of up to 0.3W/m^{2}K and a minimum of just 0.2W/m^{2}K.

Wall and floor thermal transmittance values are generally similar between all buildings (with the exeption of NREL TTF and Zion National Park Visitors' Centre with wall thermal transmittanvce values of up to 0.55W/m^{2}K and 0.84W/m^{2}K, respectively) and window thermal transmittance values are, in fact, tending to be lower in failing buildings than in successful buildings. However, when these results are examined alongside heating degree days, a different story emerges. The Bighormn Home Improvement Centre, for example, has window thermal transmittance values of between 0.6 and 1.7W/m^{2}K, yet this only accounts for approximately 10% of the wall area, with the remaining area consisting of walls with thermal transmittance values of between 0.18 and 0.24W/m^{2}K. The location, in Silverthorne, Colrado, has 6090 heating degree days and it is evident that this intense requirement for heating is not being assisted by comparitively high wall thermal transmittance values. It seems that in all of the failed nZEB cases, at least one building envelope element is not as thermally resistant as it should be in order to achieve net zero energy performance.

4.11.2 Thermal mass

Construction elements of high thermal mass are used in five of the nine buildings studied. Walls with high thermal mass have been specified in all five, roofs with high thermal mass have been used in one and floors with high thermal mass have been used in two of the buildings. Two of the buildings use high thermal mass north walls as they are partly buried into the ground and are adjacent to the soil. Thermal mass is only recommended where there is a range of diurnal temperatures (hot days and cold nights). The five buildings that use thermal mass have a significant heating requirement of between 2000 and 4000 degree days but also have a noticeable cooling requirement of between 500 and 1300 degree days (base 18℃). This statistic is possible evidence of a large range in diurnal temperatures although it could be evidence of large seasonal variations in temperature.

4.11.3 Infiltration and ventilation

Only three of the nine buildings give any indication as to the building infiltration value and, of these, only one has conducted an air infiltration test to determine the value. BigHorn Home Improvement Centre and Chesapeake Bay Foundation Phillip Merrill Centre used air infiltration values of 0.25ACH and 0.4ACH, respectively, in the modelling and energy performance simulation stages of the design phase but neither of the cases specifies an accurate and reliable value or whether an air infiltration test has been conducted. The only study to explicitly state that an air infiltration test has been conducted was NREL Thermal Test Facility, which used the tracer gas technique to determine a value of 0.1ACH.

Natural ventilation is used in seven of the nine buildings, with the other two using mechanical ventilation. Stack effect ventilation is the most commonly used natural ventilation strategy but wind driven, cross ventilation is also used in one building (Chesapeake Bay Foundation Phillip Merrill Centre). One building, Solar XXI, uses a mixture of natural and mechanical ventilation; stack effect ventilation is provided through the use of an atrium with operable clerestory windows while fans also provide cool air from buried pipes underneath the building. NREL Research Support Facility implements natural ventilation but also employs a sensor system to notify occupants when to open their windows.

4.11.4 Passive solar design

All of the buildings are located in heating dominated, cool climates (with Lisbon, Portugal being the only climate approaching a balance between heating and cooling demand) and, as such, they are all designed for passive solar gains. They are all either aligned, or at least have a major part of the building aligned, along an east-west orientation to take benefit from as much daylight as possible and to limit the area of facade exposed to intense, low angle sunlight in the morning (east facing) and evening (west facing) to mitigate the risks of glare and overheating.

All but one building (NREL Research Support Facility) have clerestory windows to enhance the exposure of the building interior to solar gains. Two of these buildings have just north facing clerestory windows (Adam Joseph Lewis Centre and Chesapeake Bay Foundation Phillip Merrill Centre), two have just south facing clerestory windows (Solar XXI and Zion National Park Visitor's Centre) and the remaining four have both north and south facing clerestory windows. In addition, most of the buildings have large areas of south facing glazing to provide natural daylight and to limit the energy requirement for artificial lighting.

The window to wall ratio has only been documented for some of the buildings and there does not seem to be a trend for low energy buildings. Bighorn Home Improvement Centre, for example, has an even distribution of windows around the facade, with a window to wall ratio of 0.09 on each face. Zion National Park Visitor's Centre, on the other hand, has a distribution of windows across the building facade with an average WWR of 0.28 for each wall. Adam Joseph Lewis Centre has the highest recorded values for WWR with 0.57 (south facade), 0.46 (east facade) 0.38 (north facade) and 0.14 (west facade). Of the other buildings that have data available for WWR, NREL Research Support Facility has an almost equal WWR on the north and south facades of 0.26 and 0.28, respectively, and Solar XXI has a south facing WWR of 0.3. While it is difficult to interpret an optimum WWR for each facade, the results do provide an interesting conclusion. The Adam Joseph Lewis Centre has the highest WWR and the highest specific annual thermal energy consumption of 67.5kWh/m^2/year (although Bighorn Home Improvement Centre has the highest value for specific annual thermal energy consumption, the fuel used is gas, which has a site to source conversion ratio of 1.084, whereas the other buildings use electricity, which has a site to source conversion ratio of 3.167; thus, the source energy consumption of the Adam Joseph Lewis Centre is 213.8kWh/m2/year). This relatively high energy consumption may coincide with the high proportion of glazing, especially when the glazing used has a relatively large thermal transmittance of between 2.0 and 2.5W/m^{2}K. It, therefore, seems prudent to limit glazing on the north facade to reduce heat loss and on east and west facades to reduce the risk of overheating while maximising glazing area on the south facade to take advantage of solar gains. In addition, if high amounts of glazing are to be used, the thermal transmittance should be low to minimise the heat loss from the building space.

4.11.5 Shading

All of the buildings incorporate some form of solar shading to limit the solar heat gains in the summer and to minimise the uncomfortable situations of overheating and glare. The solar shading, however, varies between buildings. Each has some type of fixed, horizontal shading over south facing windows but then the differences in strategy begin to appear.

Three of the buildings (NREL Research Support Facility, NREL Thermal Test Facility and Adam Joseph Lewis Centre) explicitly state that there are internal blinds installed and Solar XXI incorporates external blinds in south facing windows. Of the six buildings with south facing clerestory windows, all but Zion National Park Visitor's Centre provide a shading device over these glazing elements.

Six of the buildings have shading elements over windows other than on the south facade. Zion National Park Visitor's Centre and BigHorn Home Improvement Centre have shading over windows on all facades but the effectiveness of this strategy is questionable. Passive solar design intends to utilise solar gains (light or heat) where possible without causing discomfort but north facades of buildings in the northern hemisphere do not receive direct radiation. As such, the shading elements will not inhibit sunlight and, at worst, they will make the interior space darker and may cause the requirement for extra artificial lighting. The other buildings make use of shading on the south, east and west facades as each of these receive direct radiation and the shading will assist in reducing the risk of overheating and glare.

Two of the buildings have incorporated innovative shading strategies into the design. NREL Research Support Facility has horizontal shading above windows but also has protruding shades on the sides of the windows to reduce the glare from low angle sunlight. The south facing windows also have louvre-shaped internal blinds which reflect incoming light upwards and help to shade the occupants from direct sunlight and distribute the light further inside the building space. East facing windows are thermochromic and tint with rising temperatures while west facing windows are electrochromic and tint due to an electric current. The Department of Environmental Protection building uses photocell activated roller shutters on south facing clerestory windows to stop daylight entry and light shelves on the south facing view glass to shade occupants and reflect light upwards, distributing it further inside the building space.

4.11.6 Embodied Energy

Many of the case studies have reported low energy consumption and this is partly due to the operation and design of the buildings but also due to the low and renewable energy technologies that have been employed. While these technologies and materials have resulted in reduced energy consumption, it should be noted that they encompass an element of embodied energy – the energy required for manufacture, transportation, installation, maintenance, repair and replacement of materials and systems. Research has shown that increasing thermal energy performance of insulation can coincide with increasing levels of embodied energy. Schonhardt *et al* [95] demonstrated that the equivalent amount of Glass Wool, EPS and VIP insulation to obtain a U value of $0.15W/m^2K$ resulted in embodied energy values of $455MJ/m^2$, $890MJ/m^2$ and $999MJ/m^2$ respectively. The process of manufacturing photovoltaic panels is energy intensive. Nawaz and Tiwari [96] calculated that a typical rooftop photovoltaic panel could have an embodied energy of $4980MJ/m^2$ and may only produce $375MJ/m^2$/year (under very favourable conditions).

Although the research in this thesis is not concerned with the embodied energy of the construction of the building, it is worth noting for any future research that end use energy, whilst essential to reduce in order to increase energy efficiency, may not be solely responsible for reducing the energy impact of buildings.

4.11.7 Relevance of the buildings chosen in relation to the UK

None of the buildings that have been studied are located in the UK and, as such, the typical buildings processes and the climatic conditions of each case study have been examined to understand the relation to typical UK building processes and climate. Table 4.1 and Figure 4.13 below show the end use energy intensity per square metre of building area for most of the case study buildings and for average offices in the UK and USA. The specific end energy uses for the NREL Research Support Facility and Solar XXI were not available and have not been included in the table. Figure 4.14 shows the percentage of end use energy for the case study buildings and for average offices in the UK and USA.

Building	**Annual End Use Energy Intensity (kWh/m^2)**					
	Heating	**Cooling**	**Ventilation**	**Lighting**	**Hot water**	**Other electrical**
Adam Joseph Lewis Centre	67.7	0.0	0.0	10.9	0.0	23.4
The Science House	23.9	2.1	8.2	1.8	1.9	2.5
Bighorn Home Improvement Centre	86.1	0.0	1.6	13.6	0.3	5.1
CBF Merrill Centre	12.0	22.3	0.4	36.8	0.0	36.5
DEP Cambria	14.0	5.6	48.7	58.1	3.5	32.2
NREL Thermal Test Facility	34.1	2.1	6.3	17.5	3.5	23.2
Zion National Park Visitors' Centre	20.6	2.2	4.6	28.7	0.0	25.8
USA Office Average	103.4	28.1	16.4	72.9	6.3	27.5
UK Office Average	151.0	2.0	8.0	38.0	5.0	32.0
UK Air Conditioned Office Average	178.0	31.0	78.0	54.0	6.0	57.0

Table 4.1: Annual end use energy intensity of the case study buildings and average offices in the UK and USA.

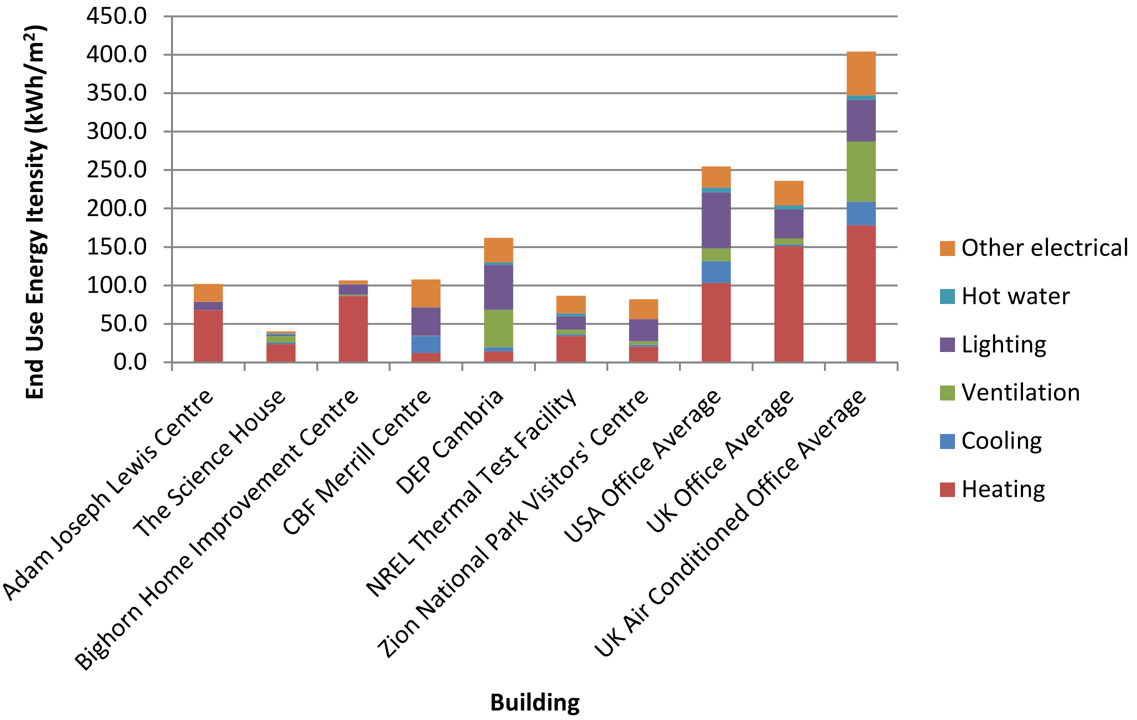


Figure 4.13: Annual end use energy intensity of the case study buildings and average offices in the UK and USA.

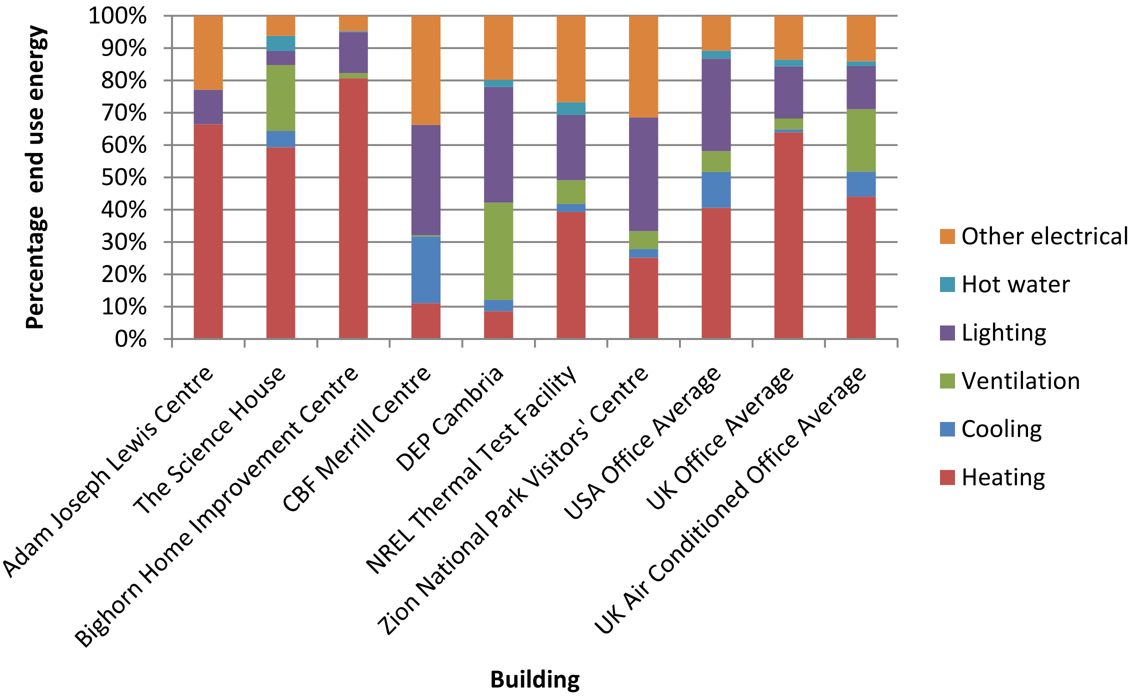


Figure 4.14: Percentage end use energy of the case study buildings and average offices in the UK and USA.

The typical building energy processes across most buildings are heating, cooling, ventilation lighting, hot water and miscellaneous electrical. The specific energy intensity varies between buildings but there is usually a significant amount of energy required for heating, lighting and electrical appliances. The end use energy intensity of the case study buildings, unsurprisingly, is significantly less than that of the average office building in the UK or USA but it is interesting to observe that there are similar end use energy intensities between the average USA office building and the average naturally ventilated UK office building. The end use energy intensity of the air conditioned UK office building and that of the average office building in the USA are also similar except for the greater amount of energy used for ventilation in UK air conditioned offices. Whilst the end use energy intensities of the case study buildings and the average UK office buildings show some variation, the building processes are fairly similar and the vast amount of data available for the selected buildings justifies their use as case study buildings for this research. More applicable buildings to the UK climate and building processes could have been chosen, but the limited amount of available data would have reduced the effectiveness of the results in formulating a low energy design strategy.

The climate in each location varies and it is interesting to examine the climate to understand the reason for the variation in building processes. The heating and cooling degree days (base 18°C) for each location and the proposed locations for testing the low energy building in the UK are as shown in Figure 4.15 below.

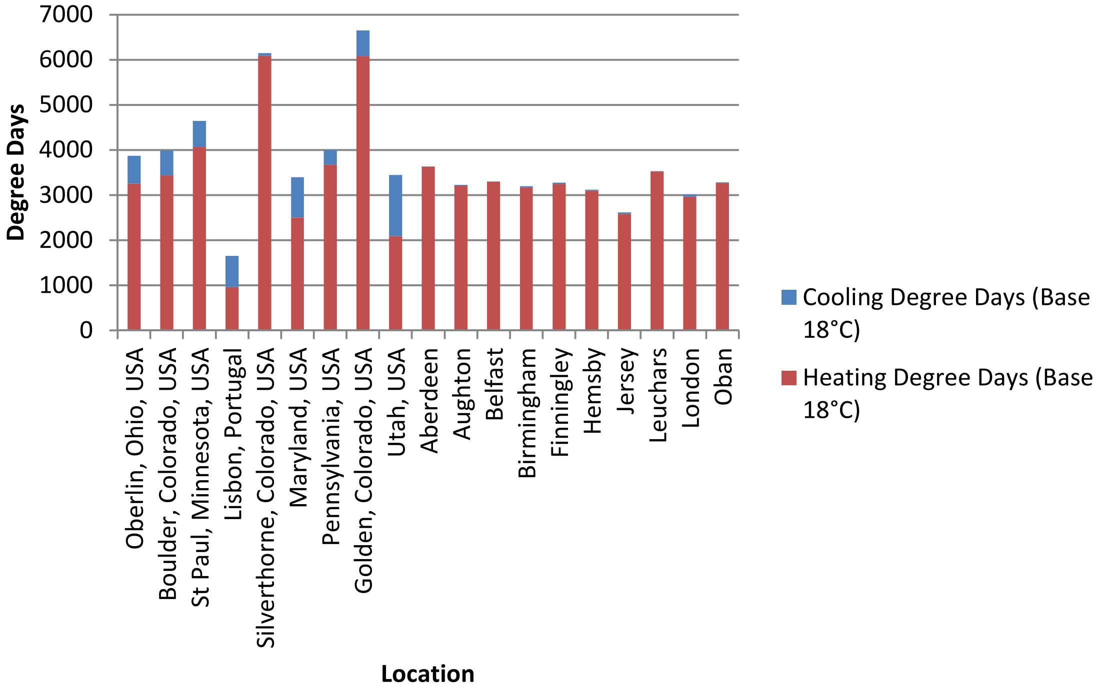


Figure 4.15: Heating and cooling degree days (base 18°C) for each building location, including the proposed locations for testing the low energy building in the UK.

The major difference between the locations in the USA and the UK is the significantly greater requirement for cooling in the USA than in the UK. However, when observing the heating degree days, there are similarities between all UK locations and many of the case study locations (except for Lisbon, Silverthorne and Golden). Upon examining the requirement for heating and cooling, it can be seen that, despite the requirement for cooling, many of the case study locations display a good correlation to the UK locations. As such the low energy design strategies that have been used in the many of the case study buildings can be reliably applied to the design of the low energy building for the UK.

4.12 Conclusions

The conclusions below are representative of all of the buildings studied, regardless of success or failure, are a short summary of the main design parameters.

- Mean thermal transmittance of floors is U=0.51W/m^{2}K with a mode of U=0.6W/m^{2}K.
- Mean thermal transmittance of external walls is U=0.34W/m^{2}K with a mode of U=0.2W/m^{2}K.
- Mean thermal transmittance of roofs is U=0.18W/m^{2}K with a mode of U=0.2W/m^{2}K.
- Mean thermal transmittance of windows is U=1.95W/m^{2}K with a mode of U=1.0-2.0W/m^{2}K.
- 5 of the 9 buildings have some facade element that has high thermal mass.
- Only one building has had an air infiltration test and this value was determined as 0.1ACH.
- 7 of the 9 buildings utilise natural, rather than mechanical, ventilation.
- The buildings are all oriented, or partly oriented, along an east west axis to take advantage of the solar gains from the south.
- All buildings incorporate shading elements over the east, west or south facades although the effectiveness of shading varies between buildings.
- 8 of the 9 buildings have clerestory windows.
- There is little data of WWR but, from what data there is available, there does not seem to be a trend in WWR; WWR ranges from 0.09 to 0.57.

It is, arguably, more informative to summarise the main design parameters of the successful nZEBs in order to assist in the design of a single, low energy building for the UK climate and also to summarise the elements that did not make a positive contribution to the low and net zero energy objective. The elements that made a positive contribution are as follows:

- Mean thermal transmittance of floors is U=0.45W/m^{2}K.
- Mean thermal transmittance of external walls is U=0.33W/m^{2}K.
- Mean thermal transmittance of roofs is U=0.17W/m^{2}K.
- Mean thermal transmittance of windows is U=2.08W/m^{2}K.
- Each of the three buildings utilise natural, rather than mechanical, ventilation.
- The buildings are all oriented, or partly oriented, along an east west axis to take advantage of the solar gains from the south.
- All buildings incorporate shading elements over the east, west or south facades although the effectiveness of shading varies between buildings.
- 2 of the 3 buildings have clerestory windows.

- WWR ranges from 0.26 to 0.38 on the north facade, 0.28 to 0.57 on the south facade, 0.48 on the east facade and 0.14 on the west facade.

The elements that did not make a positive contribution are as follows:

- The use of dark indoor finishes, which absorb incoming daylight and reduce the amount of reflected light. This was identified in the CFB Merrill Centre, the DEP Cambria building, the NREL Thermal Test Facility and the Zion National Park Visitor's Centre.
- The use of tall office cubicles. This also reduces the amount of reflected light and creates an additional requirement for artificial light.
- The low location and small area of windows. This reduces the amount of light actually entering the building and places more demand on artificial lighting.
- The use of low thermal resistance construction elements in floors. Most of the buildings used low thermal resistance construction elements in floors but the CFB Merrill incorporated this with a ground floor that was raised above the ground. This will cause additional heat loss in winter when air temperatures become lower than ground temperatures.
- The lack of control of occupant behaviour. This was identified in the Bighorn Home Improvement Centre where the cleaning crew would turn on all of the lights in the building regardless of where they were actually operating. If the cleaning crew had been adequately briefed on the aims of the building, they may have used the lights more sparingly and reduced the building's energy consumption.

It is important that as many of the positive contributions and as little of the negative contributions are incorporated into the design of a low energy building.

Name	Location	Measured Thermal energy consumption (kWh/m^2/ year)	Size (m^2)	Building type	Renewable energy system (and capacity (kWp))	Degree days (Base 18°)		Thermal transmittance (W/m^{2}K)				Infiltration (ACH)	East-West axis	Clerestory windows	Solar shading	WWR				Natural ventilation	Natural daylighting	Thermal mass
						Heat	Cool	Wall	Roof	Floor	Window					North	East	South	West			
Adam Joseph Lewis Centre for Environmental Studies at Oberlin College	Ohio, USA	67.5	1260	Educational and office	PV (160)	3254	619	0.29-0.48	0.14-0.28	0.26-0.52	2.0-2.5	-	Yes	Yes, north facing	Yes, overhanging shading on the south and east facades and internal blinds on east facing windows	0.38	0.46	0.57	0.14	Yes, stack effect ventilation through the atrium	Yes, clerestory windows and large, south facing, curtain wall glazing	Yes, high thermal mass construction elements in external walls and floor
NREL Research Support Facility	Boulder, Colorado, USA	29.7	20300	Office	PV (1700)	3442	541	0.4	0.2	-	1.9-2.5	-	Yes	No	Yes, solar shading around the edges and top of south facing windows, louvre shaped internal blinds, east facing thermochromic windows and west facing electrochromic windows	0.26	-	0.28	-	Yes, stack effect and operable windows with sensors to alert occupants when to open windows	Yes, large area of north and south facing glazing and louvre blind to reflect light upwards into building space	Yes, high thermal mass construction elements in external walls and roof
The Science House	St. Paul, Minnesota, USA	32	142	Education, classroom and office	PV 8.8	4079	572	0.2	0.1	0.5	1.8	-	Yes	Yes, north and south facing	Yes, 1.2m horizontal shading element above south facing windows	Unspecified				Yes, stack effect driven ventilation	Yes, large area of south facing glazing and clerestory windows	Yes, lower section of north wall has high thermal mass
Solar XXI	Lisbon, Portugal	4.4	1500	Office	PV 18	959	693	0.5	0.3	0.6	3.5	-	Yes	Yes, south facing	Yes, external blinds on south facing windows, internal blinds on other windows and horizontal shading element above clerestory windows	0.3 for south facade but unspecified for others				Yes, stack effect through the atrium	Yes, large area of south facing glazing and the clerestory windows supply light into the atrium	No

Name	Location	Measured Thermal energy consumption (kWh/m^2/ year)	Size (m^2)	Building type	Renewable energy system (and capacity (kWp))	Degree days (Base 18°)		Thermal transmittance (W/m^{2}K)				Infiltration (ACH)	East-West axis	Clerestory windows	Solar shading	WWR				Natural ventilation	Natural daylighting	Thermal mass
						Heat	Cool	Wall	Roof	Floor	Window					North	East	South	West			
BigHorn Home Improvement Centre	Silverthorne, Colorado, USA	84.1 (gas powered)	3939	Retail, office and warehouse	PV (8.9)	6090	55	0.18-0.24	0.2	0.6	0.6-1.7	0.25*	Yes (office and retail zones)	Yes, north and south facing	Yes, overhanging shading on the all facades and shading over clerestory windows	0.09 (distributed evenly over all external walls)				Yes, stack effect ventilation	Yes, south facing windows, clerestory windows and skylights	No
Chesapeake Bay Foundation's Philip Merrill Centre	Annapolis, Maryland, USA	37.5	2880	Office	PV 4.2	2254	902	0.2	0.2	0.6	1.4	0.4*	Yes	Yes, north facing	Yes, fixed horizontal shading above south facing windows	Unspecified values, but most of south facade is glazed				Yes, stack effect and wind driven ventilation	Yes, large area of south facing glazing and north facing clerestory windows	No
Cambria Department of Environmental Protection Building	Pennsylvania, USA	22	3205	Office and laboratory	PV (32.2)	3672	325	0.2	0.2	0.7	1.4-1.5	-	Yes	Yes, north and south facing	Yes, photocell activated roller shades on south facing clerestory windows, fixed, horizontal, overhanging shading above south facing windows and light shelves above ground floor south facing windows	Unspecified				No	Yes, clerestory windows and glazing on north and south facades in addition to light shelves on south facade	No
NREL Thermal Test Facility	Golden, Colorado, USA	49	929	Office and laboratory	None	3442	541	0.25-0.55	0.3	0.6	2.4-2.6	0.1	Yes	Yes, north and south facing	Yes, horizontal shading devices above south facing and clerestory windows	Unspecified				No	Yes, 88% of glazing located on south facade and intermediate ceiling reflect radiation into building	Yes, north wall has high thermal mass

Name	Location	Measured Thermal energy consumption (kWh/m^2/ year)	Size (m^2)	Building type	Renewable energy system (and capacity (kWp))	Degree days (Base 18°)		Thermal transmittance (W/m^2K)				Infiltration (ACH)	East-West axis	Clerestory windows	Solar shading	WWR				Natural ventilation	Natural daylighting	Thermal mass
						Heat	Cool	Wall	Roof	Floor	Window					North	East	South	West			
Zion National Park Visitor's Centre	Springdale, Utah, USA	30.2	1073	Visitor centre	PV 7.2	2095	1352	0.34-0.84	0.2	0.7	2.08-2.44	-	Yes	Yes, south facing	Yes, overhanging shading above south facing windows but not above south facing clerestory windows	0.28 (distributed over external walls)				Yes, stack effect driven ventilation with cool towers	Yes, large area of south and north facing glazing	Yes, in trombe walls and floor

Table 4.2 Summary of the building information and the key low energy design aspects

(*indicates that an air infiltration rate has been applied during simulation only but has not been tested in the completed building).

5 Designing a single low energy office building for the UK climate

5.1 Introduction

In this section, a single low energy office building for the UK climate is designed in OpenStudio [97] and modelled and simulated using EnergyPlus [98] simulation software.

OpenStudio is a collection of software that allows the user to design buildings and their associated building services and to analyse the resulting energy performance. OpenStudio utilises a Google SketchUp plug in to aid the design of a building. The building can be drawn in Google SketchUp and surfaces (such as walls, windows and floors) can be assigned physical properties. These physical properties include, but are not limited to, thickness of construction elements, building materials, thermal capacity, thermal transmittance and solar heat gain coefficients. Surfaces can, also be defined in the Model Editor part of the OpenStudio suite in addition to building services and thermal zones. All of the data from Google SketchUp and the Model Editor is stored in an EnergyPlus input file.

OpenStudio utilises the EnergyPlus simulation engine to calculate the energy performance of the building. EnergyPlus is the official building simulation software that is used by the US Department of Energy. It is widely accepted as a valid program for thermal energy simulation and research [99] and has been downloaded over 85,000 times since its first release in 2001 [100]. EnergyPlus allows the user to model heating, cooling, lighting, ventilation, infiltration, hot water and equipment within buildings. The Building Energy Software Tools Directory [100]describes EnergyPlus as:

“Next generation building energy simulation program that builds on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus includes innovative simulation capabilities including time steps of less than an hour…a heat balance-based zone simulation, and input and output data structures tailored to facilitate third party interface development. Recent additions include multizone airflow, electric power simulation…and water manager that controls and report water use throughout the building systems, rainfall, groundwater, and zone water use.’’[100]

Energy Plus has been tested and validated against the IEA BESTEST building load and HVAC tests [101-103]. The developers state that a high level of computer literacy is not required but it is useful to have an engineering background to help in the analysis of results. This made it an ideal program to use as the time spent learning how to use the software was not anticipated being long. In addition, the software is free to use.

The EnergyPlus calculation method is a heat balance model in which room air is modelled as well stirred and uniform air temperature is achieved throughout the thermal zone [104]. EnergyPlus also assumes that room surfaces have uniform surface temperatures, uniform long and short wave irradiation, diffuse radiating and reflecting surfaces and internal heat conduction (reference as above). The process that EnergyPlus simulations follow is detailed in Figure 5.1.

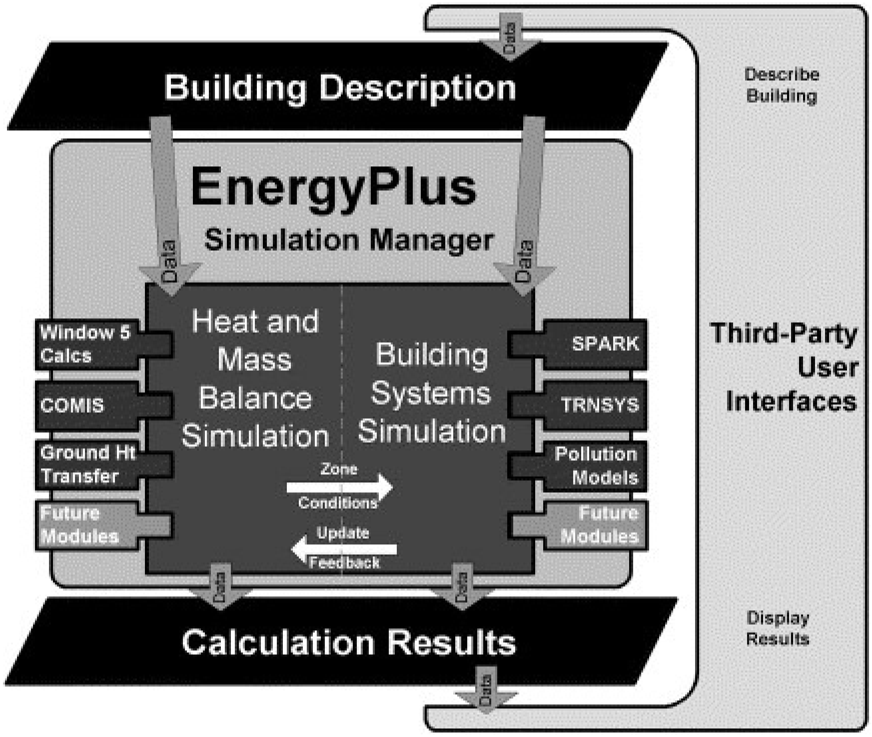


Figure 5.1: EnergyPlus modelling and simulation process [104]

EnergyPlus uses an “Integrated Solution Manager” (see Figure 5.2) to calculate the energy balance from the surface heat balance calculation, air heat balance calculation and building systems simulation.

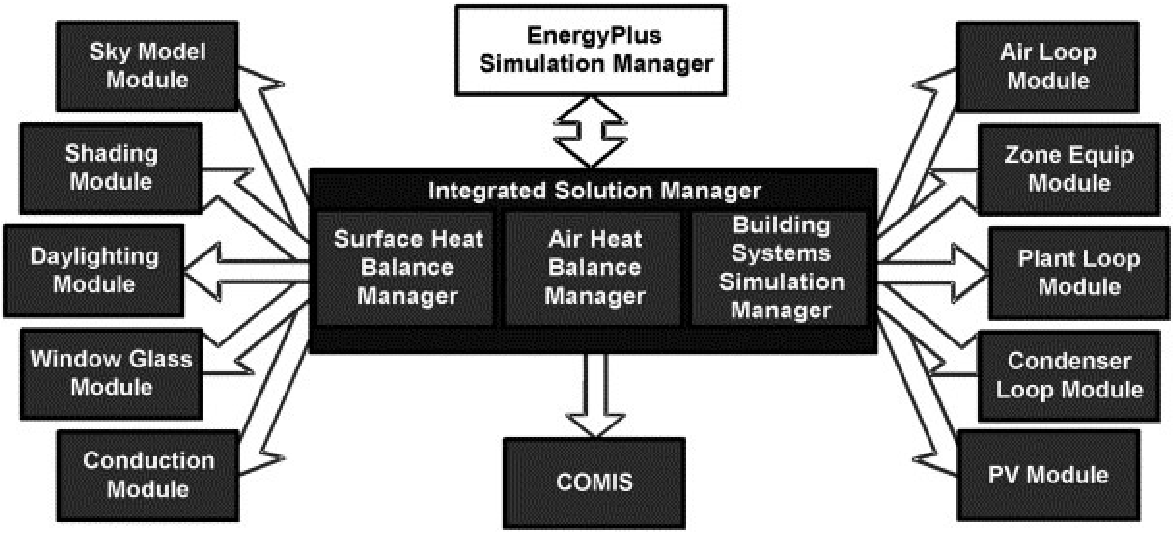


Figure 5.2: EnergyPlus Simulation Manager process [104]

The heat balance is calculated from using a weather input file. The difference between outdoor and indoor conditions is calculated taking into account radiant, convective and conductive heat transfer.

The calculation can be undertaken at a variety of time steps according the accuracy required by the end user. EnergyPlus then calculates the energy input from the building services components that is required to maintain the user defined internal conditions. Building services can be chosen from a library of typical components, can be designed by the user or can be ignored in favour of an Ideal Loads System, which calculates the required energy demand to satisfy the required internal conditions without the necessity of specifying manufacturers' specifications.

The results of the heat balance calculation can be viewed in the Results Viewer part of the OpenStudio suite. The user can choose the data they would like output by the Results Viewer in the Model Editor and Run Manager parts of the OpenStudio suite. Results can range from total heat balance for the entire building to heat balance for individual zones and operational performance of the building services.

The aim of the simulations is to create a building that functions at the same level of thermal energy performance using the same building envelope and construction elements and, ultimately, provide comfortable conditions for occupants in 10 locations across the UK, namely:

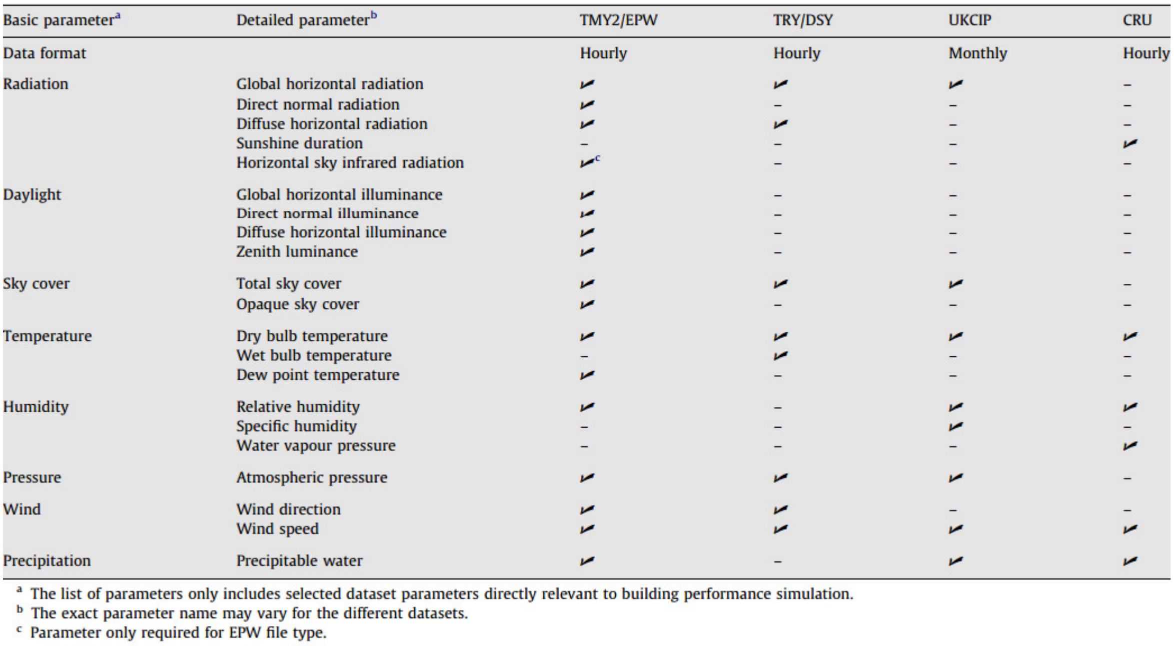
- Aberdeen;
- Aughton;
- Belfast;
- Birmingham;
- Finningley;
- Hemsby;
- Jersey;
- London;
- Leuchars; and
- Oban

The heating and cooling degree days are shown in Table 5.1 below.

Location	Heating Degree Days (Base 18℃)	Cooling Degree Days (Base 18℃)	Total Degree Days (Base 18℃)
Aberdeen	3632	2	3634
Aughton	3205	19	3224
Belfast	3299	7	3306
Birmingham	3167	31	3198
Finningley	3251	26	3277
Hemsby	3101	19	3120
Jersey	2581	37	2618
Leuchars	3523	4	3527
London	2968	44	3012
Oban	3272	10	3282

Table 5.1: Heating and cooling degree days for the locations to be tested [83].

The locations are also shown on a map of the UK in Figure 5.1. Weather files for each of the above locations have been used to accurately simulate the building's heating and cooling demands over a single year. The weather files that are used by EnergyPlus are EPW files (EnergyPlus Weather) and these are similar to TMY2 files (Typical Meteorological Year). The advantage of using EPW files over the TRY (Test Reference Year) and DSY (Design Summer Year) files that are used by other simulation software is the greater range of data that is contained in the EPW files as shown in Figure 5.2 below.



Basic parameter[a]	Detailed parameter[b]	TMY2/EPW	TRY/DSY	UKCIP	CRU
Data format		Hourly	Hourly	Monthly	Hourly
Radiation	Global horizontal radiation	✓	✓	✓	–
	Direct normal radiation	✓	–	–	–
	Diffuse horizontal radiation	✓	✓	–	–
	Sunshine duration	–	–	–	✓
	Horizontal sky infrared radiation	✓[c]	–	–	–
Daylight	Global horizontal illuminance	✓	–	–	–
	Direct normal illuminance	✓	–	–	–
	Diffuse horizontal illuminance	✓	–	–	–
	Zenith luminance	✓	–	–	–
Sky cover	Total sky cover	✓	✓	✓	–
	Opaque sky cover	✓	–	–	–
Temperature	Dry bulb temperature	✓	✓	✓	✓
	Wet bulb temperature	–	✓	–	–
	Dew point temperature	✓	–	–	–
Humidity	Relative humidity	✓	–	✓	✓
	Specific humidity	–	–	✓	–
	Water vapour pressure	–	–	–	✓
Pressure	Atmospheric pressure	✓	✓	✓	–
Wind	Wind direction	✓	✓	–	–
	Wind speed	✓	✓	✓	✓
Precipitation	Precipitable water	✓	–	✓	✓

[a] The list of parameters only includes selected dataset parameters directly relevant to building performance simulation.
[b] The exact parameter name may vary for the different datasets.
[c] Parameter only required for EPW file type.

Figure 5.3: Comparison of weather data files, taken from Jentsch et al (Reference)

EPW files have been used in a number of published research articles. Jentsch et al used EPW files to generate and assess climate change scenarios for future weather and chose EPW files above TRY and DSY files, among others. Wang et al performed a case study of zero energy house design in Cardiff, Wales. EnergyPlus was used as the modelling and simulation software for assessing the building fabric modifications and an EPW file for Cardiff was used to simulate the weather over the course of a year. These articles demonstrate the effectiveness and appropriateness of using EPW files for simulating weather conditions in EnergyPlus models.

The building has been designed using the conclusions drawn from the study of 9 low, nearly zero or net zero energy buildings described and evaluated in Chapter 4. The conclusions are detailed in section 4.12.

It is anticipated that, due to the climate variations in the UK, the building would not be able to function at the same thermal energy demand in each location purely by upgrading the building fabric to the same, high performance values although the resulting savings in thermal energy demand by upgrading the building envelope are of major importance to the aims of this research. As such, once a low energy building model has been successfully created, the temperature set point and ventilation rates will be varied to obtain a building that will function at the same thermal energy performance across the 10 UK locations without compromising basic requirements for ventilation provision and occupant comfort

Figure 5.4: Map of the 10 UK locations at which the building is simulated [105]

5.2 Creating the low energy building model

5.2.1 Base case (BC)

The base case model has been designed to England and Wales Building Regulations Part L2A for new buildings other than dwellings [1] and the specific construction details are given in Table 5.1. A summary table has been provided for each model and these are shown in Chapter 7. The building has a 1600m^2 floor area and is a two storey structure. The footprint is elongated along an east-west orientation, with 50m long north and south facing sides and 16m long east and west facing sides. The height of each storey is 3.5m, resulting in a total height of 7m. Each facade has the same construction and window to wall ratio of 0.4.

According to much of the literature that has been consulted [47, 48, 61-66, 68-81, 86], successful low and net zero energy buildings have been designed to run along a narrow east-west axis. This has two advantages: first, the largest facades of the building face either north or south, meaning that the south facade can take advantage of solar gains (heat and daylight) while the north facade can have limited glazing to minimise heat loss; and second, the narrow floor plan means that more of the building can utilise the solar heat and daylight gains, resulting in a lower energy demand for lighting and a corresponding lower internal heat gain from artificial lighting. This orientation means that there is a lower demand for heating as additional solar heat gains can supplement the building's heating strategy and there will be a lower demand for artificial lighting, which will reduce the internal heat gains and, subsequently, reduce the building's cooling load.

The building has also been specified to operate with certain loads in order to make the model more representative of a real building. The only components missing are the specific HVAC systems. OpenStudio allows the user to use HVAC Templates titled 'District Heating' and 'District Cooling' , which calculate the heat loss and gain from a building and the amount of energy required to maintain the specified temperatures in each zone. Assigning these HVAC templates provides the means for the software to undertake dynamic heat loss and heat gain calculations but do not contain performance curves or manufacturer data. This enables the energy demand of the building space to be calculated rather than the energy performance of specific HVAC units. In turn, this allows the results to be generalised to other buildings without the necessity to specify certain manufacturer's products, leaving that decision to the building designer, operator or owner. However, there may be an argument that the results are not as realistic as they could be, but the overall aim of this research is to study energy performance related to the building fabric and not the HVAC systems. The energy demand, therefore, is that required to maintain a specified temperature in the building space and is the load in the space, not the energy consumed by the HVAC plant.

The building has been modelled with internal loads in order to replicate the actual usage and to model the internal heat gains from occupants, lighting and equipment. While the lighting and equipment energy usage are nominal (rarely changing in each location), they are important for modelling as they will provide passive heating, some of which is useful (winter) although part of the load can put more demand on the cooling load in summer. The lighting has been modelled at 10W/m^2 as this is a good approximation of using low energy, LED lamps with a luminous efficacy of 60lumens/W [106] and a required luminous flux of approximately 500lux [107]. There is also a daylight strategy that turns off the interior lights when the daylight levels reach 500 lux. The equipment load has been modelled as 6.7W/m^2 as this is the load specified in the NREL Research Support Facility building [47]. The occupancy density has been modelled as 0.0954people/m^2 as this value was stated in a document pertaining to the increasing occupancy density in British offices [108].

Element	Construction	Values
External wall	1.5mm external render, 60mm expanded polystyrene insulation, 240mm aerated autoclaved concrete block	U=0.35 W/m^{2}K
Roof	20mm roof ballast, 2mm steel deck, ceiling airspace, 140mm expanded polystyrene insulation, 12.5mm plasterboard, 12.5mm plaster	U=0.25 W/m^{2}K
Floor	200mm concrete slab, 140mm expanded polystyrene insulation, 50mm screed	U=0.25 W/m^{2}K
Window	Double glazed, aluminium frame with thermal break, 5.7mm glazing, 6.4mm air gap, 5.7mm glazing	U=2.21 W/m^{2}K SHGC=0.701

Table 5.2: Thermal transmittance parameters for a building constructed to England and Wales Building Regulations 2010 Part L2A

As well as the construction elements being designed to Building Regulations Part L 2010 standards, the infiltration rate has also been specified to the same standard. For offices, the maximum air leakage rate at 50Pa pressure difference is 10m^3/hr/m^2; this corresponds to an air change rate of 0.14ACH. The calculation for this is detailed below with numbers in brackets on the left hand side to allow for shorthand to be used in later stages of the calculation:

- 1600m^2 x 10m^3/hr/m^2 = 16000m^3/hr (1)
- 50m x 16m x 7m = 5600m^3 (2)
- (1) / (2) = 2.8ACH @ 50Pa (3)

Scaling the pressure difference from the test pressure difference of 50Pa to an average working pressure difference of 4Pa means that the air infiltration rate can be scaled down by 20:

- (3) / 20 = 0.14ACH

The heating and cooling setpoints have been set at 19℃ and 25℃, respectively.

External shading located above windows can assist in regulating the indoor temperatures by admitting direct solar radiation in the winter when the sun is at its lowest angle and reflect solar radiation in the summer when the sun is at its highest angle. While shading will have the aforementioned effect, the distance that the shading element protrudes from the building will determine how much radiation enters. Creating shading elements that are too long will block most solar radiation (even in the winter) and having a shading element that doesn't protrude far at all will allow most solar radiation in. In order to limit the solar heat gains and to reduce uncomfortable glare for the occupants, the building has been designed with exterior horizontal shading above the south, east and west facing windows. The north facing windows will not require shading as they will not receive direct sunlight and should not be subject to high solar heat gains or glare. A series of simulations was undertaken with the building designed as described above but with different lengths of horizontal shading above the windows. The results are displayed in Figure 5.2 below and demonstrate that an optimum thermal energy demand has been achieved by using 1.0m horizontal shading above south, east and west facing windows:

- $y = 4.31x^2 – 8.3721x + 55.56$
- $dy/dx = 8.62x – 8.3721$

$dy/dx = 0$ when the total thermal energy demand is at its lowest, therefore:

- $8.62x = 8.3721$
- $x = 0.971$, which is approximately 1.0m

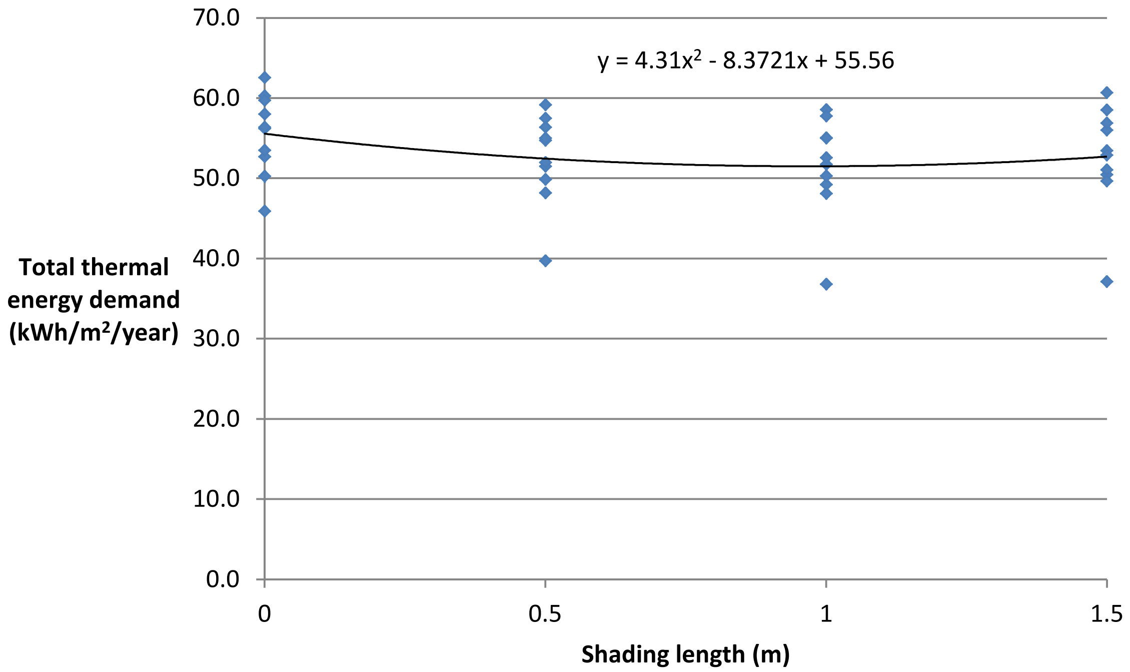


Figure 5.5: Total thermal energy demand for varying lengths of horizontal shading above windows

Each simulation runs for one year (or 8760 hours) and calculations are undertaken by the software package to calculate the heat loss and gain and subsequent heating and cooling demand. The building is simulated in each of the locations with available weather files, namely Aberdeen, Aughton, Belfast, Birmingham, Finningley, Hemsby, Jersey, Leuchars, London and Oban.

A wide variation in energy use has been observed from the simulations, the results of which are given in Table 5.2 and Figure 5.2. Figure 5.3 demonstrates the range in total thermal energy demand that has been observed across the various climate profiles.

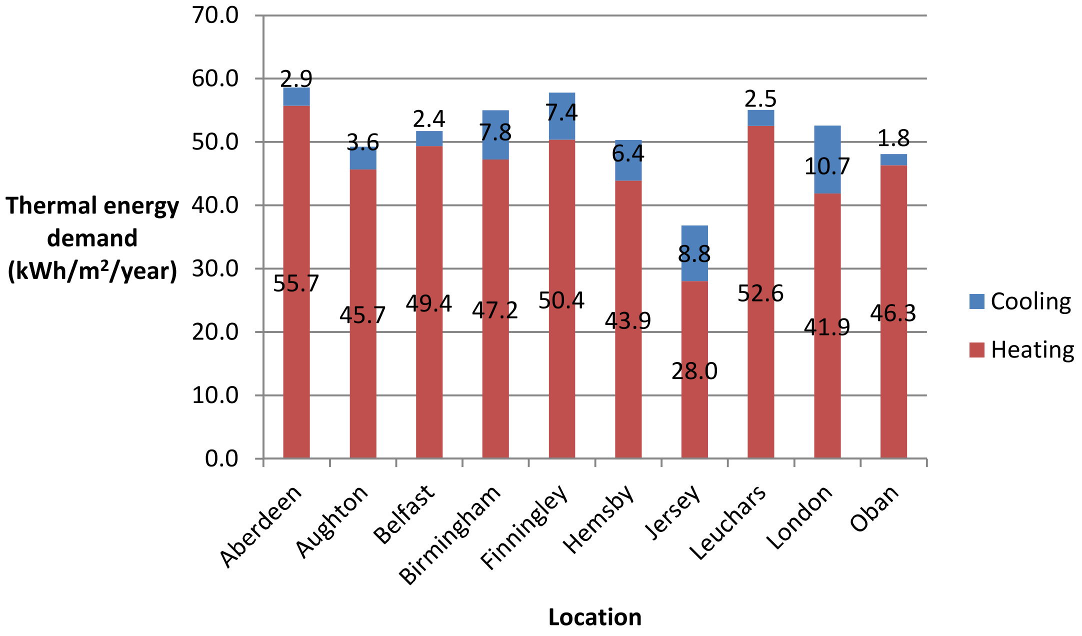


Figure 5.6: Heating, cooling and total thermal energy demand for the Base Case building

5.2.2 Model Validation

The values predicted by the EnergyPlus model have been compared with static heat loss calculations performed in Microsoft Excel in order to confirm their validity at the beginning of the study, which in turn will increase confidence in the results. Each location was tested by obtaining a monthly indoor and outdoor dry bulb temperature from the EnergyPlus simulation results and the weather files, respectively, and calculating the heat loss rate through each construction element as defined in Table 5.1 and through infiltration. The following formulae were used for calculating heat loss by conduction through the building envelope (5.9) and by infiltration (5.10):

- $Q = U \times A \times \Delta T$; (5.9)
- $Q = 1/3 \times n \times V \times \Delta T$; (5.10)

where Q is heat loss (W), U is the thermal transmittance value (W/m^2K), A is the surface area of the construction (m^2), ΔT is the difference between indoor and outdoor dry bulb temperature (K), n is the infiltration rate (air changes per hour) and V is the volume of the building space (m^3).

The external dry bulb temperature for the ground floor was estimated as being 2°C less than indoor temperature. The heat loss rate was then multiplied by the number of hours in each month to obtain a total heat loss value. As the heating is anticipated to be switched off in the summer months, the results for June, July and August were not included in the total heat loss value (although they make less than 1% difference to the heat loss value).

Heat gain was not analysed in this calculation as the average monthly outdoor dry bulb temperature never exceeded the indoor temperature and would have returned a total heat gain value of zero. This is a major limitation of conducting a simple static heat loss calculation as the variation in temperatures is not accounted for in the calculation. However, the model can be roughly validated in this way and is a very quick and simple method of understanding the magnitude of heat loss to be expected from the simulation results. Due to the above reasons and the complexity of calculating heat gain through a static calculation (especially solar heat gain), only the heat loss from the EnergyPlus model has been taken into account in this validation study. The positive to this is that the EnergyPlus and static calculations are both testing for the same thing, heat loss, and the results will not be skewed by other variables.

The EnergyPlus model has been analysed purely for conduction and infiltration heat losses to make the static and EnergyPlus calculations consistent. Although heat gains have not been analysed, they have been included in the model and simulations. This was in order to obtain an accurate indoor air temperature for each calculation.

The results of the model validation study are displayed in Figure 5.4.

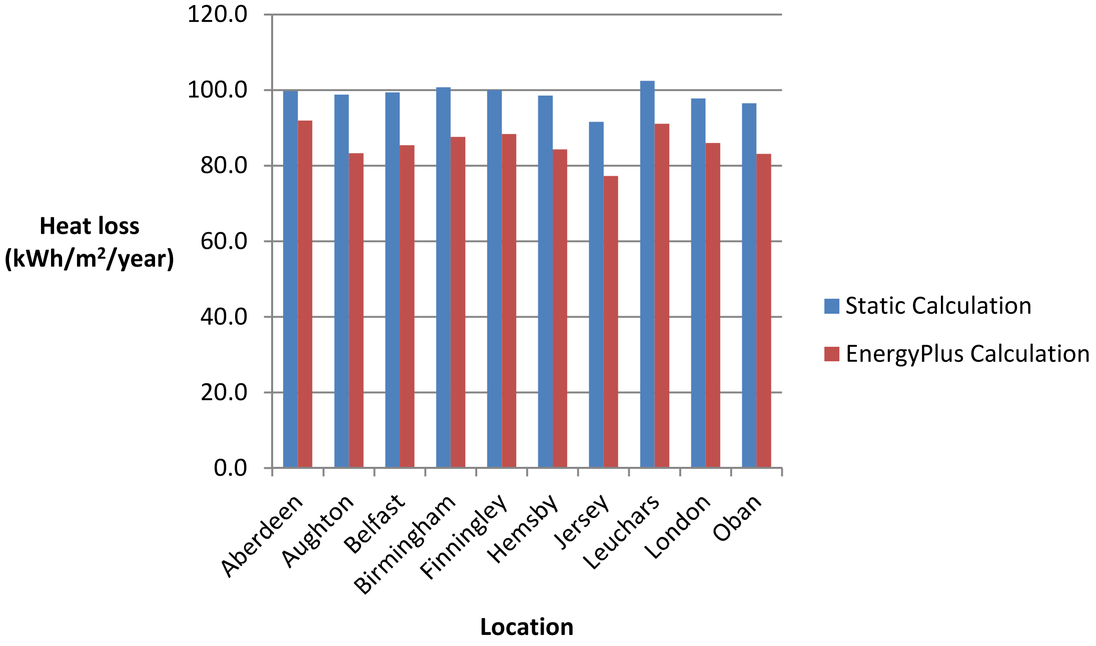


Figure 5.7: Comparison of static and EnergyPlus calculations of heat loss

The static calculation results in a heat loss value that is consistently larger (7% - 15%) than that resulting from EnergyPlus. This is due to the nature of the two calculation methods. The static calculation uses an average indoor and outdoor dry bulb temperature to calculate the heat loss by conduction and infiltration. The EnergyPlus dynamic calculation uses: dry and wet bulb indoor and outdoor temperatures, indoor and outdoor humidity, wind speed and direction and solar radiation to calculate overall indoor and outdoor temperatures and does this at 15 minute intervals during the simulation. As such, it is expected that there will be a difference between the static and EnergyPlus calculations, with EnergyPlus providing a more accurate heat loss result. However, the difference between the two calculation methods is between 7% and 15%, depending on location, and gives confidence that EnergyPlus is providing reliable results.

This is purely a test of the conductive and infiltration based heat loss for each calculation method. It was performed in this way because it made the static calculation easy to conduct. Although not all heat losses and none of the heat gains were analysed, this validation study found that the conductive and infiltration based heat losses from each calculation method were within 7% and 15% depending on the location.

5.2.3 Base case building fabric heat gains and losses

The heat gains and losses through the building fabric for the base case building have been calculated. As above, internal heat gains from occupants, lights and equipment have not been analysed in the results, although they have been modelled to obtain an accurate indoor air temperature. The results are shown in Figures 5.5 to 5.9.

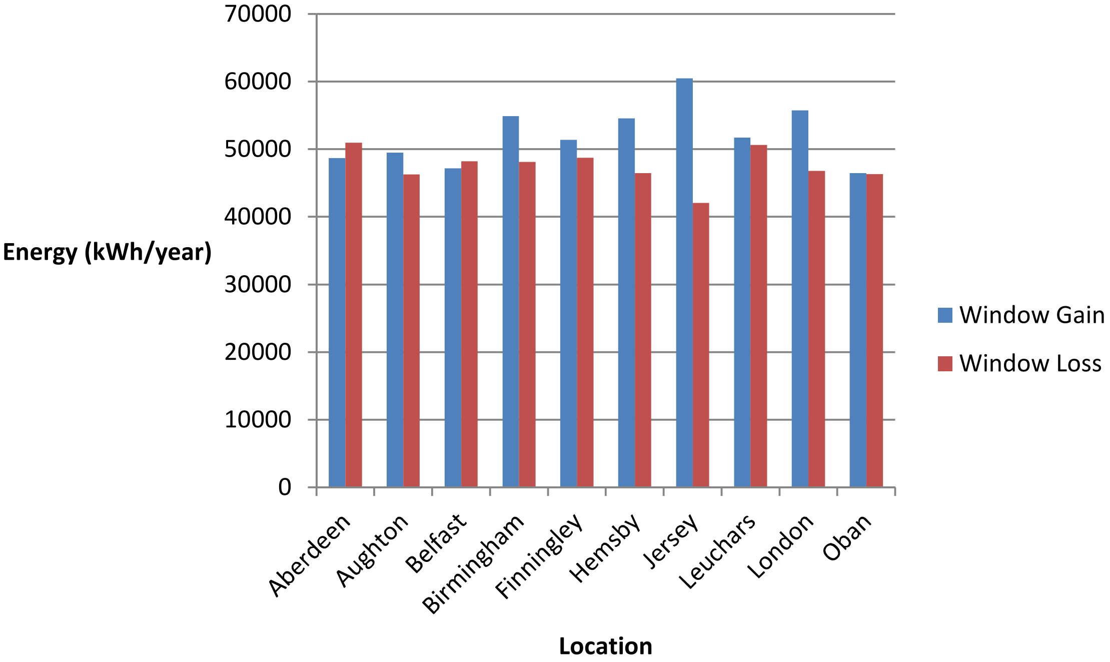


Figure 5.8: Base case window heat gains and losses

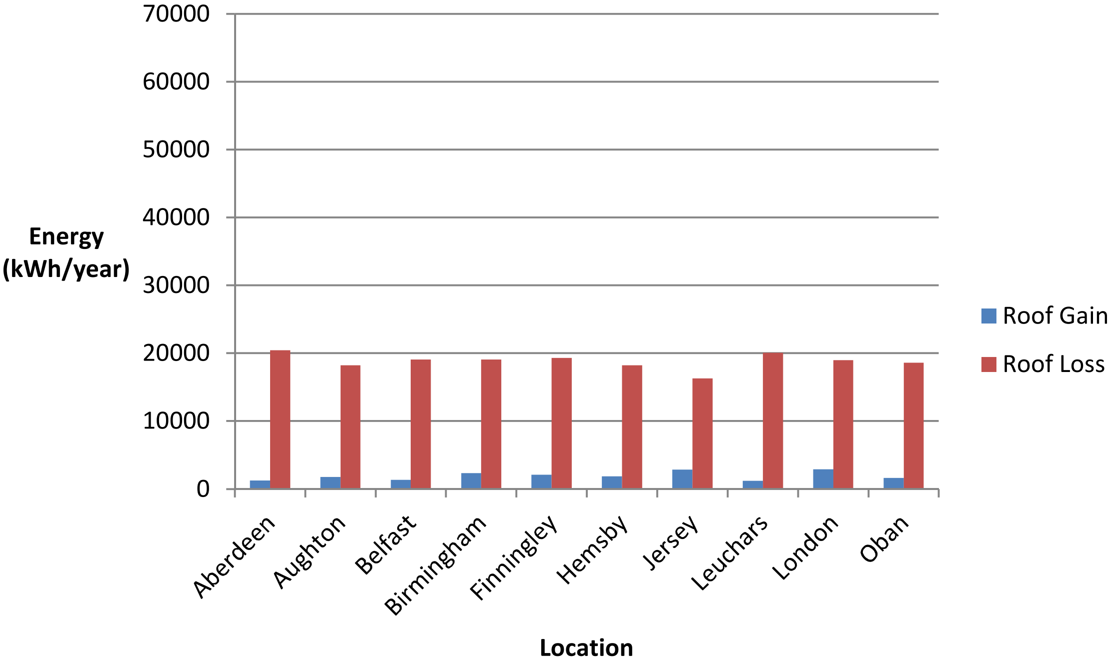


Figure 5.9: Base case roof heat gains and losses

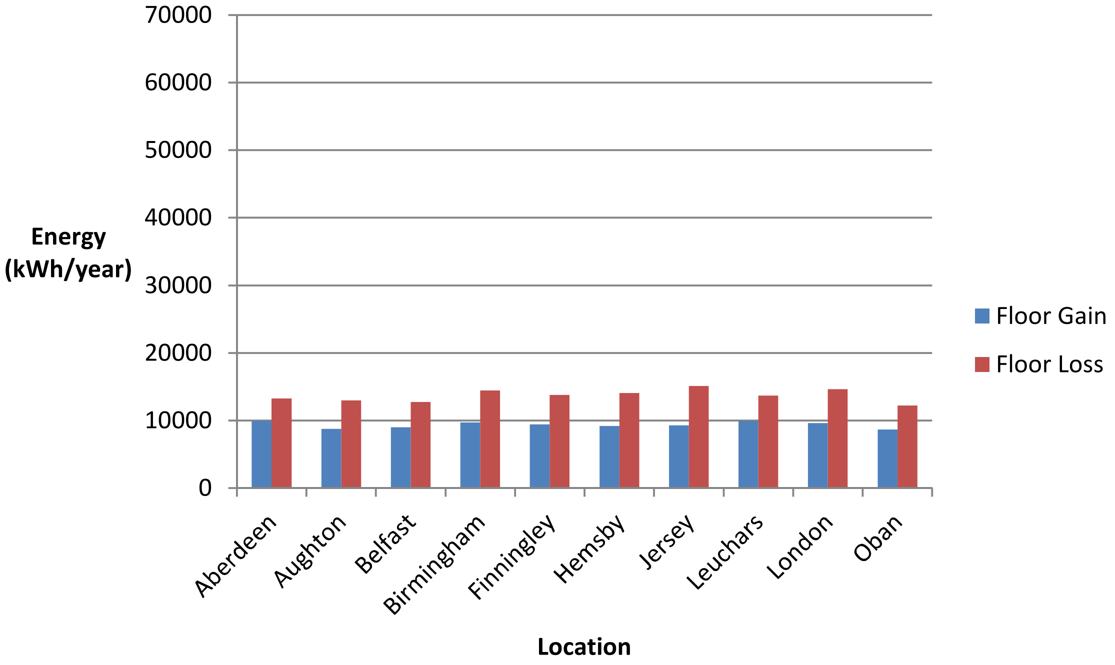


Figure 5.10: Base case floor heat gains and losses

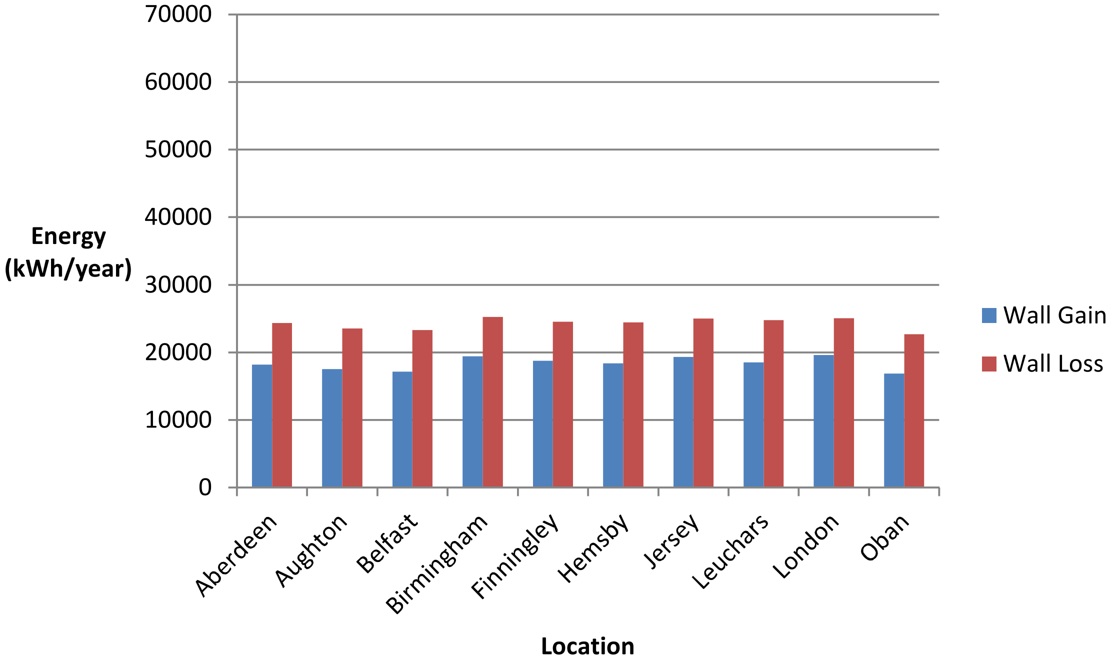


Figure 5.11: Base case wall heat gains and losses

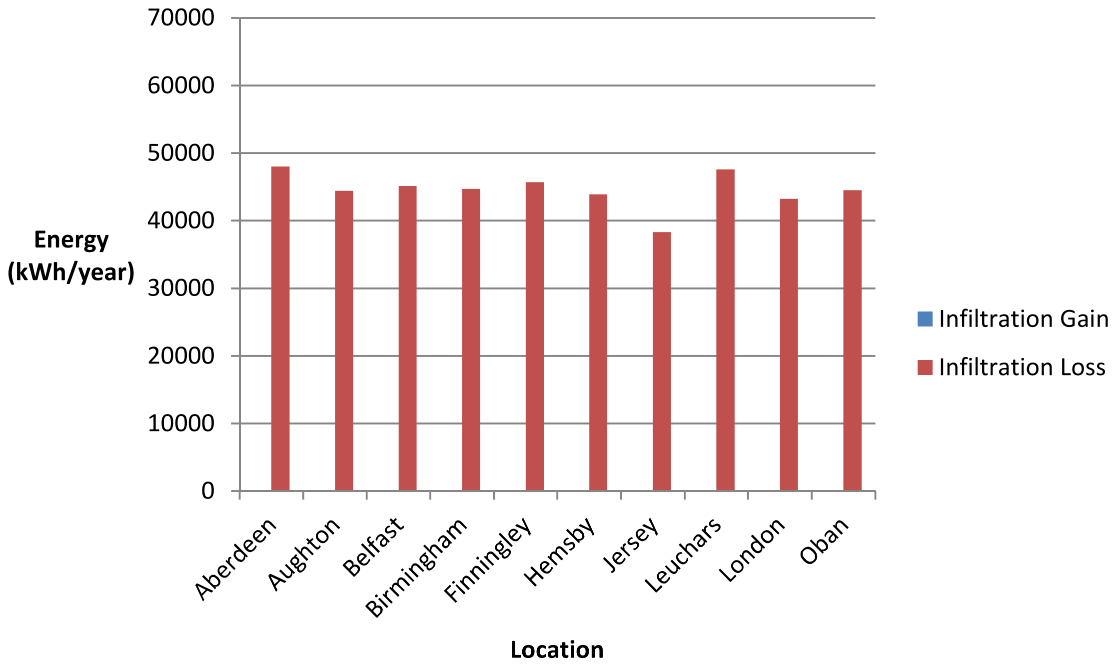


Figure 5.12: Base case infiltration heat gains and losses

It can be seen from the results in Figure 5.6 that windows provide the greatest heat gain but also the greatest heat loss. The net result however is heat gain in almost all locations. Infiltration (as shown in Figure 5.10) is responsible for the second greatest heat loss but also for the least heat gain. The heat gain through infiltration would usually only be noticeable during the summer months when the outdoor air temperature rises above the indoor air temperature. This is a rare event in the UK climate and, as such, the results show a net heat loss and also the greatest net heat loss in each location.

Unsurprisingly, the floor (Figure 5.8) experiences least heat loss, as ground temperatures beneath the floor tend to be only 2℃ less than indoor temperature. The roof and walls (Figures 5.7 and 5.9, respectively) experience similar heat losses, with the walls contributing to slightly more heat loss than the walls. However, the walls gain a lot more heat than the roof, which is mainly attributable to the long south facing wall and the intense solar radiation on the east and west facades in the morning and evening, respectively.

These results will help to inform the modifications that are made to the model in order to achieve the same thermal energy demand across all ten locations. From these results, it seems logical to make the modifications in the following order:

- Limit infiltration as far as practical;
- Limit heat losses and maximise heat gains through windows by reducing the amount of north facing glazing;
- Limit heat losses from the roof by increasing the amount of thermal insulation or by specifying a higher performance insulation product;

- Limit heat losses from the walls by increasing the amount of thermal insulation or by specifying a higher performance insulation product; and
- Make minimal changes to the floor construction as the net heat loss is comparatively very small.

5.3 Optimum Modifications

The development of the Base Case model and the investigation into heat gains and losses has demonstrated the effect of the building envelope on thermal energy demand. The findings of the previous analysis will guide the modifications to the following models. These Optimum Modification models will aim to reduce the total thermal energy demand and the range in total thermal energy demand across the tested locations.

It is evident that reducing the infiltration value is the most effective modification towards achieving the aims of reducing thermal energy demand by limiting heat loss from the interior building space. The infiltration rate should be targeted for reduction in the Optimum Modifications models.

Heat losses and gains were greatest from the window construction and sensible design and placement of glazing in the models should be used to limit heat losses and maximise heat gains. The amount of glazing on the north façade of the building should be limited. North facing glazing does not experience direct solar heat gain (in the northern hemisphere) and, as such, mainly provides daylight through reflected light. High proportions of east and west facing glazing can lead to overheating and uncomfortable glare in the mornings and evenings. South facing glazing will predominantly provide solar gains for the building space. Glazing in this façade should be maximised to allow for heat and daylight gains.

Heat loss from the roof and walls should be limited by increasing the levels of insulation. Heat losses were more predominant from the wall construction, yet walls also experienced relatively high levels of heat gain. The wall thermal transmittance value is higher than that of the roof, which will result in easier transmittance of heat from the building to the outside environment but will also enable heat to enter into the building space by conduction and radiation more easily. Wall thermal transmittance values should be limited to an extent in order to maintain a level of heat gain into the building in the cold UK climate. However, if cooling demand becomes the predominant thermal energy demand, it may be necessary to limit the reduction in thermal transmittance to allow heat loss through the walls.

Roof heat loss should be limited in all instances. As heated air rises and temperatures tend to increase at the ceiling of a building, roof constructions are very susceptible to heat loss despite their usual lower thermal transmittance values. As was seen in the heat losses and gains of the Base Case, the roof experienced a great amount of heat loss and a very low amount of heat gain, despite the lower thermal transmittance value and lower area than the wall construction.

The floor construction experienced limited heat gains and losses due to the low temperature gradient between the ground and the inside air temperature. As such, the floor construction will remain the same as it is not envisaged that this will contribute significantly to the reduction of thermal energy demand.

As well as using the findings from the case studies and the development of the Base Case model to reduce the total thermal energy demand, this section will also help to understand how the modifications can contribute towards achieving the same total thermal energy demand in any UK location.

One key further modification should also be made to the building model to help achieve the overall aims: introducing a night time set back temperature for heating and cooling should reduce needless energy consumption when the building is not in use.

5.3.1 Optimum modifications 1 (OM1)

This model makes modifications to the building envelope in line with the conclusions from the case studies and Base Case model development and combines them into one model in a practical and achievable way: night time thermostat setback temperature has been set to 14℃ for heating and 40℃ for cooling; an infiltration value 0.04ACH has been applied as this represents an achievable and very airtight building [109]; the insulation thickness has been increased to 300mm in the roof and 200mm in the walls, which corresponds to thermal transmittance values of $U=0.125W/m^2K$ and $U=0.157W/m^2K$ respectively; and glazing elements with thermal transmittance value of $U=0.7W/m^2K$ and SHGC of 0.5 have been specified.

Increasing the thickness of wall and roof insulation any further raises issues with practicality. Increasing the wall insulation will result in either a reduced space inside the building or a larger building footprint to maintain the required amount of space. Increasing the roof insulation will also leave less space inside the building or the ceiling height will have to be raised to achieve the required space. A loss of internal space will result in less usable area inside the building and extending the building (either outwards or upwards) will incur additional costs. Figure 5.34 shows the cooling, heating and total thermal energy demand for each location.

According to much of the literature that has been consulted [47, 48, 61-66, 68-81, 86], successful low and net zero energy buildings have been designed to run along a narrow east-west axis. This has two advantages: first, the largest facades of the building face either north or south, meaning that the south facade can take advantage of solar gains (heat and daylight) while the north facade can have limited glazing to minimise heat loss; and second, the narrow floor plan means that more of the building can utilise the solar heat and daylight gains, resulting in a lower energy demand for lighting and a corresponding lower internal heat gain from artificial lighting.

In order to reduce heat loss further, the window to wall ratio has been optimised. From the findings of Wang et al [49], it was found that WWRs of 0.1 on the north, west and east facades and a WWR of 0.4 on the south facade was optimal. This has been incorporated into this model.

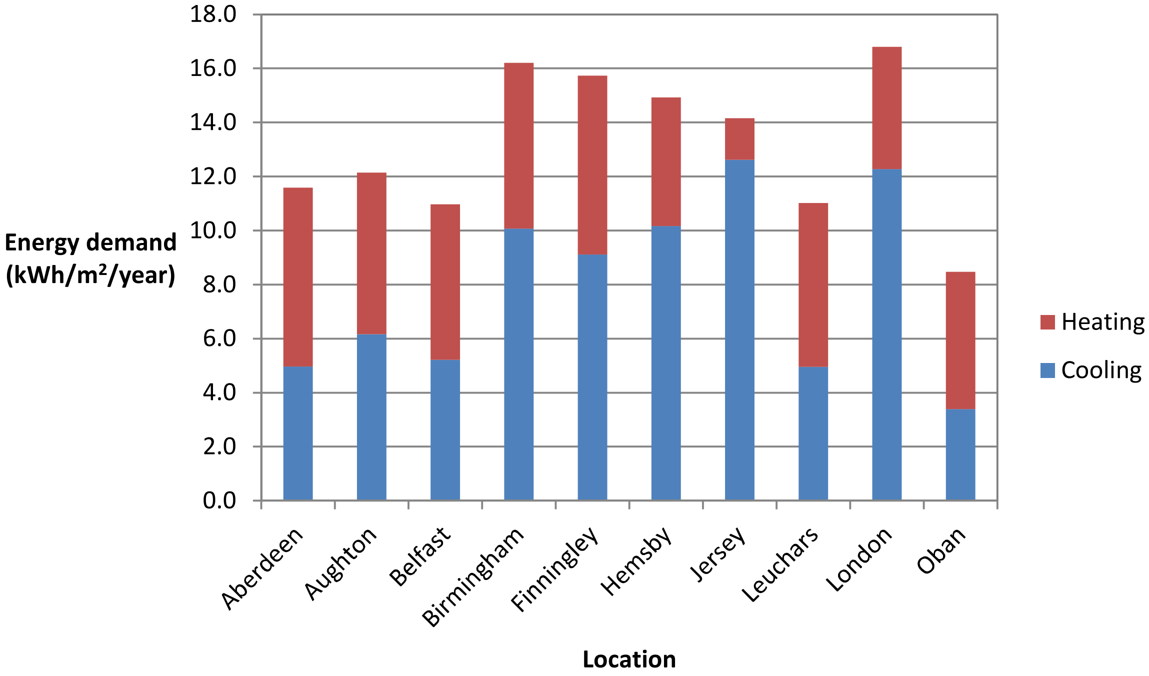


Figure 5.13: Breakdown of heating, cooling and total thermal energy demand for the building with the OM1 scenario

The results of OM1 show that the cooling energy demand is greater than the heating demand in many of the tested locations. This is unusual for a climate that is primarily heating dominated and there are a number of reasons that this has occurred. The increased thickness of wall and roof insulation and glazing systems has increased the thermal resistance of these elements, subsequently reducing the heat loss from inside the building space. When this is coupled with the high solar heat gain coefficient of the windows (allowing a greater amount of the heat component of solar radiation into the building) and a low infiltration value (reducing the more rapid element of heat loss), the building is experiencing overheating more frequently.

The results are, however, encouraging for the overall aim of the building; to reduce total thermal energy demand and to reduce the range of annual thermal energy demand. Average total thermal energy demand is reduced to 11.8kWh/m^2/year and the range of thermal energy demand has decreased to 6.6kWh/m^2/year.

5.3.2 Optimum modifications 2 (OM2)

The OM2 model has continued in the same vein as the previous model; the only change that has been made is reducing the solar heat gain coefficient to 0.5. The intention of this model is to reduce the cooling energy demand for each location in comparison to the OM1 model whilst not incurring increased heating energy demands to the point where the total annual thermal energy demand is increased from the OM1 model. It is envisaged that reducing the SHGC will reduce the rate of heat transfer into the building and will reduce the thermal energy demand and range of thermal energy demand between locations. Figure 5.36 shows the cooling, heating and total thermal energy demand for each location.

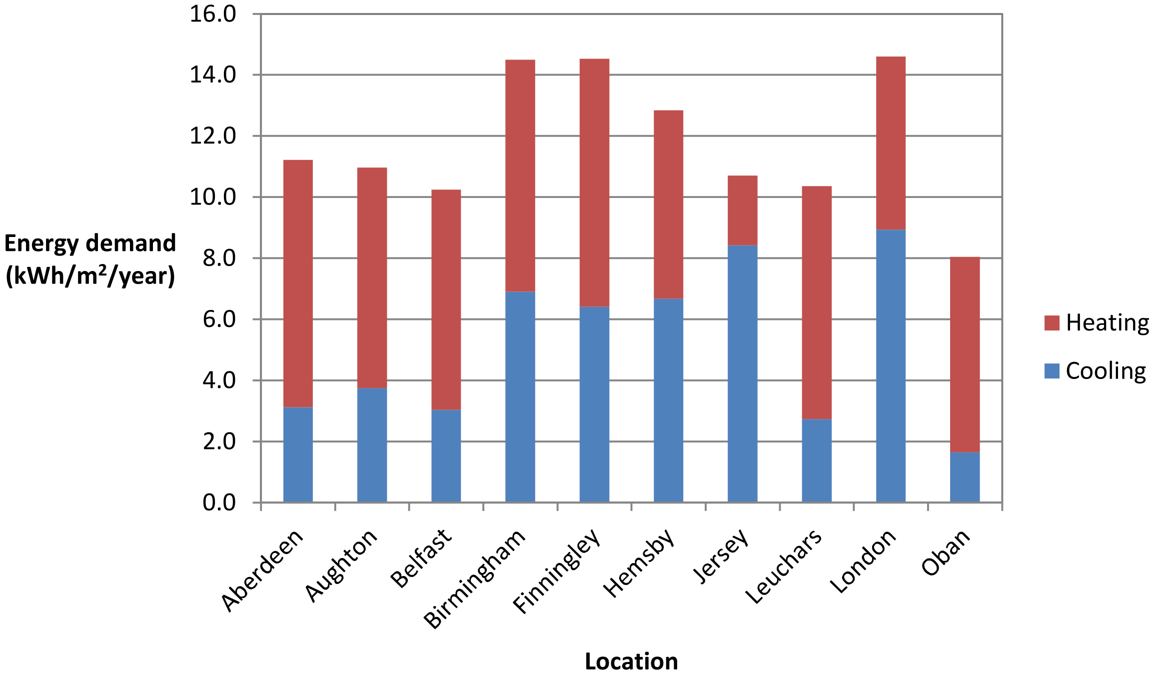


Figure 5.14: Breakdown of heating, cooling and total thermal energy demand for the building with the OM2 scenario

The reduction of the solar heat gain coefficient to 0.5 has resulted in an average reduction in cooling energy demand of 2.8kWh/m^2/year whilst only incurring an additional average heating demand of 1.3kWh/m^2/year. This translates as a reduction in annual thermal energy demand of 1.5kWh/m^2/year (mean=11.8kWh/m^2/year) and a more uniform annual thermal energy demand (range=6.0kWh/m^2/year); an overall improvement upon the OM1 model.

5.3.3 Optimum modifications 3 (OM3)

The OM2 model demonstrated that lowering the value of solar heat gain coefficient in the glazing elements will produce a building that not only requires a lower energy demand but also functions at a more uniform thermal energy consumption in UK locations. However, the cooling demand is still high and, in some locations, is higher than the heating energy demand (Hemsby, Jersey, and London). While reducing the insulation thickness, increasing the glazing thermal transmittance or increasing the infiltration rate will result in a lower cooling demand, it is envisaged that these alternatives will result in a higher heating energy demand and, possibly, a higher total thermal energy demand. As such, the SHGC is being reduced even further to 0.2. This value of SHGC is also more realistic of a low thermal transmittance glazing element as the increasing number of glass panes will reflect more radiation and inhibit the rate of heat transfer into the building. Table 5.18 and Figure 5.38 show the cooling, heating and total thermal energy demand and Figure 5.39 shows the total thermal energy demand plotted against degree days for each location.

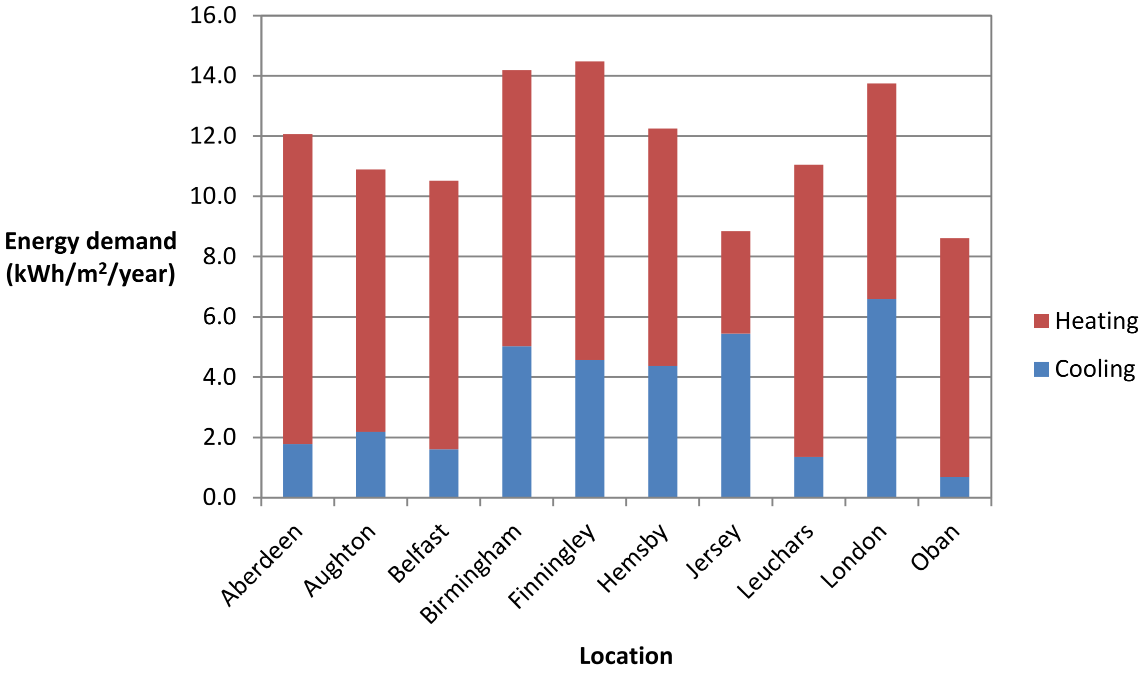


Figure 5.15: Breakdown of heating, cooling and total thermal energy demand for the building with the OM3 scenario

Reducing the SHGC to 0.2 has had the effect of reducing the cooling energy demand by 1.8kWh/m^2/year but has caused an increase in heating energy demand of 1.7kWh/m^2/year. This is as predicted but has resulted in an average total energy consumption of 11.7kWh/m^2/year; a reduction in annual thermal energy demand of just 0.1kWh/m^2/year. The resulting range of total thermal energy demand has also reduced by 0.1kWh/m^2/year to 5.9kWh/m^2/year. It can be concluded that there will be little, if any, benefit to reducing thermal energy demand by reducing the glazing SHGC any further. As such, a SHGC value of 0.2 will be maintained and building operational parameters will now be adjusted to achieve a single, low energy building regardless of UK location.

5.3.4 Optimum Modifications 4 (OM4)

The SHGC has reached a point at which it no longer significantly affects the thermal energy demand or uniformity of thermal energy demand across different UK locations. The most effective fabric modifications from the Parametric Study have each been applied to the model but there have not been any further temperature controls, other than the night time temperature setback. As such, temperature controls during occupancy hours have been applied to the OM4 model. As the cooling energy demand is still relatively high, the cooling temperature setpoint has been increased from 25℃ to 30℃. This setback temperature has been set in the aim of reducing the cooling energy demand. Table 5.19 and Figure 5.40 show the cooling, heating and total thermal energy demand and Figure 5.41 shows the total thermal energy demand plotted against degree days for each location.

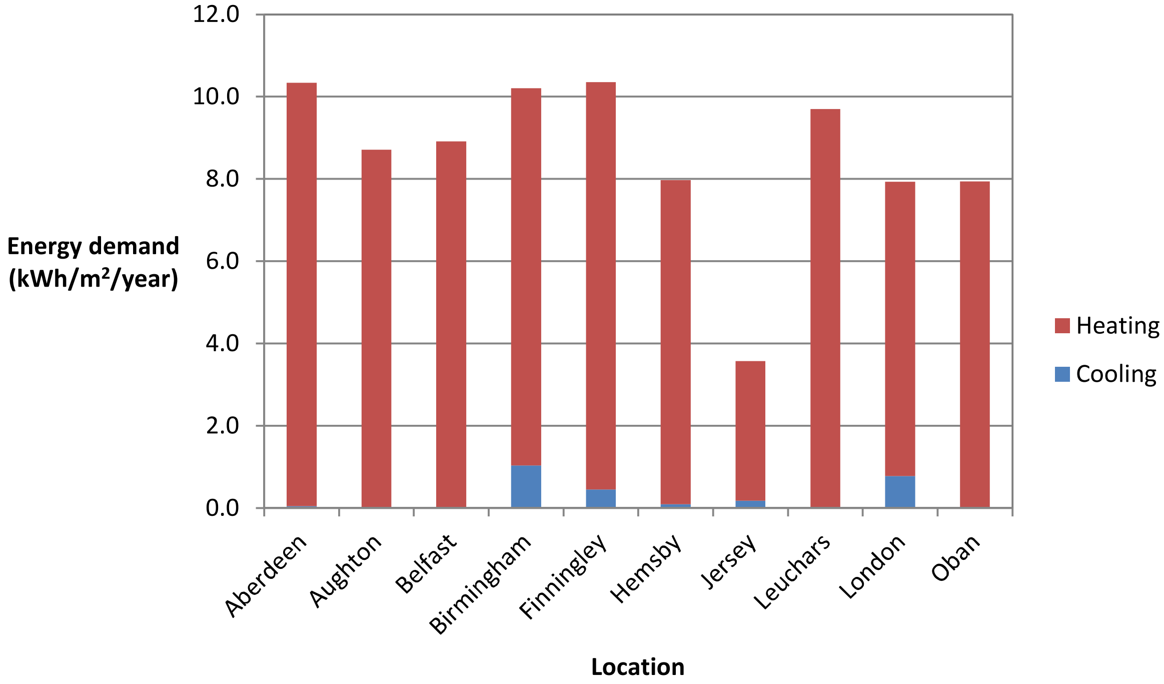


Figure 5.16: Breakdown of heating, cooling and total thermal energy demand for the building with the OM4 scenario

The OM4 model has produced a very interesting result; raising the cooling temperature setpoint from 26℃ to 30℃ has almost nullified the cooling energy demand across the locations, with half of the tested buildings requiring no cooling energy whatsoever. The coldest locations of Aberdeen, Aughton, Belfast, Leuchars and Oban require no cooling energy. The mean cooling energy demand across the locations that do require some cooling energy is just 0.5kWh/m^2/year and, across all locations, the mean is even less at 0.25kWh/m^2/year. This is a vast improvement on the reduction of cooling energy demand and changing a temperature setpoint is a relatively simple modification to apply to the building. The significance of this model and its accompanying results is that temperature setpoints, for heating or cooling, can be adjusted in order to obtain, not only an extremely low thermal energy demand but also, uniform total thermal energy demand across the country. From a statistical point of view of the aim to achieve the same thermal energy demand in each location, the results for the range alone are misleading; the range actually increases to 6.7kWh/m^2/year. However, if the results for Jersey are omitted for OM3 and OM4, the range for OM3 is 4.0kWh/m^2/year and for OM4 is 2.5kWh/m^2/year; demonstrating a decreasing range. The Jersey results have been omitted for this calculation as they are misrepresentative of a real building in the warmer climate of the Channel Islands; they have not just been omitted purely for the sake of achieving uniform thermal energy demand. Incorporating a cooling setpoint temperature of 30°C in Jersey would lead to uncomfortable indoor temperatures in the summer. A lower cooling setpoint temperature will be required to maintain comfortable conditions in the Jersey building. As such, while the building fabric will remain identical in each location, the internal controls will vary. The OM5 model addresses this issue.

5.3.5 Optimum modifications 5 (OM5)

Following on from the previous model, this model aims to establish a building with uniform energy consumption for all of the tested locations and to provide each building with a comfortable indoor environment. The temperature setpoints have been adjusted and are as shown in Table 5.20 below.

Location	Setpoint (°C)	
	Heating	Cooling
Aberdeen	17.4	27.7
Aughton	17.8	28
Belfast	17.9	28
Birmingham	17.2	28
Finningley	17	28
Hemsby	17.7	27.4
Jersey	18	26
Leuchars	17	27.2
London	17.5	27.9
Oban	18.1	26.2

Table 5.3: Individual heating and cooling setpoints for the OM5 scenario building in each of the ten locations to achieve equal thermal energy demand

The result is uniform thermal energy consumption across all 10 locations, albeit with a substantial cooling energy requirement for the building in Jersey and London. This strategy has proved successful in achieving a low energy building that functions with the same thermal energy demand in each of the ten locations across the UK. Table 5.21 and Figure 5.42 show the cooling, heating and total thermal energy demand and Figure 5.43 shows the total thermal energy demand plotted against degree days for each location. The main drawback to this strategy is that the design is not very practical; large thicknesses of insulation will result in less internal space and/or a larger building footprint, which will increase the costs associated with building materials and land, and mechanical cooling is required in all locations – even the coolest locations on test. The next model, OM6, aims to achieve a more practical and achievable solution to deliver a building that functions with the same thermal energy demand regardless of UK location.

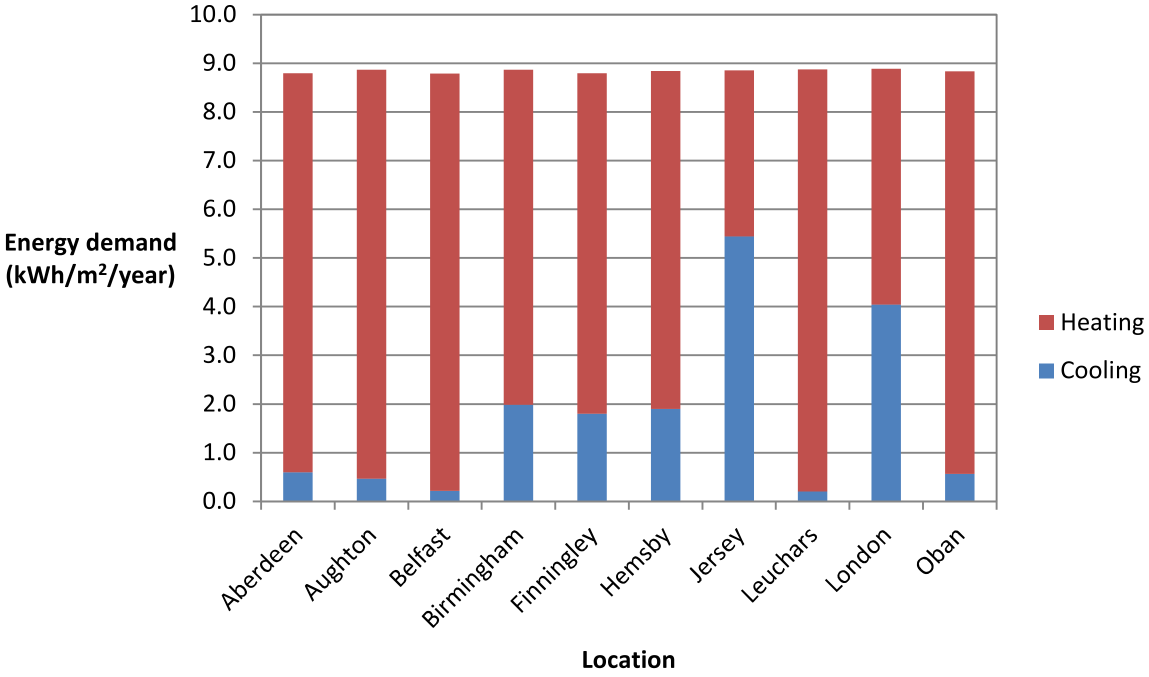


Figure 5.17: Breakdown of heating, cooling and total thermal energy demand for the building with the OM5 scenario

5.3.6 Optimum modifications 6 (OM6)

The previous building model simulation demonstrated that uniform energy consumption in an office building is achievable in 10 locations across the UK. However, the building requires a substantial cooling energy demand in two locations (Jersey and London) and a cooling load in even the coldest locations that have been tested (Aberdeen, Oban and Leuchars). Also, the insulation thickness in the walls, roof and floor is too large to be practical. This model has, therefore, incorporated a different type of thermal insulation and has introduced a natural ventilation strategy for cooling.

The thermal insulation previously used was expanded polystyrene and ranged in thickness from 140mm up to 300mm. The new strategy is to use vacuum insulation panels, which have a typical thermal conductance of 0.004W/mK (10 times less than EPS), thus a thinner insulation element can be used without sacrificing the observed thermal energy savings. The vacuum insulation can provide the same thermal transmittance value for external walls, roof and floor but with reduced thicknesses of 20mm, 30mm and 14mm respectively.

The implications of the previous model meant that the building had considerable cooling energy requirements for most locations. As such, the heating setpoint temperature had to be reduced in all locations (except Jersey) to accommodate an, albeit still high, lower cooling setpoint. This model assumes that the building is naturally ventilated and that occupants will open windows in the summer when the internal air temperature becomes too high. Although the resulting maximum indoor air temperatures are still high, research has shown that these temperatures may be acceptable in buildings where the occupants have control over their own environment [55, 110]. The ventilation rate has been adjusted from 10l/s/person in all locations in order to meet comfort criteria, where possible, without sacrificing the low, uniform thermal energy demand objective.

The result of this set of simulations is a building that operates with a thermal energy demand of between 7.4 and 7.7kWh/m^2/year, as shown in Table 5.23. This thermal energy demand is approximately a quarter of the maximum allowable thermal energy demand for a building constructed to Passive House standards [26]. The range of annual thermal energy demand is 0.3kWh/m^2/year, which corresponds to a difference in annual thermal energy demand of less than 4%. Table 5.22 and Figure 5.44 show the cooling, heating and total thermal energy demand and Figure 5.45 shows the total thermal energy demand plotted against degree days for each location.

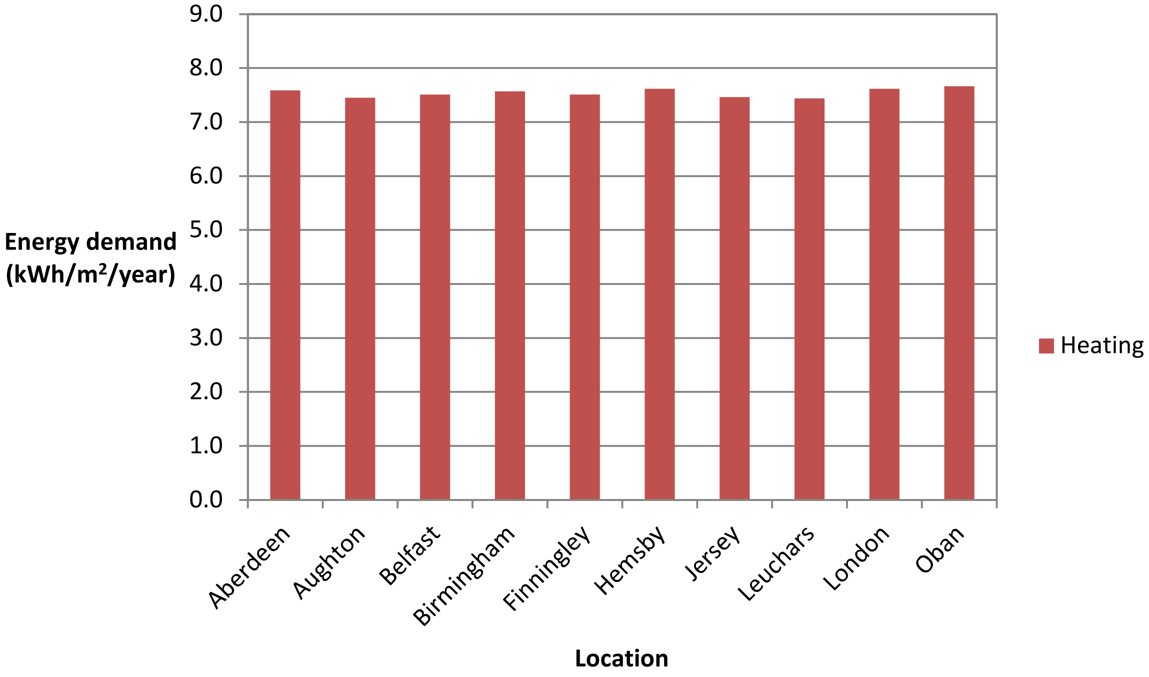


Figure 5.18: Breakdown of heating, cooling and total thermal energy demand for the building with the OM6 scenario

5.3.7 Optimum modifications conclusion

The aim of this research was to create a model of a building that could operate at the same thermal energy demand, regardless of location in the UK, by altering the air tightness and thermal resistance of the building envelope. A model of an office building that functions at the same thermal energy demand (range<4%) in 10 locations across the UK, using the same building envelope has been successfully developed. The internal controls for ventilation have been modified in each location but the ventilation rate is never below the CIBSE recommended level of 8l/s/person. In four of the locations (Birmingham, Finningley, Hemsby and London) the internal air temperature reaches a maximum that is greater than 28℃. While this is deemed an uncomfortable temperature in offices by CIBSE [51], it is predicted that, as occupants will have control over their internal environment (as the building is naturally ventilated), they will be proactive and open windows to allow an adequate airflow through the building to reduce internal air temperatures. There are methods of simulating an additional airflow rate for when temperatures increase above a comfortable limit but that is beyond the scope of this project.

The final model is a two storey building, oriented along a long east-west axis with 1600m^2 of internal floor area. The building measures 50m long by 16m deep and with room heights of 3.5m. The construction of the building envelope elements are shown in Table 5.24.

Element	Construction (from outside to inside)	Values
Floor	200mm concrete slab, 14mm VIP insulation, 50mm screed	U=0.25W/m^{2}K
Roof	20mm ballast, 2mm steel deck, ceiling air space, 30mm VIP insulation, 12.5mm plasterboard, 12.5mm plaster	U=0.13W/m^{2}K
Wall	1.5mm external render, 20mm VIP insulation, 240mm AAC block	U=0.16W/m^{2}K
Window	Triple glazed, timber frame unit: 4mm glass pane with low-e coating, 16mm argon filled gap, 4mm glass pane, 16mm argon filled gap, 4mm glass pane with low-e coating	U=0.7W/m^{2}K SHGC=0.2

Table 5.4: Thermal transmittance parameters for a building with OM6 scenario

The building has an air infiltration rate of 0.04ACH, WWR of 0.4 on south facade and 0.1 on all other facades, horizontal shading that protrudes 1m from the vertical surface over windows on south, east and west facades, a heating setpoint of 18℃ and varying ventilation rates that are never below the recommended level set by CIBSE. The occupancy level of the building is 1 person per 10m^2 of floor area. The building is occupied between 8:00 and 18:00 during weekdays and is unoccupied on weekends.

Using these parameters in the model, an annual thermal energy demand of between 7.4 and 7.7kWh/m^2/year is achieved for all of the 10 locations. This corresponds to a quarter of the maximum allowable thermal energy demand of a building constructed to PassivHaus standard [26]. The building has achieved an average reduction in annual thermal energy demand of 84% compared to the base case model.

This final model can be judged as both a success and a failure in achieving the aims of the research. A model of a building that operates at the same annual thermal energy demand in each of the ten UK locations on test has been successfully developed. However, in order to meet this objective, the alterations to the building model have gone beyond the original scope of research. Increasing building envelope thermal resistance and reducing air infiltration is able to take the building to uniform thermal energy demand across each location but this has resulted in a requirement for an unfeasibly large volume of wall and roof insulation and substantial mechanical cooling in all locations.

In order to reduce the problems associated with exceptionally thick layers of insulation, vacuum insulation panels have been specified. Vacuum insulation has a thermal conductivity of approximately 1/10th of that of expanded polystyrene insulation and, as such, is able to achieve the same level of thermal transmittance at 1/10th of the thickness of expanded polystyrene.

In order to remove the requirement for mechanical cooling, the building is assumed to be naturally ventilated and this is the only method of cooling. As such, there is no longer a cooling setpoint temperature and, if the ventilation rate is left unchanged in the summer, the internal air temperature can reach as high as 29.7°C. Although this is higher than the maximum comfortable internal air temperature of 28°C (recommended by CIBSE), research suggests that this temperature may be acceptable[37, 55, 58]. Nevertheless, it is assumed that in a real building that is constructed to the standard in Table 5.24, occupants will adjust the natural ventilation rate according to the weather conditions and, as such, internal air temperatures in practice should not reach the levels observed in the simulations. In addition, studies of thermal comfort by Nicol and Humphreys [55], de Dear and Brager [56] and Humphreys [57] [58] have demonstrated that high indoor temperatures can deemed comfortable in naturally ventilated buildings. The building that has been modelled in this study could only achieve uniform annual thermal energy demand when it was naturally ventilated and the high internal air temperatures observed may be tolerable in reality.

While introducing natural ventilation has countered the need for mechanical cooling in all locations, the natural ventilation rate varies between locations and, as such, the objective of developing a single building design has not been entirely achieved. This, however, is the only variation in the building design and the building envelope and annual thermal energy consumption remains consistent in each location.

The results of the simulations, although demonstrating a remarkable achievement in developing a building that can perform with the same thermal energy demand at any one of ten locations in the UK, do have their limitations and these should be taken into account when drawing conclusions and furthering this research. The building that has been simulated is just one building type and, due to the differences in occupancy profiles and size of buildings, the results may not generalise to other building types. Further research may be required to understand the effects of varying occupancy profiles and building size on the thermal energy demand of different buildings and whether the same specific thermal energy demand can still be achieved. In addition, this building has been modelled in a simplistic way, using just on zone per floor and omitting the modelling of HVAC systems. While a rationale was given for the omission of HVAC systems, the inclusion of them in a model may give a better understanding of how this building would function in reality. The simplistic zoning meant that models could be created and the results of simulations could be analysed more easily. Be that as it may, the inclusion of HVAC systems and a more complex zoning of the building may give more accurate results. This statement then leads into the fundamental limitation of these results; there does not exist an actual building with which to test the results against. It is somewhat of a large request to construct and monitor a building purely for the purposes of validating a computational model. However, this research could be furthered by using the same methodology for creating the model and applying it to a building that already has been monitored in order to provide validation for the model.

The results collected from the simulations show agreement with the research studied in previous sections of this work. The effect of infiltration on thermal energy demand has been highlighted in the work of Jokisalo *et al* [29], Emmerich *et al* [30], Cummins *et al* [31], Nabinger and Persily [32] and Liddament and Orme [33]. It is evident that air infiltration is one of the largest contributors to thermal energy demand and this was observed in the findings from this study. It was concluded in the parametric study that reducing infiltration has the most effect on reducing thermal energy demand and this claim is supported by the aforementioned authors.

Although limitations have been identified, this research does demonstrate practicalities for advancing low energy building design. All of the technologies that have been used in this building are currently available and the building has been modelled as it would operate in reality with representative occupancy profiles. The research demonstrates that low energy buildings can theoretically operate at thermal energy performances considerably beyond the standard set by PassivHaus and that thermal energy performance can theoretically become independent of the variations in climate in the UK.

6 Conclusions

This programme of research used thermal simulation software to answer the following questions:

- To what extent does reducing the building's thermal transmittance value reduce thermal energy demand?
- To what extent does reducing the building's air permeability reduce thermal energy demand?
- To what extent does reducing the building's thermal transmittance and air permeability reduce the range in annual thermal energy demand for the building in each location?
- To what extent do temperature and ventilation controls reduce the building's thermal energy demand and range of annual thermal energy demand?

Climate change and the Energy Performance of Buildings Directive (EPBD) are drivers for change in the construction industry. Buildings in the UK account for approximately 40% of the country's total energy consumption and, as such, contribute a large amount of CO2 emissions into the atmosphere. Research has shown that greenhouse gas emissions from the burning of fossil fuels are the major cause of climate change and unprecedented temperature increases. In order to mitigate the rise in temperature and its subsequent effects, building energy usage is a prime target for energy reduction. The EPBD mandates that all new commercial buildings will be required to perform at net- or nearly zero energy consumption as of 2020. As of now, there does not exist a substantial net zero energy commercial building stock in the UK, thus a proposal for a low energy building design that performs with the same thermal energy demand, regardless of location in the UK, has been put forward in this thesis. The rationale behind a single low energy building design that performs with the same thermal energy demand is that the building can be constructed in any location in the UK, with the benefits of highly predictable energy demand and simplified sizing of heating plant and renewable energy systems, which will result in the building achieving net zero energy performance. It is envisaged that this template could be used for commercial building construction in the UK in order to meet the mandate of the EPBD.

The aim of net zero energy buildings is to provide as much energy through on site renewable energy systems as the building consumes over an annual period. In order to achieve this aim effectively, many authors agree that the first step is to reduce energy consumption to a very low level and only then to specify low energy HVAC systems and a renewable energy system to provide the required energy.

In the literature review, it became apparent that air infiltration and thermal transmittance of construction elements were the parameters to target to achieve buildings with very low energy consumption. Any air that unintentionally enters or escapes through the building fabric will result in a loss of energy for three reasons:

1) The air has been heated or cooled and has subsequently left the building fabric, meaning that the energy has been wasted.
2) The escaped air will be replaced by further incoming air, which will require heating or cooling to provide comfortable temperatures.
3) The escaping air, if the flow rate is high enough, can cause uncomfortable conditions in the form of draughts, resulting in the occupants increasing the temperature provided by heating system.

It is, thus, important to retain as much of the incoming air as possible, while still providing an adequate amount of ventilation to remove odours, harmful gases and pollutants. It can be seen that escaping air results in wasted energy, so minimising the air infiltration rate will result in energy savings. Thermal transmittance of construction elements should be as low as possible without compromising the integrity of the structural components of the building fabric. It was found that glazing typically has the highest thermal transmittance values of all building fabric elements but this can be of benefit for solar heat gains in the heating season. Be that as it may, limiting thermal transmittance of glazing, or any other building fabric element, will reduce the rate of heat loss and will result in low thermal energy consumption.

The literature review then examined the techniques and materials used for achieving low energy consumption in buildings. This section looked in detail at: different types of thermal insulation; the effect of thermal mass on indoor air temperatures; window thermal transmittance, orientation and area; shading elements; sealing the building envelope to air infiltration,; building orientation; natural ventilation and intelligent zoning within the building. These low energy design techniques are all passive in that they reduce energy consumption by utilising natural heating and cooling sources, thereby requiring no additional energy input. These passive techniques were chosen as they would have they would be able to reduce the thermal energy demand without the requirement for additional energy, such as in the case of heat pumps.

The next chapter of the thesis examined nine low energy buildings around the world to identify the passive low energy design techniques that have been utilised to achieve low- and net zero energy buildings. The aim was to identify the common themes in order to aid the design of the low energy building proposal in this project. The analysis concluded that:

- Mean thermal transmittance of floors is U=0.51W/m^{2}K with a mode of U=0.6W/m^{2}K.
- Mean thermal transmittance of external walls is U=0.34W/m^{2}K with a mode of U=0.2W/m^{2}K.
- Mean thermal transmittance of roofs is U=0.18W/m^{2}K with a mode of U=0.2W/m^{2}K.
- Mean thermal transmittance of windows is U=1.95W/m^{2}K with a mode of U=1.0-2.0W/m^{2}K.
- 5 of the 9 buildings have some facade element that has high thermal mass.
- Only one building has had an air infiltration test and this value was determined as 0.1ACH.
- 7 of the 9 buildings utilise natural, rather than mechanical, ventilation.

- The buildings are all oriented, or partly oriented, along an east west axis to take advantage of the solar gains from the south.
- All buildings incorporate shading elements over the east, west or south facades although the effectiveness of shading varies between buildings.
- 8 of the 9 buildings have clerestory windows.
- There is little data of WWR but, from what data there is available, there does not seem to be a trend in WWR; WWR ranges from 0.09 to 0.57.

A single low energy office building for the UK climate was designed, modelled and simulated. The aim was to create a building that will operate at the same thermal energy performance using the same building envelope and construction elements and, ultimately, provide comfortable conditions for occupants in 10 locations across the UK. The building was designed using the conclusions drawn from the study of nine low, nearly zero or net zero energy buildings.

The base case model was designed to England and Wales Building Regulations Part L2A for new buildings other than dwellings. The building is a 1600m^2, single storey structure. The footprint is elongated along an east-west orientation, with 50m long north and south facing sides and 16m long east and west facing sides. The height of each storey is 3.5m, resulting in a total height of 7m. Each facade has the same construction and window to wall ratio of 0.4. The infiltration rate has also been specified to the minimum standard for offices (the maximum air leakage rate at 50Pa pressure difference is 10m^3/hr/m^2) of an air change rate of 0.2ACH. The setpoints for heating and cooling were 19°C and 25°C, respectively. The building has also been specified to perform with lighting, equipment and occupancy loads in order to make the model more representative of a real building. The internal lighting has been modelled at 10W/m^2 as this is in line with a typical low energy office building. There is also a daylight strategy that turns off the interior lights when the daylight levels reach 500lux. The equipment load has been modelled as 6.7W/m^2 and the occupancy density has been modelled as 0.0954people/m^2. The results of this simulation gave an average energy consumption of 51.54kWh/m^2/year.

This building model was then validated using static heat loss calculations in Microsoft Excel. The static calculation produced a heat loss value that is consistently larger than that resulting from EnergyPlus. This was due to the nature of the two calculation methods and the inherent greater accuracy of a simulation that undertakes dynamic heat balance calculations at 15 minute intervals. However this validation study found that the conductive and infiltration based heat losses from each calculation method were within 7% and 15% depending on the location and gave confidence that EnergyPlus was providing reliable results.

The model was also tested to understand the magnitude and areas of the building envelope and construction that resulted in greatest heat gains and losses. It was found that:

- Infiltration was responsible for the largest net heat loss;

- Glazing was responsible for the largest heat gain and heat loss although provided a relatively low net heat loss;
- The roof provided an overall heat loss that was greater than the walls, despite a lower thermal transmittance value and a lower overall area;
- The floor construction was responsible for a net heat loss but this was comparatively very small.

Using the results of the study into heat loss and gain, a series of optimum modification simulations were carried out to determine the design of a building that would function at uniform and low energy consumption. The final model is a two storey building, oriented along a long east-west axis with 1600m^2 of internal floor area. The building measures 50m long by 16m deep and with room heights of 3.5m. The construction of the building envelope elements are as follows:

Element	Construction (from outside to inside)	Values
Floor	200mm concrete slab, 14mm VIP insulation, 50mm screed	U=0.25W/m^{2}K
Roof	20mm ballast, 2mm steel deck, ceiling air space, 30mm VIP insulation, 12.5mm plasterboard, 12.5mm plaster	U=0.13W/m^{2}K
Wall	1.5mm external render, 20mm VIP insulation, 240mm AAC block	U=0.16W/m^{2}K
Window	Triple glazed, timber frame unit: 4mm glass pane with low-e coating, 16mm argon filled gap, 4mm glass pane, 16mm argon filled gap, 4mm glass pane with low-e coating	U=0.7W/m^{2}K SHGC=0.2

Table 6.1: Thermal transmittance parameters for a building with OM6 scenario

The building has an air infiltration rate of 0.04ACH, WWR of 0.4 on the south facade and 0.1 on all other facades, horizontal shading that protrudes 1m from the vertical surface over windows on south, east and west facades, a heating setpoint of 18℃ and varying ventilation rates that are never below the recommended level set by CIBSE. The occupancy level of the building is 1 person per 10m^2 of floor area and the building is occupied between 8:00 and 18:00 during weekdays while there is no occupancy on weekends.

Using these parameters in the model, a thermal energy demand of just 7.4 to 7.7kWh/m^2/year is achieved across the 10 locations, which corresponds to an average reduction in thermal energy demand of 84% compared to the base case model.

This building is capable of being constructed and operated using current building technology and provides a platform for the net zero energy building concept. The roof is large enough to incorporate up to 800m^2 of photovoltaic panels and the uniform energy consumption is beneficial to designers of HVAC and renewable energy systems for correctly sizing equipment capacities. This template for a low energy office building that can function at the same thermal energy requirement can be effectively used by designers in the UK for achieving the EPBD mandate of all new commercial buildings functioning at net- or nearly zero energy consumption from 2020.

6.1 Limitations and areas for future research

The results of this body of research show positivity towards achieving a single low energy commercial building in the UK. However, the research has limitations and there are areas that can provide the basis for further investigation. This research focussed on just the building envelope and it is envisaged that this is not the only change that can be adopted in the construction and operation of UK buildings. The following section will highlight the limitations of the research and will provide topics that could be investigated further through continued research in this area.

6.1.1 Case study

The buildings that were investigated in the Case Study chapter are all located outside of the UK and, as such, the typical buildings processes and the climatic conditions of each case study were examined to understand the relation to typical UK building processes and climate.

The typical building energy processes across most buildings were heating, cooling, ventilation lighting, hot water and miscellaneous electrical. The specific energy intensity varied between buildings but there was usually a significant amount of energy required for heating, lighting and electrical appliances. The end use energy intensity of the case study buildings, unsurprisingly, was significantly less than that of the average office building in the UK or USA but it was interesting to observe that there were similar end use energy intensities between the average USA office building and the average naturally ventilated UK office building.

The end use energy intensity of the air conditioned UK office building and that of the average office building in the USA were also similar except for the greater amount of energy used for ventilation in UK air conditioned offices. Whilst the end use energy intensities of the case study buildings and the average UK office buildings showed some variation, the building processes were fairly similar and the vast amount of data available for the selected buildings justified their use as case study buildings for this research.

The climate in each location varies and this was examined in order to understand the reason for the variation in building processes. The heating and cooling degree days (base 18℃) for each location and the proposed locations for testing the low energy building in the UK were compared against each other to determine any similarities

The major difference between the locations in the USA and the UK is the significantly greater requirement for cooling in the USA than in the UK. However, after investigating the heating degree days, there are similarities between all UK locations and many of the case study locations (except for Lisbon, Silverthorne and Golden). Upon examining the requirement for heating and cooling, it can be seen that, despite the requirement for cooling, many of the case study locations display a good similarity to the UK locations. As such the low energy design strategies that were used in the many of the case study buildings could potentially be reliably applied to the design of the low energy building for the UK.

It would have been ideal to investigate a number of low energy building s in the UK as these buildings would have been designed to British Standards built with typical British construction practices and would have been designed to function under the UK climate. These reasons would have made these buildings more applicable to formulating a low energy design strategy but the lack of available data meant that the buildings that were analysed for the case study were those that had a suitable amount of available building information.

6.1.2 Building type

The building that has been simulated is just one building type and, due to the differences in occupancy profiles and size of buildings, the results may not generalise to other building types. Commercial buildings include a number of different building types, such as hotels, supermarkets and high rise buildings.

Each commercial building has a different occupancy profile and heating, cooling and ventilation strategy, even if the buildings are used for the same purpose and have the same building services. Occupants may spend 8 hours in a commercial office but may spend an entire 24 hours in a hotel. This means that the commercial office would only require its building services to function at the level to provide occupant comfort for a significantly less amount of time than a hotel. Hotels would almost always have a higher demand for hot water and lighting, which would affect the thermal energy demand. Supermarkets, on the other hand, would use a significant proportion of thermal energy on refrigeration to provide fresh food to consumers.

Further research should be undertaken to understand the effects of varying occupancy profiles and building size and building type on the thermal energy demand of different buildings and whether the same specific thermal energy demand can still be achieved. It is envisaged that it would be very difficult to replicate the same thermal energy demand for this body of research in another building type although this would need to be confirmed through thermal energy modelling, simulations and acquisition of real data from building in use. The results of this research should not be blindly applied to other types or size of building but rather be used as a starting point for developing a low energy design strategy that could provide uniformity of thermal energy demand between locations.

In addition, this building has been modelled in a simplistic way, using just on zone per floor and omitting the modelling of HVAC systems. While a rationale was given for the omission of HVAC systems, the inclusion of them in a model may give a better understanding of how this building would function in reality.

The simplistic zoning meant that models could be created and the results of simulations could be analysed more easily but the inclusion of HVAC systems and a more complex zoning of the building may give more accurate results.

6.1.3 Weather data

The building was simulated with weather conditions in ten locations in the UK and, while the results show that the building can function at the same annual thermal energy demand in each location, the reader must remember that only ten locations have been used for the simulations. This decision was governed by the amount of UK weather data files available in EnergyPlus.

A number of articles have been cited in Chapter 5, which demonstrate the effectiveness and appropriateness of using EPW (EnergyPlus Weather) files for simulating weather conditions in EnergyPlus models. These articles help to set a precedent for the use of EPW files for thermal modelling. However, before the findings of this research can be applied to a building design strategy, a more rigorous testing of the building with a greater number of weather data files should be undertaken. Many weather files can be made available for use in EnergyPlus, provided they are converted to the EPW file format.

It is also possible to use data collected at weather stations and convert these into EPW format. In doing so, a vast number of current or past weather data sets could be used when performing simulations. A body of research using a greater number of weather data sets could confirm or reject the findings of this research and could help to apply the findings to the building design and construction industries in the UK. It would be of interest to further this research by using weather data collected from various locations across the UK and simulating the building with the new weather data.

The other major limitation of using the weather data that has been used in this research is that the data is historical. The weather data has been collected from weather stations but this is always data that is either current or historical. EnergyPlus does not have an in built weather file that takes into account future weather patterns and climate change and the reason for not using a future weather file that incorporated climate change predictions was purely due to cost.

This limits the applicability of the research as temperatures are predicted to rise in the next century and extreme weather events are predicted to occur more often. It would have increased the validity of the findings in this research if the building had been simulated for future weather patterns. This may have had a major impact on the specific use of thermal energy in the building; cooling may have become more predominant and the need for high performance insulation may have been reduced. During the simulations, it was observed that cooling became predominant in some of the models and this is an area that would be worth investigating further.

6.1.4 Software and calculation methods

The low energy building model was designed in OpenStudio [97] and simulated using EnergyPlus simulation software.

OpenStudio is a collection of software that allows the user to design buildings and their associated building services and to analyse the resulting energy performance. OpenStudio utilises a Google SketchUp plug in to aid the design of a building. The building can be drawn in Google SketchUp and surfaces (such as walls, windows and floors) can be assigned physical properties. All of the data from Google SketchUp and the Model Editor is then stored in an EnergyPlus input file. OpenStudio is purely an interface between the user and EnergyPlus and provides a free, user friendly platform for designing building models.

OpenStudio utilises the EnergyPlus simulation engine to undertake dynamic heat balance calculations to then calculate the energy performance of the building. The EnergyPlus calculation method is a heat balance model in which room air is modelled as well stirred and uniform air temperature is achieved throughout the thermal zone. EnergyPlus also assumes that room surfaces have uniform surface temperatures, uniform long and short wave irradiation, diffuse radiating and reflecting surfaces and internal heat conduction (reference as above). The heat balance is then calculated from using a weather input file. The difference between outdoor and indoor conditions is calculated taking into account radiant, convective and conductive heat transfer. The calculation can be undertaken at a variety of time steps according the accuracy required by the end user. EnergyPlus then calculates the energy input from the building services components that is required to maintain the user defined internal conditions. Building services can be chosen from a library of typical components, can be designed by the user or can be ignored in favour of an Ideal Loads System, which calculates the required energy demand to satisfy the required internal conditions without the necessity of specifying manufacturers' specifications.

The use of a software package that undertakes dynamic heat balance calculations is significantly more appropriate for this body of research than simply performing static calculations. Dynamic calculations in EnergyPlus use: dry and wet bulb indoor and outdoor temperatures, indoor and outdoor humidity, wind speed and direction and solar radiation to calculate overall indoor and outdoor temperatures and does this at 15 minute intervals during the simulation. The level of details that a dynamic calculation performs at provides a much more realistic result for the energy performance of the building model. Applying this level of detail to a static calculation would be extremely time consuming and would typically include errors, especially if the calculations were undertaken manually.

However, a static calculation had to be used to verify the energy performance results of the building model. Using a manual static calculation may be more prone to user errors but this does provide a check of the results from the static calculation. It would be very extremely time consuming to take into account all of the data that a dynamic calculation uses but, by testing using a relatively simple calculation, an aspect of the dynamic calculation can be replicated by hand. While not providing the most rigorous check, using a static calculation can help to identify user errors in the input of information into the dynamic calculation software.

6.1.5 Application of the findings

The fundamental limitation of these results and, in turn, a major area for future research is that there does not exist an actual building with which to test the results against. The results of the simulations, although demonstrating a remarkable achievement in developing a building that can perform with the same thermal energy demand at any one of ten locations in the UK, do have their limitations as these results cannot yet be truly validated. It is somewhat of a large request to construct and monitor a building purely for the purposes of validating a computational model, yet, if the model can be successfully validated, the results will have major implications on the methods of construction and operation of buildings in the UK. This research could be furthered by using the same methodology for creating the model and applying it to a building that already has been monitored in order to provide validation for the model.

7 Simulation Data

Table 7.1: Simulation data, settings and justifications for the Base Case model

Field	**EnergyPlus Input**	**Units**	**Justification**
Building and Simulation Data			
North Axis	0		EnergyPlus default
Terrain	City		To account for the building being in an urban environment
Building length	50	m	
Building depth	16	m	
Building height	7	m	
Number of floors	2		
Loads Convergence Tolerance Value	0.04		EnergyPlus default
Temperature Convergence Tolerance Value	0.4		EnergyPlus default
Solar Distribution	FullExterior		To simulate the building in an area that was not shaded
Maximum Number of Warmup Days	25		EnergyPlus default
Minimum Number of Warmup Days	6		EnergyPlus default
Number of Timesteps per Hour	4		EnergyPlus default and this gave the greatest accuracy
Begin Month	1		To simulate the building over the course of a year
Begin Day of Month	1		
End Month	12		
End Day of Month	31		
Schedules			
Office Equipment Schedule			
Weekdays			
Until: 08:00	0.4		A multiplier for the equipment load to account for varied times of occupancy in the building
Until: 12:00	0.9		
Until: 13:00	0.8		

Field	EnergyPlus Input	Units	Justification
Until: 17:00	0.9		
Until: 18:00	0.5		
Until: 24:00	0.4		
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	15.6	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	19	℃	
Until: 24:00	15.6	℃	
Sunday, Holidays and All Other Days			
All day	15.6	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	30	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	25	℃	
Until: 24:00	30	℃	
Sunday, Holidays and All Other Days	30	℃	
Infiltration Schedule			
Every day			
All day	1		A multiplier for the infiltration value
Office Occupancy Schedule			
Weekdays and Saturday			
Until: 06:00	0		A multiplier for the occupancy density
Until: 07:00	0.1		
Until: 08:00	0.2		
Until: 12:00	0.95		
Until: 13:00	0.5		
Until: 17:00	0.95		
Until: 18:00	0.3		

Field	**EnergyPlus Input**	**Units**	**Justification**
Until: 20:00	0.1		
Until: 24:00	0.05		
Sunday, Holidays and All Other Days			
Until: 06:00	0		
Until: 18:00	0		
Until: 24:00	0		
Office Lights Schedule			
Weekdays and Saturday			A multiplier for the lighting use
Until: 05:00	0.05		
Until: 07:00	0.1		
Until: 08:00	0.3		
Until: 17:00	0.9		
Until: 18:00	0.5		
Until: 20:00	0.3		
Until: 22:00	0.2		
Until: 23:00	0.1		
Until: 24:00	0.05		
Sunday, Holidays and All Other Days			
Until: 24:00	0.05		
Materials			
240mm AAC Block			
Thickness	0.24	m	
Conductivity	0.2	W/m.K	
Density	700	kg/m^3	
Specific Heat	1000	J/kg.K	
140mm EPS Insulation			
Thickness	0.14	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
12.5mm Plaster			
Thickness	0.0125	m	
Conductivity	0.18	W/m.K	
Density	600	kg/m^3	
Specific Heat	1000	J/kg.K	
1.5mm External Render			
Thickness	0.0015	m	

Field	EnergyPlus Input	Units	Justification
Conductivity	1	W/m.K	
Density	1800	kg/m^3	
Specific Heat	1000	J/kg.K	
60mm EPS Insulation			
Thickness	0.06	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
200mm Concrete Slab			
Thickness	0.2	m	
Conductivity	1.33	W/m.K	
Density	2000	kg/m^3	
Specific Heat	1000	J/kg.K	
50mm Screed			
Thickness	0.05	m	
Conductivity	0.46	W/m.K	
Density	1200	kg/m^3	
Specific Heat	1000	J/kg.K	
20mm Roof Ballast			
Thickness	0.02	m	
Conductivity	1.1	W/m.K	
Density	1800	kg/m^3	
Specific Heat	1000	J/kg.K	
2mm Steel Deck			
Thickness	0.002	m	
Conductivity	50	W/m.K	
Density	7800	kg/m^3	
Specific Heat	460	J/kg.K	
12.5mm Plasterboard			
Thickness	0.0125	m	
Conductivity	0.21	W/m.K	
Density	700	kg/m^3	
Specific Heat	1000	J/kg.K	
Ceiling Air Space			
Thermal Resistance	0.18	m^2.K/W	
U-Factor	2.21	W/m^2.K	
Solar Heat Gain Coefficient	0.702		
Construction			
Floor 0.25W/m^2K			

Field	**EnergyPlus Input**	**Units**	**Justification**
Outside Layer	200mm Concrete Slab		
	140mm EPS Insulation		
Inside Layer	50mm Screed		
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBreak:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	60mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	140mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Shading	External shading		A block element with no thermal properties that inhibits daylight ingress. Simulated as 0m, 0.5m, 1m and 1.5m width from the building façade.
People			
Number of People Schedule Name	Office Occupancy Schedule		
Number of People Calculation Method	People/Area		
People per Zone Floor Area	0.09542		
Lights			
Schedule Name	Office Lights Schedule		
Design Level Calculation Method	Watts/Area		

Field	EnergyPlus Input	Units	Justification
Watts per Zone Floor Area	10	W/m^2	
Electric Equipment			
Schedule Name	Office Equipment Schedule		
Design Level Calculation Method	Watts/Area		
Watts per Zone Floor Area	6.67	W/m^2	
Daylighting			
Illuminance Setpoint	500	lux	
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.14	ACH	
Ventilation			
Schedule Name	Office Occupancy Schedule		
Design Flow Rate Calculation Method	Flow/Area		
Flow Rate per Floor Area	0.001	m^3/s/m	
Ventilation Type	Natural		
HVAC Template	District Heating and District Cooling		A HVAC template that calculates thermal energy demand without the need to specify manufacturer's parameters and performance data.

Table 7.2: Changes to Base Case simulation data, settings and justifications for the Optimum Modifications 1 model

Field	EnergyPlus Input	Units	Justification
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	14	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	19	℃	
Until: 24:00	14	℃	
Sunday, Holidays and All Other Days			
All day	14	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	40	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	25	℃	
Until: 24:00	40	℃	
Sunday, Holidays and All Other Days	40	℃	
300mm EPS Insulation			
Thickness	0.3	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
200mm EPS Insulation			
Thickness	0.2	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
Double Glazing:AluFrameThermalBreak:5.7/6.4/5.7			
U-Factor	0.7	W/m^2.K	
Solar Heat Gain Coefficient	0.7		
Construction			

Field	**EnergyPlus Input**	**Units**	**Justification**
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBreak:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	200mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	300mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.04	ACH	

Table 7.3: Changes to Base Case simulation data, settings and justifications for the Optimum Modifications 2 model

Field	EnergyPlus Input	Units	Justification
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	14	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	19	℃	
Until: 24:00	14	℃	
Sunday, Holidays and All Other Days			
All day	14	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	40	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	25	℃	
Until: 24:00	40	℃	
Sunday, Holidays and All Other Days	40	℃	
300mm EPS Insulation			
Thickness	0.3	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
200mm EPS Insulation			
Thickness	0.2	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
U-Factor	0.7	W/m^2.K	
Solar Heat Gain Coefficient	0.5		
Construction			
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBrea		

Field	**EnergyPlus Input**	**Units**	**Justification**
	k:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	200mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	300mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.04	ACH	

Table 7.4: Changes to Base Case simulation data, settings and justifications for the Optimum Modifications 3 model

Field	EnergyPlus Input	Units	Justification
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	14	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	19	℃	
Until: 24:00	14	℃	
Sunday, Holidays and All Other Days			
All day	14	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	40	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	25	℃	
Until: 24:00	40	℃	
Sunday, Holidays and All Other Days	40	℃	
300mm EPS Insulation			
Thickness	0.3	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
200mm EPS Insulation			
Thickness	0.2	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
Double Glazing:AluFrameThermalBreak:5.7/6.4/5.7			
U-Factor	0.7	W/m^2.K	
Solar Heat Gain Coefficient	0.2		
Construction			

Field	**EnergyPlus Input**	**Units**	**Justification**
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBreak:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	200mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	300mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.04	ACH	

Table 7.5: Changes to Base Case simulation data, settings and justifications for the Optimum Modifications 4 model

Field	**EnergyPlus Input**	**Units**	**Justification**
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	14	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	19	℃	
Until: 24:00	14	℃	
Sunday, Holidays and All Other Days			
All day	14	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	40	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	30	℃	
Until: 24:00	40	℃	
Sunday, Holidays and All Other Days	40	℃	
300mm EPS Insulation			
Thickness	0.3	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
200mm EPS Insulation			
Thickness	0.2	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
Double Glazing:AluFrameThermalBreak:5.7/6.4/5.7			
U-Factor	0.7	W/m^2.K	
Solar Heat Gain Coefficient	0.2		
Construction			

Field	**EnergyPlus Input**	**Units**	**Justification**
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBreak:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	200mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	300mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.04	ACH	

Table 7.6: Changes to Base Case simulation data, settings and justifications for the Optimum Modifications 5 model

Field	EnergyPlus Input	Units	Justification
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	14	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	Detailed in Table 5.2	℃	
Until: 24:00	14	℃	
Sunday, Holidays and All Other Days			
All day	14	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	40	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	Detailed in Table 5.2	℃	
Until: 24:00	40	℃	
Sunday, Holidays and All Other Days	40	℃	
300mm EPS Insulation			
Thickness	0.3	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
200mm EPS Insulation			
Thickness	0.2	m	
Conductivity	0.04	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
Double Glazing:AluFrameThermalBreak:5.7/6.4/5.7			
U-Factor	0.7	W/m^2.K	

Field	**EnergyPlus Input**	**Units**	**Justification**
Solar Heat Gain Coefficient	0.2		
Construction			
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBreak:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	200mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	300mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.04	ACH	

Table 7.7: Changes to Base Case simulation data, settings and justifications for the Optimum Modifications 6 model

Field	EnergyPlus Input	Units	Justification
Heating Setpoint Schedule			
Weekdays and Saturday			
Until: 05:00	14	℃	Heating setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 19:00	Detailed in Table 5.2	℃	
Until: 24:00	14	℃	
Sunday, Holidays and All Other Days			
All day	14	℃	
Cooling Setpoint Schedule			
Weekdays and Saturday			
Until: 06:00	40	℃	Cooling setpoint temperature for comfort and only to be used during the day of weekdays and Saturdays and not on a Sunday
Until: 22:00	Detailed in Table 5.2	℃	
Until: 24:00	40	℃	
Sunday, Holidays and All Other Days	40	℃	
30mm Vacuum Insulation			
Thickness	0.3	m	
Conductivity	0.004	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
20mm Vacuum Insulation			
Thickness	0.2	m	
Conductivity	0.004	W/m.K	
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
14mm Vacuum Insulation			
Thickness	0.014	m	
Conductivity	0.004	W/m.K	

Field	EnergyPlus Input	Units	Justification
Density	15	kg/m^3	
Specific Heat	1450	J/kg.K	
Double Glazing:AluFrameThermalBreak:5.7/6.4/5.7			
U-Factor	0.7	W/m^2.K	
Solar Heat Gain Coefficient	0.2		
Construction			
Window 2.21W/m^2K	DoubleGlazing:AluFrameThermalBreak:5.7/6.4/5.7		
Wall 0.35W/m^2K			
Outside Layer	1.5mm External Render		
	200mm EPS Insulation		
Inside Layer	240mm AAC Block		
Roof 0.25W/m^2K			
Outside Layer	20mm Roof Ballast		
	2mm Steel Deck		
	Ceiling Air Space		
	300mm EPS Insulation		
	12.5mm Plasterboard		
Inside Layer	12.5mm Plaster		
Airflow			
Infiltration			
Schedule Name	Always On		
Design Flow Rate Calculation Method	Air Changes/Hour		
Air Changes per Hour	0.04	ACH	

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