Low-energy SIPs building in Northwest of England

(Energy performance under the current and future weather climate change)

A Thesis Submitted in Accordance with the Requirements of the University of Liverpool for the Degree of Doctor of Philosophy (PhD)

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2022

بسم الله الرحمن الرحيم

Bismillahir Rahmanir Rahim

1 Declaration

I certify that this thesis constitutes my own work/investigation, except where otherwise stated; other sources are acknowledged by explicit references.

I declare that this thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Signed: Bushra Al Derbi

Date: 31th March 2022

Acknowledgement

I dedicate this thesis to my mother

Badriya Bent Abdulla Mohamed

How truly lucky I am to have a mother as giving and supportive as you. Thank you for always believing in me, even when I didn't believe in me.

and

To my Lovely Daughters

Afra and Badrya

My Precious girls, thank you for bearing all the ups and down during my PhD, for being so supportive when I have to be away from you, and for continuous encouragement. Thank you for being such outstanding daughters.

I Like to thank my family, my source of inspiration who taught me to believe in myself, dream, and have the courage to pursue. This work is also dedicated to my best friend Khadija, who stood by me in good and bad times and loved me unconditionally. Also, I would like to thank Adel, who I have started the higher education dream with, and I would like to thank him for all support and encouragement he gave me and for always believing in me.

With immense gratitude to my supervisor Dr Stephen Finnegan, who supported me throughout my PhD. And with special thanks to Dr Andew Shea and my internal examiner Dr Haniyeh Mohammadpourkarbasi who this PhD was not possible without her continuous encouragement, knowledge, and endless support.

Next, I would like to thank Mr. John Harrison and his lovely wife, the owners of SIPs House in Heswall, for allowing me to use their home as a case study and providing me with all the necessary information needed. Also, I would like to thank all my PhD friends with whom I shared wonderful memories and made friends for a lifetime.

Lastly but not the least, I would like to thank the Ministry of Higher Education in Abu Dhabi-UAE for their continues support.

Abstract

Currently, the UK is challenged by two main factors in the built environment, first is the rising demand for new housing, and second, all new buildings are recommended to adhere the energy-efficient standards (like, the nearly Zero Energy Building [nZEB] and Net Zero [NZ]) to reduce the CO_2 emissions in buildings. The primary aim of this research is to determine whether modern methods of construction (MMC), specifically using magnesium oxide (MgO) structural insulated panels (SIPs) in housing design, can meet the required thermal and energy efficiency. The research evaluates the carbon impact of using MgO SIPs in constructing new houses and is quantified through a detailed energy performance analysis. A real-world case study was chosen as the research methodology to compare real-world data with simulated building energy modelling conducted in the software DesignBuilder. A detached house in Heswall, Merseyside, UK, constructed from MgO SIPs in 2016, was selected as the case study for the research. The study involved collecting and monitoring 1) heating, HVAC, and domestic hot water etc., 2) temperature, and RH% data over 12 months to evaluate the energy performance under current and future weather scenarios based on the predicted acceleration of anthropogenic climate change for three test periods: 2030, 2050 and 2080. Based on real case study on site measurements were conducted, two validation procedures were conducted to validate the recorded thermal performance against the simulated results. First, during the holiday time when the building's appliances are switched off the hourly temperature calibrations were conducted by comparing the recorded indoor temperature with simulated results from DesignBuilder model by data loggers on hourly bases. Second, the energy performance for were simulated and recorded by energy loggers for 12 months and the results were compared with electricity consumption bill. Finally, to evaluate the comfort level of the SIP house, I used thermal models (including the Passivhaus summer comfort design, Schneider thermal comfort chart, and Climate Consultant) to compare the energy consumption with thermal comfort. A parametric study was conducted in DesignBuilder using measured weather files to improve the current building envelope to reduce energy consumption. Five parameters of the building envelope were evaluated. The study highlighted that potential energy reductions could be made in the window glazing type of the SIP house; The results indicated that the most effective areas of energy saving relate to the following main parametric variables: roof insulation enhancement of 60%, making the thickness of the SIP roof 277 mm, can reduce total energy consumption by 8%; exterior wall thermal enhancement can contribute a 6% of energy reduction; and window glazing type changes can contribute to the total energy reduction by 10%. Moreover, 10% reduction in the annual energy consumption could be achieved by modify the window glazing type using argon gas instead of air between the gaps in windowpanes. However, the other parameters slightly affected the overall energy reduction, indicating that the SIP fabric has excellent insulating properties that prevented heat loss and could therefore stabilise the interior temperature throughout the year with minimum energy required. Based on the weather and energy parameters used in the simulations and thermal comfort analysis, the

SIP house used as a case study for the research demonstrated the potential for meeting most energy efficiency standards (such as nZEB, NZ and Passivhaus). Furthermore, the assessment results indicate that despise noticeable temperature increase in the three timelines of 2030,2050 and 2080 the SIPs house's fabric has the ability to withstand the effect of future climate change. In addition, long term monitoring of the energy used was calculated in the research by monitoring the energy used via the data loggers. Based on the annual energy consumption, the SIP house had a lower kWh/year consumption than similar households in the UK, and the energy consumption rate was further reduced by implementing the use of renewable energy on the roof. Finally, based on the results, the using MgO SIPs in the housing sector can support the creation of nZEB/NZ homes by 2050. It is recommended that MgO SIP homes are accompanied by renewable energy as a key factor in meeting nZEB/NZ standards.

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List of Abbreviations

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

BME Building Modeling Energy

BRE Building Research Establishment

BREEAM Building Research Establishment Environmental Assessment Method

CCC Climate Change Committee

CET Central England Temperature

CH_4 Methane

CIBSE Chartered Institution of Building Services Engineers

CO_2 Carbon dioxide

CO_2e Greenhouse gas equivalent

DB Design Builder

DEFRA Department of Environment, Food and Rural Affairs

EC embodied carbon

EPBD Energy Performance of Building Directive

EPC Energy Performance Certificate

EPD Environmental product declaration

EPW Energy plus weather files

FEES Fabric Energy Efficiency Standard

GHG Greenhouse gases

IEA Environmental Impact Assessment

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

LCA Life cycle assessment

LETI London energy transformation initiative

LEB Low Energy Building

LEED Leadership in Energy and Environmental Design

LEED Leadership in Energy and Environmental Design

MET office Metrological office

MgO Magnesium Oxide

MgO SIPs Magnesium Oxide Structural Insulated Panels

MMC Modern method of construction

Mt CO_2e Million tons of greenhouse gas equivalent

N_2O Nitrous oxide

NZC Net Zero Carbon

NZC Net Zero Carbon

nZEB/NZC Nearly Zero Energy Building concept

OC operational carbon

PH Passivhaus

PPHP Passivhaus Planning Package

PV Photovoltaic

SAP Standard Assessment Procedure

SRES Special Report on Emissions

UKCP18 UK Climate Projections 2018

UKGBC UK Green Building Counsel

WMO World Meteorological Organization

ZEB Zero Energy Building

"We really need to kick the carbon habit and stop making our energy from burning things. Climate change is also really important. You can wreck one rainforest then move, drain one area of resources and move onto another, but climate change is global." *Sir David Attenborough, Natural World Broadcaster*

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Chapter One: Introduction

1.1 Overview

In 1918, Le Corbusier famously stated that a "house is a machine for living in," defining a home as an artificial intelligence robot with the capacity to identify efficient means to comfort the living while conserving energy (Tsai et al., 2003). Long ago, before the climate change calamity emerged, the idea of utilising technology to create functional environments called smart homes had been considered, but it was described in a different context; nevertheless, the drive to create such an environment was the same. All the ubiquitous technological advancements in science have led to the conclusion that homes rely on energy to be comfortable, but energy comes at an environmental cost called global warming.

Although addressing climate change can be a daunting and challenging task, the continuous advancement in fossil-fuel-free energy production and integration of building technology and design strategy can save the world from an ambiguous future. The European roadmap of 2050 strategy to combat carbon was revised in 2010 under the Energy Performance of Building Directive (EPBD) and introduced the Nearly Zero Energy Building (nZEB), which defines a very high energy performance building with low energy requirement (D'Agostino et al. 2019.; European Commission 2012). The regulations state that all commercial buildings built after December 2018 and residential buildings built after December 2020 need to meet the nZEB energy requirement; until Brexit, the United Kingdom was subject to these regulations. The UK government initiated further step to address the environmental threats by acknowledging the need to take urgent action to address climate change. They have structured Net Zero Carbon (NZC) which means creating a balance between the carbon emitted into the atmosphere and the carbon removed from it. The aim of this initiative was to drive the transition of the economy to Zero Carbon (ZC) by 2050, and as stated by the UK Green Building Counsel (UKGBC), the best approach to energy reduction in a building is obtaining the right fabric efficiency of the building envelope in the early design stage and in the construction process; this has opened a window of opportunities for building material innovations and technologies in the field of construction (UKGBC, 2021). One of the most recognised advancements in the construction industry is the prefabricated method of construction, which has been gaining popularity over the traditional method of construction because of the vast environmental and cost benefits. As a result, a clear understanding of climate change's impact on the environment and identifying the best practices to combat carbon reduction is the key to achieving the national agenda of nZEB/NZC by 2050.

In Europe, the building industry is responsible for 36% of final energy use and 40% of energy related to operational use, and one quarter of the world emission comes from the construction sector (Karlsson, et al., 2020; Skea 2012). The direct CO_2e from buildings was 87 Mt CO_2e in 2019, accounting for 17% of UK CO_2e (CCC, 2019a). The data presented the amount of combustion fossil fuels used for heating purposes, primarily from gas. These direct emissions were accountable for 87 Mt CO_2e in 2019; of these emissions, 77% came from residential heating and only 23% from public and commercial buildings. There has been a sharp decrease of almost 20% in direct emissions and 10% in indirect emissions from the 1990 level. Moreover, the indirect emissions reduction was supported by the implementations of decarbonising energy via the use of and investment in renewable energy (CCC, 2019) ; in Appendix 1.A depicts the amount of energy consumed by the residential sector compared with public and commercial buildings since 1990. The recognised energy reduction in carbon emissions has been supported by the country's commitment to reduce energy consumption. The carbon emission fall reflects the increased energy efficiency in building design and incorporation of renewable energies, supported by the plan in the European 2050 Roadmap stating that 30% of energy needs to come from renewable sources. Moreover, the report titled NZ by 2050 (Skea, 2012) states that the transition towards a large decarbonising economy requires a fundamental economic transformation. This goal can be achieved by decarbonising the electricity sector. Furthermore, decarbonisation of electricity is not limited to carbon emission reduction; it also has substantial benefits to withstand the volatility of fossil fuel prices. The government policy's framework for carbon reduction is undoubtedly complex and requires comprehensive efforts from every party in the built environment, particularly because of the vast stock of existing inefficient housing, which existed long before the European building standards were established, and the growing demand for constructing new homes.

Buildings are a main source of energy use in Europe and the United Kingdom, and most of the building stock that exists today will still exist in 2050 (Hong et al., 2018). As of 2015, there has been a record of more than 2.5 million houses with inefficient energy standards, and a Committee on Climate change report (IPPC, 2014) stated that the current UK housing stock is not well adapted to current and future weather, with more than 4.5 million homes currently overheated because of poor insulation and requiring more energy consumption to maintain a given level of comfort. Sustainable refurbishment is economically challenging, although it is possible with government funding support; however, UK housing must refurbish thousands of existing homes daily to reach the 2050 carbon reduction target (Mohammadpourkarbasi, 2015). To keep up with the current trend of energy reduction in the existing UK housing stock, two major transformations need to be adopted—the enhancement of thermal properties of the envelope and substitute energy sources. The importance of constructing very high energy efficiency buildings to help the government reach its climate change target is widely accepted. Apart from environmental factors, the subject has been of great interest to many researchers, architects, scholars and engineers owing to the vast opportunities that the built environment can offer in terms of economic and social benefits. One of the main aspects of GHG reduction is the policy to achieve zero energy, and therefore, zero-carbon housing; this has been laid out by the EPBD, which mandates that all commercial and residential buildings across Europe should be nZEB by 2021 and ZC by 2050. This thesis focusses only on new residential buildings, and it does not consider the existing housing stock or refurbishment. nZEB/NZC are characterised by very high energy performance because most of the energy used is sourced from renewable energy. Despite the policy of imposing energy reductions on both domestic and commercial buildings, domestic buildings focus on energy reduction. In 2016, UK Housing reported that more than 60% of the total UK electricity use—and of that, 70% of the energy—was used for space heating and hot water. Figure 1-1 depicts the four main energy consumers in the economy; the figure shows that domestic consumption being the second highest compared of these sectors in the United Kingdom

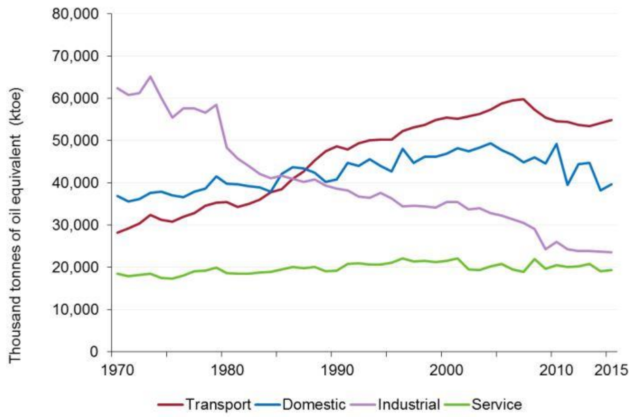

Figure 1. 1: Final energy consumption by sector in the United Kingdom (The Department for Business, Energy & Industrial Strategy, 2020)

In the built environment, the domestic sector's energy consumption has been recorded as the highest among all building types. This drastic increase in energy use in the domestic sector was reported at 211% from 1979 to 2011 (Jones & Lomas, 2016). Over the past few decades, with the country's notable population growth, the demand for building services and models of accessible comfort levels has become the norm in society, and the rate of energy in the domestic sector has seen steady growth of around 0.5% yearly (Cuce, 2016). Moreover, the domestic sector's energy consumption is dominated by several factors that affect this consumption, such as the climatic condition of the house, overall floor area, construction materials, occupants' lifestyle, home appliances and mechanics. Developed countries consume more energy in housing than developing ones do. In 2016, the domestic sector in the United Kingdom consumed around 28% of total energy use; in the United States, the rate was 22%, and in Europe, it was 26%, making the United Kingdom the highest in the world for domestic energy use (Chwieduk, 2003; Cuce, 2016). Moreover, 70% of the total energy use is consumed for heating purposes only.

There is great potential for energy reduction in the domestic sector that can be address via energy efficiency measures. As Chwieduk, (2003) stated, innovative technologies in the built environment provide an added value to the energy consumption rate, and with the current measurement of improved fabric and heating systems, further reductions can be realised.

The UK government has realized the environmental impact of energy consumption in the domestic sector and created several measures to mitigate the carbon emission (UGBC, 2015). Moreover, the EPBD introduced a mandatory measure to make all buildings consume nearly zero energy in all member states (Moran et al., 2020). Most European countries have adopted lifecycle cost assessment to calculate the whole life impact of a building, including building materials. Although the method of carbon calculation incorporates adding the building materials' carbon impact, the focus is on the building's operational energy reduction policies rather than the embodied carbon (EC) associated with the building materials.

In the United Kingdom, there are some energy efficiency standards that have introduced mitigation measures to reduce energy consumption in the residential sector. These include the European nZEB standards, Passivehaus, net zero carbon and many more, so far, the ultimate level of energy savings has been found in Passivehaus building so far. In the United Kingdom, there are currently 1000 certified Passivhaus buildings (Passivehaus Trust, 2016). Nonetheless, the focus on achieving the Passivehaus certification only revolves around a total reduction in operational carbon (OC). Currently, there are many types of building material with minimal embodied energy that need to be further investigated because they have greater potential for energy reduction than traditional building materials do.

As stated above, the construction industry is one of the most energy consuming industries in any nation. Previous studies have reported that on average, the construction industry utilises 60% of raw materials internationally and produces a tremendous amount of waste (Kisku et al. 2017; Kumar et al,. 2020). As the economy moves towards sustainable development, the demand for innovative methods of construction is rising. The high demand for developing environmental construction has resulted in multiple options in the modern method of construction (MMC) that combine speed to meet the current demand and fulfilment of the nZEB/NZC energy requirement. One of the latest innovations in the MMC industry is the construction of magnesium oxide structural insulated panels (MgO SIPs). MgO SIPs appear to be a construction alternative that simultaneously offers the speed required to address the UK housing shortage and the energy efficiency that meets the nZEB or NZC standards. However, despite the great potential that MMC offers to address the current challenge, the public response to adapting these methods is stagnant. Surprisingly, there has been limited research conducted in this field to evaluate the advantages of using MgO SIPs as a method to meet the nZEB/NZC housing for 2050. Therefore, the aim of this study is to assess the environmental impact of the MgO SIPs House in the United Kingdom by assessing energy performance under the current and future weather climate. The study is dominated mainly by considering energy consumption of the SIPs House; however, a thermal comfort study is also conducted to evaluate the fabric efficiency of the MgO envelope to compare the overall thermal comfort with energy used in the building. Moreover, another assessment is conducted to calculate EC of the SIPs House to identify the total energy used in $kgCO_2/m^2$/year used to build a single-family home in the UK, and results are then compared with those of a similar method of construction. Finally, the study intends to identify the SIPs method of construction as a solution to meeting the United Kingdom's NZC standard by 2050 and nZEB.

1.2 Research problem

As mentioned above, energy efficiency in buildings is a compulsory target to meeting the net zero carbon buildings standard. As stated in an EY report and by the London School of Economics and Political Science (2018), the residential sector consumes 40% of the overall usage in the UK and emits 36% of total CO_2e. Since the building industry has been classified as one of the greatest energy-consuming sectors in the economy, numerous mitigation policies have been initiated by the UK government. Furthermore, in addition to conventional methods of construction, there are new and advanced MMCs. The prefabrication method of construction has gained popularity in recent years. This is regarded as a method of sustainable construction based on the capability to deliver faster projects with lower environmental impact (Ismail et al., 2021). These benefits are associated with energy reduction because materials are processed offsite in prefabricated construction methods; here, the components are manufactured and delivered to the site ready for construction, reducing the construction time and allowing the effective management of construction waste. As Steinhardt & Manley, (2016) stated, in Hong Kong, there was a 52% reduction in construction waste associated with prefabricated buildings, which reduced the total energy consumption.

Prefabricated construction offers superior wall insulation, enhancing the building's energy performance and the occupants' comfort levels. MgO SIPs represent a new prefabricated typology that has the potential to meet the nZEB/NZC by 2050 and address the current housing demand. However, despite the demonstrated potential of prefabricated structures using MgO SIPs, the intake has been poor; prefabricated construction has copious benefits, but people are still reluctant to use it, instead relegating it to industrial usage. Moreover, for MMC SIPs, there is limited information on the energy associated with making and operating them; in the current initiatives, the building standard provides the boundary of OC and EC but does not focus specifically on the method of construction.

This research intends to address the identified gap in the current body of knowledge. MgO SIPs are fairly new method of construction, and the emphasis of this research is on proposing the use of SIPs as a potential solution of construction of nZEB/NZC. This research quantifies the effects of climate change on building energy-efficient SIP homes in the United Kingdom under the current nZEB/NZC 2050 target. Since there has been limited research done to evaluate the use of MgO SIP construction in the United Kingdom, a real-world case study of SIP construction is selected to be identified as a model of energy efficiency in the country. The study focusses on evaluating the model via four main research approaches, which are as follows: 1) calculating the total energy used and comparing it with the nZEB/NZC energy standards, 2) assessing the thermal comfort of the current and future weather scenarios, 3) evaluating the envelope's thermal properties and 4) examining envelope enhancement through parametric studies.

1.3 Hypothesis

The hypothesis in this thesis is that MgO SIPs construction will be able to meet the nZEB/NZC standards in the United Kingdom by 2050.

1.4 Aims and objectives

The aim of the research is to address the current gap in the body of knowledge by investigating the potential benefits of using MgO SIPs in the UK housing sector in terms of energy savings, particularly by evaluating the capability of the MgO SIPs to meet the nZEB/NZC 2050 plan. To achieve these aims, the following objectives have been identified:

1. To propose MgO SIPs as an energy efficiency prototype that meets the energy standard by 2050.
2. To investigate the energy savings achieved by using MgO SIPs as an MMC.
3. To measure the thermal comfort level as a tool to identify the durability of MgO SIP construction.
4. To assess the capabilities of the current heating system in the MgO SIPs House to meet current energy efficiency standards under the United Kingdom's current and future climate change conditions.
5. To perform a parametric study to identify the optimum possible solutions to energy savings in the MgO SIPs House.

1.5 Research questions

In association with the aims and objectives listed above, this research aims to answer the following questions:

1. What is the SIPs House energy consumption rate compared with other houses using similar methods of construction??
2. Is the SIPs House really capable of meeting the nZEB/NZC standards for the 2050 plan?

3. How well does the envelope of the SIPs House perform under the current and future UK climate?
4. How does the SIPs House compare with other energy efficiency standards like Passivehaus?
5. Can the MgO SIPs House be classified as an energy-efficient design for the future?

1.6 General methodology

To address the research questions, a framework is established that includes an empirical method of research to evaluate the overall performance of the MgO SIPs House. Mixed-methods research synthesising both qualitative and quantitative approaches is conducted, combining a literature review and analysis of the real-world case study to observe and analyse the findings. The general methodology is divided into four main stages: The first stage establishes the research, which covers the identification of the case study through a literature review; the second stage classifies monitoring boundaries and identifies suitable monitoring tools to perform the data collections; the third stage is the analysis of the results from the second stage, including data interpretation based on the current and future climate scenarios; and finally, the fourth stage involves drawing conclusions based on the evidence provided.

1.7 Thesis structure

The research is divided into eight chapters, each comprising an overview that presents an introductory statement and introduces an outline and flowchart. A brief description of the contents of each chapter is given below.

1.7.1 Chapter One: Introduction

The introductory chapter provides a background to the thesis that sets out the context of this research. It also presents the global phenomenon of climate change, its causes and effects and the national mechanism to combat global warming via CO_2e abatement. Moreover, it identifies the industries engaged in the most energy consumption, including the construction sector, which is connected to domestic and public housing. The focus of this research is on the residential sector because this sector has been identified as one of the top carbon emitters. The chapter showcases the United Kingdom's current challenges of constructing new homes at the required speed and simultaneously meeting the current energy reduction standards in the built environment. In addition, the chapter presents the research problem, aims and objectives, general methodology of the research and research structure.

1.7.2 Chapter Two: Literature review

Chapter two provides detailed information on climate change in the UK context. It presents the impact of climate change on the built environment and national measures and tools to mitigate the risk of global warming. The UK Climate Projections 2018 (UKCP18) report presents reliable projections and compelling datasets based on climate science and discusses the dominant driver of climate change—the high concentration of CO_2 and other gases in the atmosphere. The results of the science-based data are presented in the form of graphs and tables to draw a main conclusion about how to mitigate the risk of climate change. The chapter also showcases the current national energy reduction plan by presenting a list of energy reduction initiatives in the United Kingdom. It discusses the most energy-consuming sector in the country, which is the housing sector. The discussion highlights the most prominent national agendas of carbon reduction and identifies the challenges of current UK housing stocks and the measures currently in place. Furthermore, the chapter identifies the building standards in the UK and their applications in domestic buildings. Moreover, it showcases different building typologies that are characterised as energy efficient, such as the nZEB/NZC, Passivehaus), and later draws a baseline of these standards to build a strong case in the research context. Finally, it presents the gap in knowledge by identifying a new typology in the construction industry that has attracted limited research interest—the innovative MgO SIP. This type of MMC has merely been evaluated in terms of its environmental benefits, which can be useful for the national agenda of meeting nZEB/NZC by 2050.

1.7.3 Chapter three: Research methodology

The methodology chapter covers the research framework. It starts from observation by collecting evidence from the literature review regarding climate change, carbon reduction plans, energy and buildings and how the UK government is tackling these issues. Following this, in the identification phase, a gap is identified in the literature, and the case study approach is selected to fill the gap by addressing the research questions. Next, the investigation phase is carried out, in which the data collected from the research are evaluated and modified using the parametric analysis approach. Consequently, this part of the chapter highlights the measures selected and the design tools, particularly for this research, to assist in finding the answers to the research questions.

Chapter three describes the measurement tools and how they are implemented in the research. The tools of thermal energy and operational energy are discussed in detail, along with their placement on site and off site in relation to the case study and the data transmission and storage techniques. Correspondingly, this chapter presents a selection of suitable weather data files and methods for importing them into the selected software programs for current and future weather analysis. In addition, the data collected from the measuring tools are recorded, modified and validated using the cross-reference technique for consistency. Finally, the method of calculating the EC is presented.

1.7.4 Chapter four: Model development and validation

Chapter four describes the tools and models used, as well as the input parameters. It provides an explanation of the measures and tools selected for the research and gives the rationale for how and why they are implemented. The first section discusses the method of technical procedures for creating the three-dimensional (3D) model in DB by giving a step-by-step description of the model development process in the building environmental performance software, spanning from the process of importing the architecture drawing into the program to the site survey for detailing inputs.

Detailed descriptions of the validation process of the data loggers and energy loggers are presented, and the recorded data are calibrated and validated via cross-checking with existing datasets. For example, the energy data are validated using the SIPs House utility bill and DB simulation results, and a similar approach is applied for the thermal data using existing recorded data

1.7.5 Chapter five: Results

Chapter five presents a detailed analysis of the research and the evaluation methods adopted for this case study. The chapter puts forward the thermal and energy results through on-site measuring tools and compares the results with simulation outputs. The data are presented and evaluated for assessment at the end of each table or graph. In addition to the energy thermal performance, this chapter discusses the thermal comfort of the SIPs House in detail by implementing three thermal comfort models for assessment, and the results are validated via standard measurement compared with the on-site measurement of temperature and relative humidity.

The results included the energy outputs of using renewable energy in the house compared with the energy efficiency standards in the United Kingdom. Furthermore, the current performance is compared with the future performance by applying the use of parametric analysis. The results assist in creating an optimum model that fits the nZEB/NZC energy requirement in the three timelines of the present to 2030, 2050 and 2080. Finally, the analysis and discussion of the results of the current model and the future scenarios from the simulations are presented.

1.7.6 Chapter six: Discussion

The discussion chapter provides more evidence from the results to answer the main research questions via an extensive analysis of the findings. The chapter gives insights into climate risk and discusses in detail how the building sector can combat global warming using a holistic approach. The main findings describe the case study extensively in terms of the overall carbon impact of using these specific types of construction.

Following the latest approach of net zero building, the SIPs House is assessed using the whole life carbon impact. The total operation energy, as discussed in chapter six, is presented and compared with the current energy efficiency rate; and compared with the current national building standard context.

1.7.7 Chapter seven: Conclusion

The last chapter concludes this study by summarising the relevance of the research; it also discusses the main findings, interpretations and limitations of this work. It answers the main research questions and subordinate questions, along with addressing the hypothesis of the thesis. Finally, it highlights the study limitations and future possible work, and it discusses the recommendations related to using MgO SIPs as a potentially energy efficient model for the nZEB/NZC buildings. Further information is provided in the appendices at the end of the thesis to provide supplementary details.

Chapter Two: Literature review

2.1 Overview

Climate change is inevitable. Scientists have calculated the risk of unprecedented climate change, and it is evident in the extreme weather changes and natural disasters. Undoubtedly, the earth’s climate has changed throughout history, and major changes have occurred in the past; in the last 650,000 years, many glacier changes advanced and retreat, with the most prominent one occurring at the end of the last ice age about 11,700 years ago, marking the era of a new climate (World Meteorological Organization, 2020). It represents the change in weather patterns and average temperature over the course of time as a result of human activities and natural influences. These changes have a wide range of effects on our ecosystem. For example, Human activities, primarily burning fossil fuels, have increased the amount of heat-trapping known as Greenhouse Gases (GHGs) in the atmosphere, caused the average global temperature to rise.

In the United Kingdom (UK), houses have been suffering great overheating in the summer specially in buildings that lacks air conditioning, the overheating is a result of heatwaves during the summer season caused be the climate change. (Auzeby et al., 2016), the temperature is predicted to reach +1.4 by 2050 and according to United Kingdom climate impact program (UKCIP). According to (Ozarisoy & Elsharkawy, 2019) the existing social housing from the past decades are thermally insufficient, they which has effected the vulnerable population   The UK faced exacerbated heat weave of +35C^{o} between 13 April 2018 21 July 2018, which created relatively higher indoor thermal discomfort and consequently effected the wellbeing and health of the occupant.

The UK government has launched many initiatives to control the impact of CO_2e in the built environment. While currently there are codes and regulations in place, more studies and innovations are required to ensure that new constructions are fit for the future and to understand which building materials and techniques must be used today to prepare for the climate scenario in 2050.

2.2 Climate change in the UK

2.2.1 Climate change Protocols and emission targets

The UKCP18 is an important step to understand the complexities of climate change. This report predicts the nature of climate change in the UK in the future. Though they contain many assumptions, with the right tools, these projections can assist in quantifying the risks associated with climate change. The report presents reliable and compelling sets of data that are based on climate science (UNFCCC, 2015). UKCP09 was founded in 2009 by a group of research centres, led by the Department of Environment, Food and Rural Affairs (DEFRA), and the latest and most comprehensive report to date is UKCP18, produced by the Met Office Hadley Centre. Its aim is to recommend a set of projects for the future to address the impacts of climate change, and its projections are based on CO_2 emissions (McSweeney, 2018).

In 1991 and 1996, DEFRA published the UK climate projections, and these early projections were based on a single emission scenario, including seasonal precipitation and temperature. Later, the UKCP98 in 1998 included for the first time four emission scenarios – "low", "medium-low", "medium-high", and "high" – since climate change is unpredictable, having one scenario is limited to the other possibilities. (Met Office, 2020). The main driver of climate change is the high concentration of CO_2 and the other six GHGs in the atmosphere. These gases get trapped in the air, creating a huge blanket around the earth's surface causing an increase in air temperature; they could be an act of nature or related to human activities.

Since pre-industrial times, human activities have led to an increase in GHGs' concentration; between 1970 and 2004, the concentration of CO_2e increased by 70% (IPCC, 2000). Globally, 82% of the energy consumed in the construction sector is attributed to the burning of fossil fuels (Dean et al., 2016). Energy supply through burning fossil fuels has been the main source of the increase in GHG emissions across all sectors of the economy; the growth in direct emissions from transportation show a 120% increase, change in land use 40%, agriculture 27%, and construction 26%. However, the building sector is also responsible for indirect and direct CO_2e emissions through electricity usage. Based on the Global Status Report 2017, the sector is responsible for 30% of the total final energy used (Dean et al., 2016) (See Figure 2.1) However, it is easy to modify residential and commercial buildings to reduce their carbon footprints, and thus adopting climate change mitigation strategies is less complicated in the construction sector than in the other sectors of the economy.

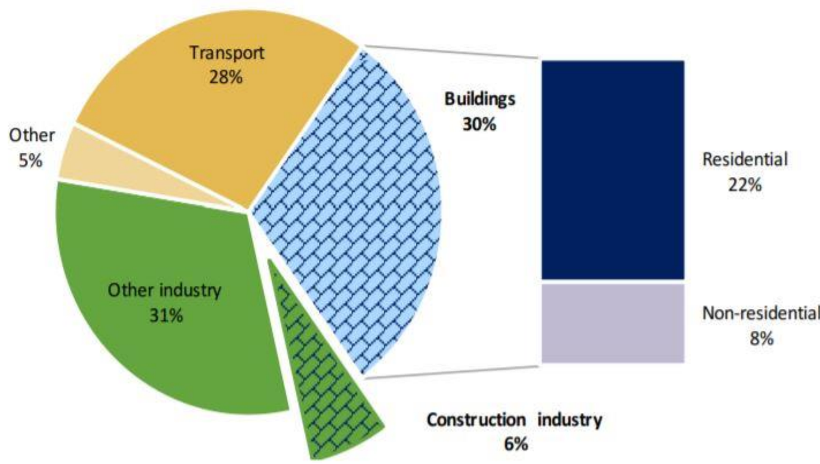

Figure 2. 1 : Share of global final energy consumption by sector 2015.

2.2.1 Kyoto protocol

Concerns over climate change in many countries around the world led to the signing of the Kyoto Protocol in Kyoto, Japan, in December 1997, which came into force in February 2005. The members of the United Nations, including more than 190 countries, committed to limiting CO_2e emissions in accordance with the individual targets set. These parties had to adopt innovative mechanisms to keep their commitments. The core commitment in the Kyoto Protocol involved the reduction of GHG emissions due to energy supply, industrial practices, agriculture, and waste disposal. Legally binding targets were set specifically for industrialized countries and were to be achieved in the 5 years between 2008 and 2012; each member was obliged to reduce CO_2e production from the base year, which was calculated in metric tons. The Kyoto Protocol is a flexible international law that provides valuable information for enacting efficient climate regulations (Böhringer, 2003).

2.2.2 UK carbon emission target

To mitigate climate change, the UK and European Union (EU) members committed to limiting global warming by 2^oC; to achieve this target, the UK and EU made a commitment to reduce CO_2e by 8% between 1990 and 2012. By 2012, the UK managed to reduce its CO_2e by 12.5% from the baseline, which was considered a great start to meeting its carbon reduction targets. Moreover, the country progressed even further, since by 2018 its GHG emissions fell by 40% from the 1990 baseline (Department for Business, Energy & Industrial Strategy 2019). Figure 2.2 depicts the declining trend of total GHG emissions in comparison to net CO_2 production since the 1990 baseline which is a result of grid decarbonization and therefore, the target of 80% reduction by 2050 has been set.

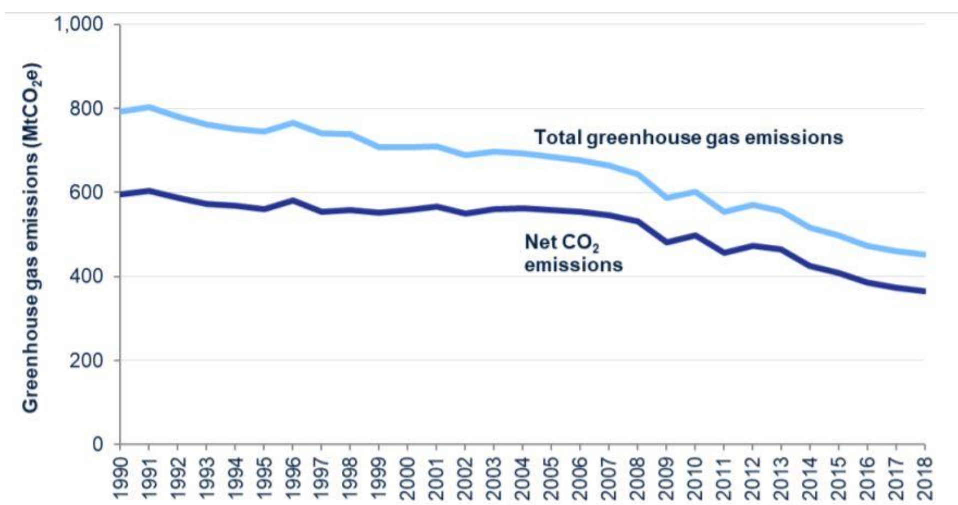

Figure 2. 2. : Total greenhouse gas emissions for the period of 1990-2018 ($MtCO_2e$)

2.2.3 Carbon emission impact

Several studies conducted in the past two decades have proven that human activities such as burning fossil fuels have contributed to changes the earth's atmosphere and that the main contributor to climate change in the significate increase in the production of CO_2 and other long-living GHGs. The GHGs and aerosol in the atmosphere disrupt the balance of incoming solar radiation and outgoing infrared. Changing these natural phenomena can lead to warming or cooling of the climate. Not only a noticeable increase in CO_2e that is linked to the direct burning of fossil fuels for energy used in transportation, heating and cooling and manufacturing but also an increase of CO_2e can be found in the act of deforestation The amounts of methane, fluorinated gases and nitrous oxide too have increased due to agriculture and fertilization, but the most prominent gas is CO_2. Figure 2.3 shows the proportion of CO_2 emissions from activity 1990–2019.

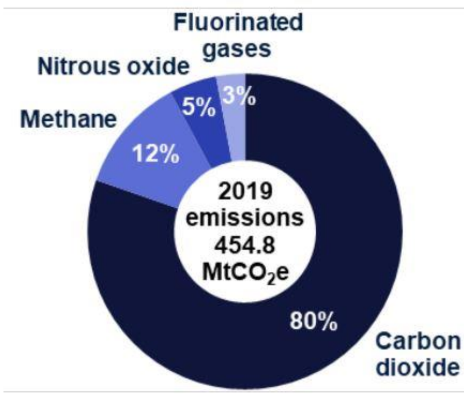

Figure 2. 3: Share of different anthropogenic GHGe in total emissions in terms of CO_2e.(Department for Business, Energy & Industrial Strategy (2019)

Since 1990, GHG emissions have been declining in the UK. The emissions dropped by 43% in 2018 and by 45.2% in 2019. Energy supply was the largest contributor to the CO_2e reduction in 2019. The decrease of carbon dioxide was driven from the energy station, mainly from switching the use of coal as fuel to a more sustain mixed use of electricity combined with efficiency in technology driven by clean and renewable energy sources.

In 2019, coal as a source of electrical energy accounted for 3%, compared to 65% in 1990. The use of renewable energy and technologies witnessed a 48% increase in 2019, compared to 22% in 1990. The rise in renewable energies has contributed to a significant decline in CO_2e production for energy supply. Two major sectors in the economy responsible for CO_2e production are the transportation and residential sectors. The transportation sector with a decrease of 4.6% from the 1990 baseline, the road transportation account for 34% of total carbon emission with the population growth the call for transportation is the norm. However, with regards to road transportation, the fuel consumption of cars has fallen slightly due to the use of more efficient fuel and the rise of electric cars. The residential sector accounted for 19% of the total CO_2 emissions in 2019, recording a 17% fall from the 1990 baseline. The main cause of carbon emissions in the residential sector is the usage of natural gas for heating and cooking.

2.2.2 Climate impacts and adaptation

Climate change is defined by The Intergovernmental Panel on Climate Change (IPCC) as "*A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use*" (IPCC 2000). However, many scientists use the definition provided by the United Nations Framework Convention on Climate Change in its Article 1: that climate change is a result of human activities that directly and/or indirectly alter the global atmospheric composition.

This definition attributes the steady rise in the earth's temperature to the increase in GHG production through burning fossils fuels such as oil, gas, and coal. It also refers to the changes in land use which cause deforestation. Hence, there is a correlation between human activities and the rise in global temperature. The earth's average temperature is likely to be 1^{o}C above that in the pre-industrial period (1850–1900), and in each of the coming years (2020–2025), there is a chance of a 20%

increase in the global temperature by 1.5^{o}C according to the World Meteorological Organization (WMO), as displayed in Figure 2.4

The average global temperature has increased by 0.9^{o}C since the late 19th century, and the majority of the change is ascribed to the increase in the amounts of CO_2e and other gases in the atmosphere caused by human activities. It has been recorded over the past 35 years that the earth is getting noticeably warmer with each year; observations show warming weather since 1960, and 2016 and 2020 saw the highest average temperatures ever recorded. The gradual increase in sea level has been consistent with global warming. The global sea level has risen since 1961 at an average rate of 1.8 (1.3–2.3) mm/year, mainly due to melting glaciers and ice caps (Bernstein et al. 2015). In another noticeable change, the amount of snow in Northern Hampshire has sharply fallen in the last five years, while the Arctic Sea ice is shrinking by 2.7 (2.2–3.3)% annually (WMO, 2020) refer to Figure 2.5

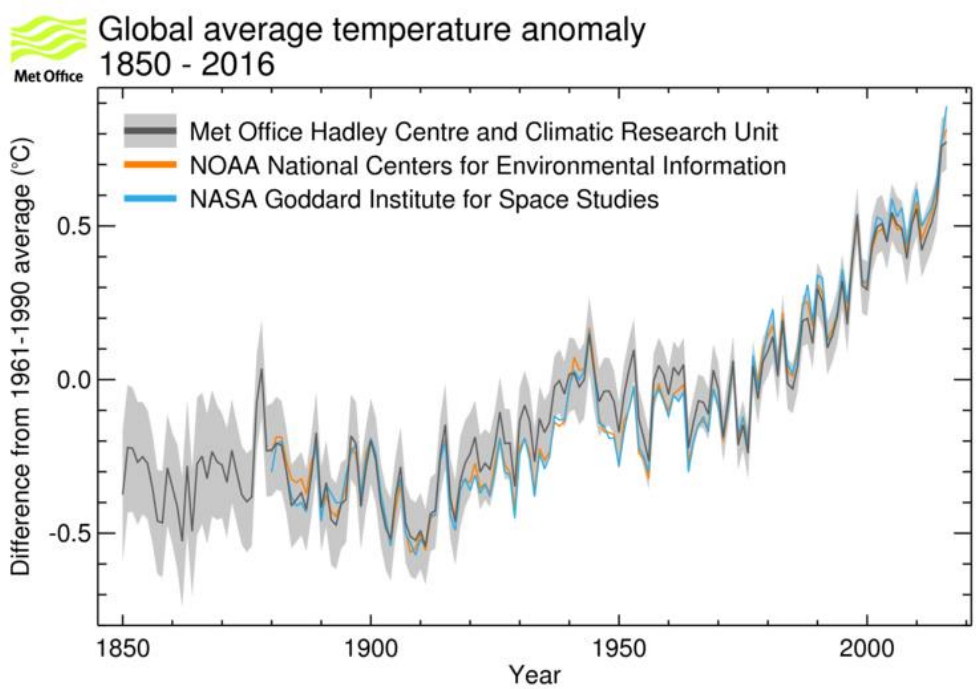

Figure 2. 4: Global temperature changes from 1850 to 2016, compared to the 1961-1990 average temperature.

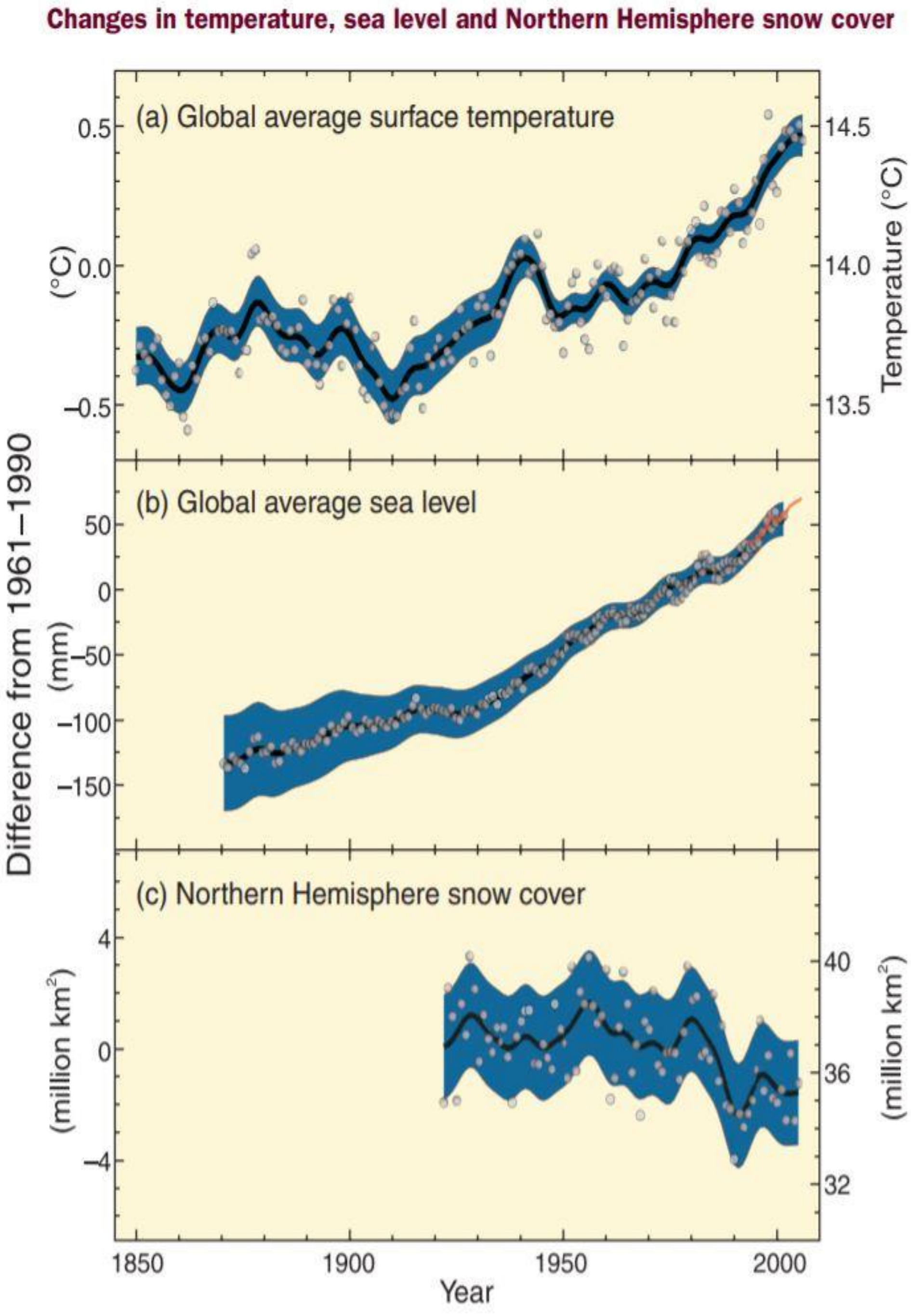

Figure 2. 5: Observed changes in the global average surface temperature, global average sea level and Northern Hemisphere snow cover from March-April.

Human activities have been identified as the main contributor to GHG emissions, which is directly linked to global warming. At this stage, curbing the impact of global warming is challenging; however, many initiatives and measures are being studied and launched in every sector of the economy to tackle its impacts. Many governments around the world have developed measures and policies to prepare for the future.

In 2015, it was reported that buildings accounted for 40% of the UK's GHG emissions and that residences were responsible for 70% of these (Climate change committee, 2013). Older buildering that were built in many decades ago, have become more vulnerable to weather changes, and more energy is required to maintain a certain level of indoor comfort due to the fact that the insulation and ventilation requirements don't meet the current thermal requirement (D. Li et al., 2012). Furthermore, many houses in the UK were built with poorly insulated external walls that lead to high rates of heat loss.

Over the past decade, many environmental centres have created a set of regulations to minimize the thermal bridging in buildings by building with structural insulated panels, the use of advance framing techniques, adding insulation on the exterior of the basement wall and the use of insulated wood studs.(Writer, 2021) Therefore, buildings have a great potential in mitigating the production of carbon dioxide (CO_2), through the use of highly insulated walls with proper ventilation system that prevent heat loss during winter times and consequently reduce the energy consumption that cause the rise of carbon emission.

"The IPCC is the United Nations body for assessing the science related to climate change" (IPCC, 2020). Since its creation in 1988 by the WMO, IPCC has been striving to provide governments with the latest scientific information related to climate change to help them develop their own climate policies. The organization is divided into three groups: Group 1 deals with the physical science of climate change, group 2 deals with the impacts of climate change, and group 3 handles mitigation of and adaptation to the phenomenon. IPCC looks at the future in a set of stories and pathways that might develop, based on the current energy sector, population increase and climate change. In 1990, its group 3 published the first set of climate change scenarios of the future, and in 1992 a revised scenario called IS92-f was published. The scenarios developed by group 1 produce an estimate of the global average surface temperature (Mitchell and Natarajan, 2020). In 2000, IPCC released a second generation of projection referred to as Special Report on Emissions Scenarios (SRES), and in 2007, it modified the SRES to Assessment Report Five (Graham, 2020); AR6 is due in 2022. These special reports provide evidence of climate change and are based on event analysis, providing a detailed assessment of current and future climate change scenarios.

2.3 The impact of Climate change in the UK

The UK are expected to face unprecedented climates and changes in natural resources. The figure below presents the evidence of rising temperature over the last decade (HadCET, 2020) based on Parker et al. (1992) See Figure 2.6

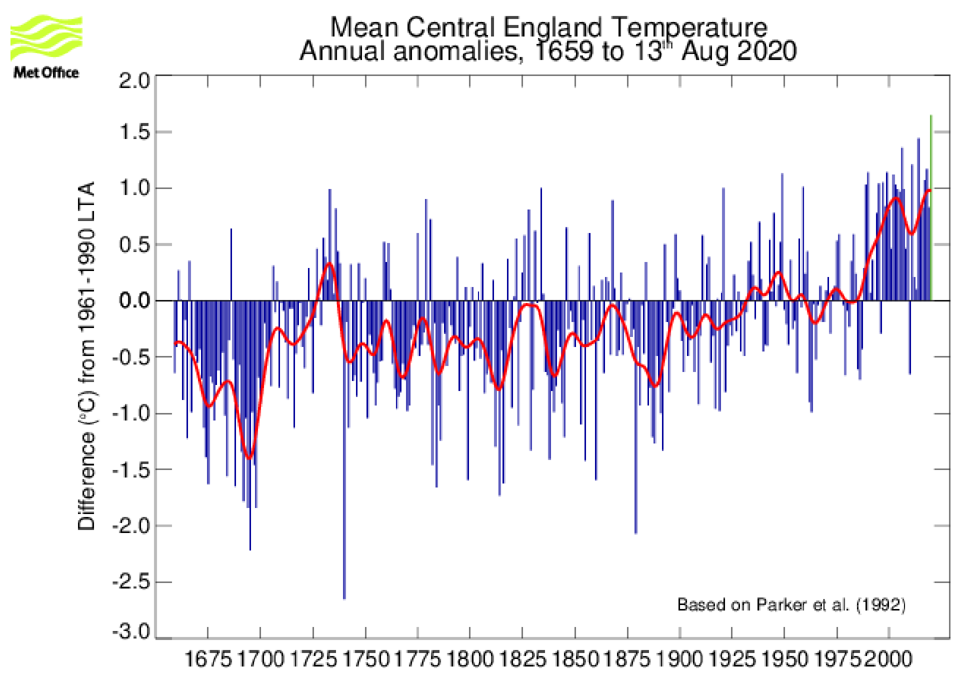

Figure 2. 6: Annual mean central England temperature and the red line represents a 10-year running mean (HadCET, 2020) based on Parker et al., (1992)

2.2.2.1 Mean Surface Temperature in the UK

The mean global land temperature for 2015–2019 was recorded at 1.7 ^{o}C above that in the pre-industrial age and 0.3^{o}C warmer than that in 2015. According to Central England Temperature (CET) data (See Figure 3), there has been a trend of warming across the UK since 1960. In the UK, the average surface temperature has been rising at the rates of 0.28 ^{o}C per decade in summers and 0.23 ^{o}C per decade in winters. It has been increasing since pre-industrial times at a rate of around 0.25 ^{o}C per decade since the 1960s (Heaviside et al., 2012). The highest temperature was recorded in the University of Cambridge botanical garden in July 2019 at 38.7 ^{o}C, beating the previous record of 38.5 ^{o}C in Faversham, Kent, in August 2003. A significant rise in mortality risk due to climate change has been reported periodically by the Office for National Statistics. In the absence of any modification to the current situation, deaths related to a heat wave are expected to reach 257% by 2050 from the baseline of around 2000 death; these projections are based on the rate of population growth and the proportion of older people (Hajat et al., 2014). In the summer of 2019, Europe faced two major and extended heatwaves; southern France recorded a temperature of 46 ^{o}C, and similar records were observed in Germany, the Netherlands, Luxembourg, and the UK (World Meteorological Organization, 2019).

In the UK, more than 1,000 deaths occur annually due to extreme weather conditions, especially during an event such as the 2003 heatwave. The death rate in the UK and Europe has increased sharply as a result of such heatwaves; in 2003, England and Wales recorded more than 2,000 deaths while France registered more than 15,000 deaths (Hajat et al. 2014; Heaviside et al. 2012).

On the other hand, Europe witnessed a severely cold winter in 2009–2010 (Cattiaux et al., 2010), with unusual snow accumulation in Northern Hemisphere countries. The UK experienced both an extreme heatwave and a severely cold winter in the same year of 2013. In this year, April and May were the coldest months, and the North of England recorded 20 cm of ice during the months of March and April. Such extreme weather caused a disturbance in the economy, since schools had to be closed and transportation was halted (World Meteorological Organization, 2015). As the average temperature increases along with the number of hot days in a year, the Meteorological Office argues that this will be the norm by 2040 (Tang & Dessai, 2012).

There has been a noticeable change in the number of cool and warm days; that the number of hot days recorded by the CET (daily mean temperature above 20°C) increased by 2 days per year in 1772–1900 and by 5 days per year from 2004 until the present. On the other hand, a very high variable number of cold days (mean temperature below 0°C) for the period of 1772–1964 has decreased to 20 days per year, and for the period of 1964–2004, the number of days has fallen to 10 days per year. Refer to Figures 2.7 and 2.8 for the total number of hot and cold days.

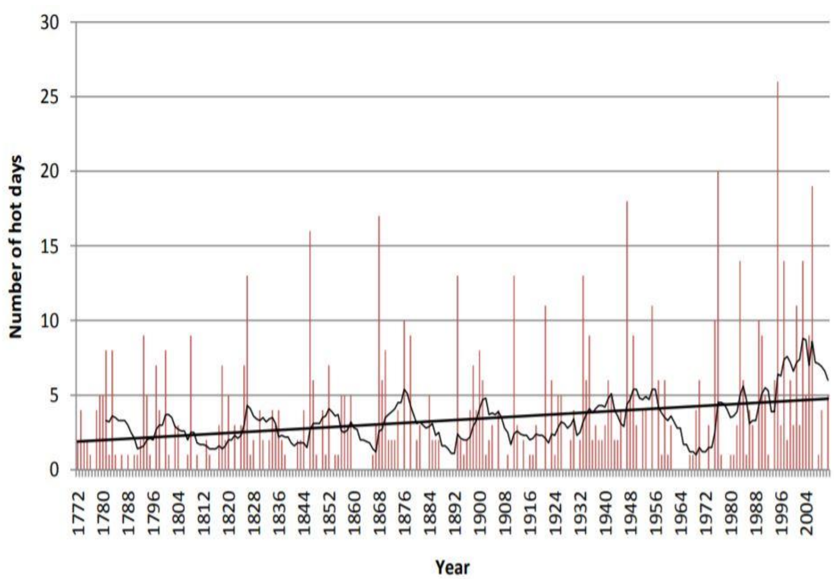

Figure 2. 7: Number of hot days (with mean temperature over 20°C) per year from daily mean CET from 1772-2011. The straight black line shows the linear trend and the other black line shows the 10-year moving average.

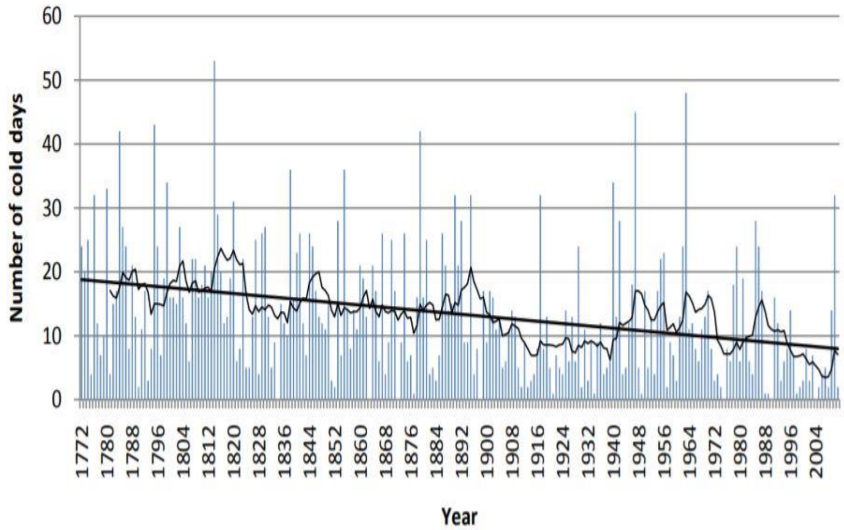

Figure 2. 8: Number of cold days (with mean temperature below 0°C) per year calculated from daily mean CET from 1772-2011. The straight black line shows the linear trend, and the other black line shows the 10- year moving average

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2.2.2.2 Mean Precipitation in the UK

The UK's rainfall rate is highly variable, since there is an increase in rainfall during winters and a decrease during summers. However, low rainfall was reported in the 2011–2012 winter which led to water shortage. In winter, the soil tends to be highly moist, limiting the absorption of water; hence, heavy rains in winter can cause flooding. In contrast, the soil in summers tends to be dry due to the high temperature; thus, with no rains, there is a high chance of a drought (Heaviside et al., 2012; Met Office, 2020; Tang & Dessai, 2012).

On 19 and 20 July 2007, the UK witnessed exceptionally heavy rains resulting in the worst flood in the region in 60 years. The flood caused widespread disruption; thousands of people had to leave their homes, and many were left without water or power. It was also reported that about 10,000 motorists were trapped in their vehicles on the M5 motorway and surrounding roads. Gloucestershire received its average monthly rainfall in one day, leading to £50 million worth of damages to public buildings, highway repairs and waste disposal (Tang & Dessai, 2012).

It is now clear that climate change has been inevitable based on scientific evidence since the mid-20th century. Thus, the UK and other countries around the world will face immeasurable challenges in the future if they do not mitigate the phenomenon's impacts and adapt to the changes in weather patterns. In the UK, many sectors of the economy are prone to risk, including the following: (a) transportation; (b) healthcare; (c) agriculture; and (d) construction and infrastructure. Thus, it is vital to understand the nature of climate changes today to be prepared for tomorrow. These parameters can minimize the likelihood of possible damages caused by extreme weather conditions by offering a range of possible options.

Moreover, Climate change poses a serious threat to the world, with overwhelming scientific evidence that human activities are responsible for temperature anomalies. However, the UK accounts for less than 1.5% of global CO_2e (Department of Energy and Climate Change, 2011), and since the 1990 figures there has been around 26% in 2019 decrease of annual volume CO_2 emissions in the UK, clearly showing its commitment to the carbon reduction plan. The government has set carbon targets to limit carbon emission impacts for example committing to Zero Carbon by 2025, and as a result of this commitment there will be changes in the way citizens source energy and use it.

The ultimate goal is to replace fossil fuels with renewable sources of energy. One of the most robust sectors in the economy is the built environment. In the UK, there are 29 million homes, and the government is planning to build 1.5 million new homes by 2022 (Committee on Climate Change, 2019). In 2009, domestic buildings were responsible for 25% of CO_2e production, with 12% attributed to energy use. Most of the CO_2e is produced through heating and hot water consumption from either gas or the electricity grid, both of which have relatively high carbon emission rates. However, 2020 recorded the highest decarbonization of electricity and it was reported 66% a total reduction of average 181 CO_2 kWh from 529CO_2 kWh from 2013's figure (Ltd, 2020). To take the carbon reduction plan forward, the current and future weather data are required to evaluate and analyse the overall performance of houses. With temperature on the rise, it is crucial to assess and model the performance of buildings in future climate scenarios in their respective locations. Obtaining relevant data through modelling houses using climate projections will help scientists and designers make decisions at an early stage to identify the best methods of construction and combine them with sustainable technologies.

2.2.2.3 Climate change Act 2008

The Climate Change Act was first established in 2008, with a commitment to reduce CO_2e by 80% from the 1990 baseline by 2050. However, this goal was replaced in 2019 by the UK government's ambitious target of "net zero" emissions. The act also provides a systematic approach to achieve this target through a series of six carbon budgets, and these budgeting systems led to the creation of the Committee on Climate Change (CCC). The objective of CCC is to monitor the carbon budget and report the progress periodically to each participant country (UK legislation, 2008).

2.3 Building performance standards and definitions

Regulations for new buildings are an ancient invention; one of the earliest codes for construction safety and occupants' health is Hammurabi's law for Mesopotamia dated to around 1790. Many countries around the world established their own laws based on their proximity to areas prone to earthquake, sea, or even fire, to ensure the safety of their citizens (International Energy Agency, 2008). One of the early responses to energy efficiency in the building was the poor wall insulation levels which were associated with health problems through the moisture created due to air infiltration, mainly in the cold weather countries. The practical and simple approach was to construct two layers of floor with an air layer in cavity walls. Further, in late 1950, Scandinavian countries started measuring the indoor comfort level, linked to insulation, through the U-value and R-value, material specification, and double glazing, as providing better and improved indoor conditions became a national agenda. Today, these standards and codes are mandatory requirements in the built environment.

According to the Chartered Institution of Building Services Engineers' (CIBSE) Energy Efficiency in Buildings guide, "An energy-efficient building provides the required internal environment and services with minimum energy use in a cost-effective and environmentally sensitive manner" (CIBSE, 2005). The guide takes a holistic approach to designing and operating buildings. Its emphasis is on the correlation between the skin of the building and the heating/cooling and lighting system. The suggested approach is to improve energy efficiency and minimize environmental impact through design and technologies.

Since the first and second oil crises in 1973 and 1979, respectively, many non-oil-producing economies have released the risk of oil dependency and oil price fluctuation that is associated with politics. Thus, the government decided to address the matter by establishing a public organization like the energy agencies and creating energy standards for conserving energy. In Europe, the first building standard was established in 1970 following oil crises, with the main focus on heat transfer. Later, in 1980, building envelope designs were introduced to address solar radiations (Pérez-Lombard et al., 2011). And BRE had widely used and validated domestic energy model (BREDEM) by mid-1980s.

An increasing number of designers, builders, and homeowners are becoming more interested in energy efficiency and green design. With the government promoting green buildings and rating systems, there is higher confidence in green constructions in terms of aesthetics, conform, and energy efficiency (Allouhi et al., 2015; Kubba, 2010). The building sector accounts for around one-third of the final energy used, and most of this is attributed to building design and construction. Building regulations, "codes," and "standards" are tools to regulate and improve the energy efficiency of the built environment (Pérez-Lombard et al., 2011). Reducing energy demand through building regulation is key, In the 1990 under Part L the drive to lower energy consumption was established through lower U-values for construction materials to mainly focus of energy efficiency through fabric insulation standard which reduce heating demand (DeCort, 2022b). For example, the wall's U-value in L1 during 1991 was limited to 0.35 W/m^2K in comparison to 2016 figure of 0.28 W/m^2K, Modern construction requires value less than this and further stringent standards are recommended to meet the national agenda.

Many measures can be considered for reducing energy consumption. First and foremost, the fabric of a building could contribute significantly to energy reduction, and second, efficient technologies could be used to maintain an optimum indoor comfort level at minimum cost. There are also other factors that contribute to energy consumption internally and externally. Figure 2.9 in the CIBSE guide presents four factors that contribute to energy consumption: (a) the systems used and their sizes and sources; (b) the building envelope, in terms of the materials used, shape, orientation, and size; (c) the human factor, which represents the occupancy rate, activities, and management; and (d) the climate factor, which represents the outdoor weather "(Johns, 1997) cited in (CIBSE Guide F, 2012)". However, the majority of these factors can be amended or modified in the early stages of design to reduce energy consumption. Building regulations include prescriptions for thermal properties of the building envelope and for double-glazed windows, heating, ventilation, and air conditioning (HVAC) systems, lighting systems, electrical power, renewables integration, and building maintenance (Allouhi et al., 2015). These approaches are considered the most adopted strategy to promote energy efficiency in building environments. (Pérez-Lombard et al., 2011).

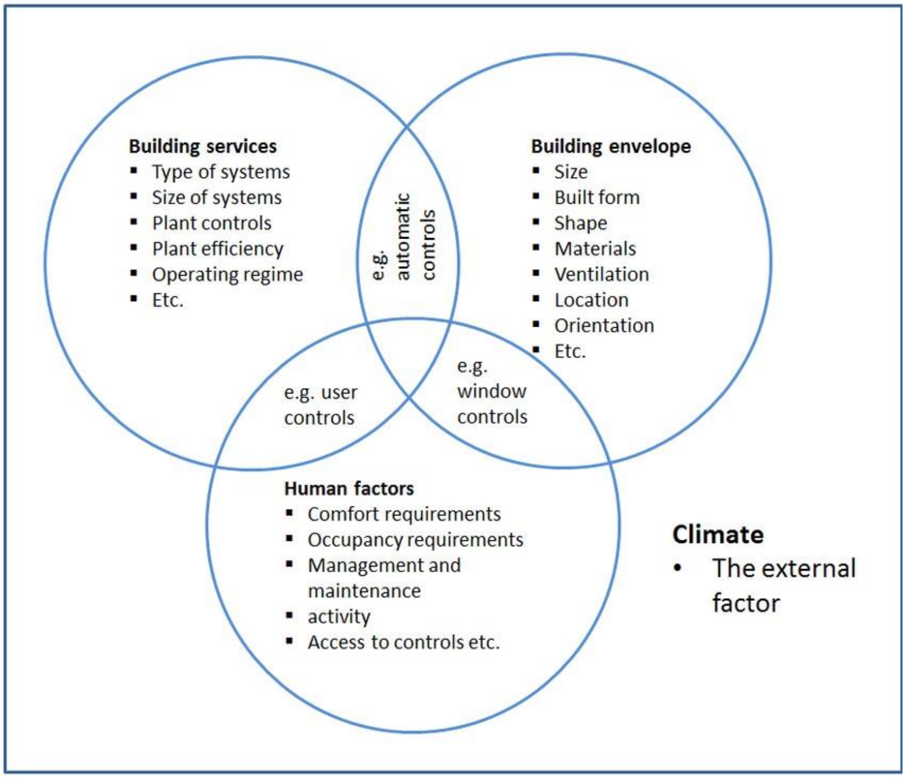


Figure 2. 9: Key factors that influence energy consumption.

2.3.1 Standard Assessment Procedures SAP.

There has been a growing demand by the government and local authorities to meet the carbon target through conserving energy and reducing carbon emissions. One of the initiatives in this regard is the Standard Assessment Procedure (SAP), which was developed in 1992 by the Building Research Establishment (BRE) as a framework to assess energy efficiency in the residential sector. A methodology for calculating energy use was established to monitor the energy consumption in houses, in line with the government policies for energy efficiency (Department for Business, Energy & Industrial Strategy, 2016). SAP includes two sets of energy assessments: (a) energy upgrades for existing houses in the UK (L1B); and (b) fulfilment of energy requirements in new houses (L1A). SAP quantifies energy performance in terms of energy used per unit floor area, fuel-cost-based energy rating, and CO_2. It uses a performance scale ranging from 1 to 100, where 1 represents the lowest efficiency and

100 the highest efficiency; these scales later are graded an award certification programme called Energy Performance Certificate (EPC; Figure 2.10).

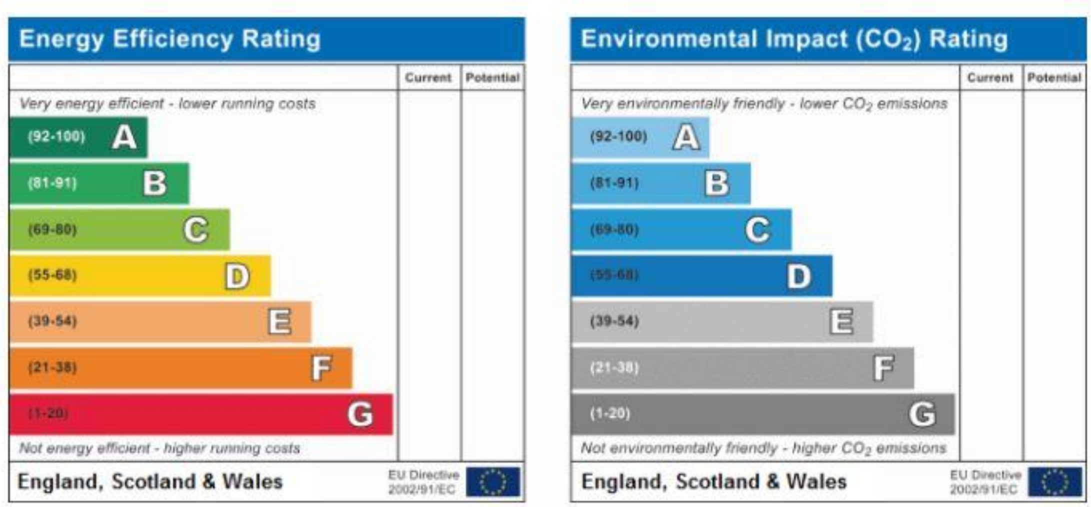


Figure 2. 10: Standard Assessment Procedures (SAP) rating to efficiency scale

2.3.2 Part L Building Regulations - England & Wales

Part L of the England and Wales building regulations includes legal documents that set the energy efficiency standards for residences. These documents provide limiting standards for newly constructed buildings (L1A) and renovations for existing housing (L1B; BRE, 2010), and the regulations are part of the government agenda to meet the carbon reduction plan through fuel and energy conservation. L1A discusses energy conservation in new dwellings and specifies the minimum energy to be used in the construction and post-occupancy phases. Part L1 focuses on the building fabric and fixed building services, such as heating, cooling, lighting, water heating, and mechanical ventilation. There are several criteria provided to meet the approved documents L, which consist of the calculation of carbon emission rate that should not exceed the target emission rate for a notional building and must be expressed in $kgCO^2/m^2$per year, all building fixed services should be designed based on energy efficiency, solar gain need to be limited, as build air permeability testing should be carried out, providing building owners with energy efficiency information, on the other hand, Notional building follows building specification that influence the energy performance of dwellings as part of the government's target to meet zero carbon by 2050. The building specification focus on fabric energy efficiency rate to mitigate the rise of CO_2 rather than improving the building system and implementing renewable energy. The new Notional Building specification is published within PartL1 documents under section 5.(Building Regulations,2010) with 2013 edition incorporating 2016 amendments.

Table 2.1 presents limiting values of fabric properties in terms of U-value in England and Wales 2013 edition with 2016 amendments ((Building Regulations, 2010. approved document L1, 2013) .

Table 2. 1: Limiting fabric parameters for new dwellings.

Fabric	Required U-Value (W/m^{2}K)
Roof	0.13
Wall	0.18
Party wall	0.00
Windows, roof windows, glazed roof lights, curtain walls and pedestrian walls	1.4
Air Permeability	5 m^3 /h.m^2 at 50 Pa

In 2017, there were around 28.5 million residential buildings in the UK versus 1.8 non-domestic buildings (Zero carbon hub, 2021). Multiple studies (Brown 2018; EKINS et al., 2011; Kannan & Strachan, 2009; Li & Colombier, 2009) show that there is a large potential for carbon reduction in residences. The majority of houses in England were constructed in the traditional way using bricks, concrete or cement blocks, and stones, while flats and tall buildings were built using concrete and steel frames. The heating system in a residence contributes largely to its overall energy consumption. The majority of houses in UK use gas fired central heating as primary method of heating , with 83% of dwellings consume energy from gas-fired central heating systems and only 3.9% on oil central heating (See figure 2.11) . Eight out of ten homes in UK depend on gas for heating and gas dominates consumption in the transportation and industrial sectors and electricity is mainly used for home appliances (refer to Figure 2.12). (Acquah et al., 2019). Currently 80% of UK domestic heating demand comes from natural gas (Watson et al., 2019), however, the UK begun energy diversification to reduce dependency on fossil fuel and implementing energy efficiency principles to achieve zero carbon by 2050 (Kattirtzi et al., 2021). One of the methods to decarbonize heating system is through district heating, and since the UK is densely populated it presents a great opportunity for this method of district heating and cooling called the 5th generation, which can use electrified heat pumps fed from zero carbon electricity and without the particulate emissions of biomass. Cities like Plymouth and Aberdeen have already been on pilot to evaluate the system.(Interreg, 2020).

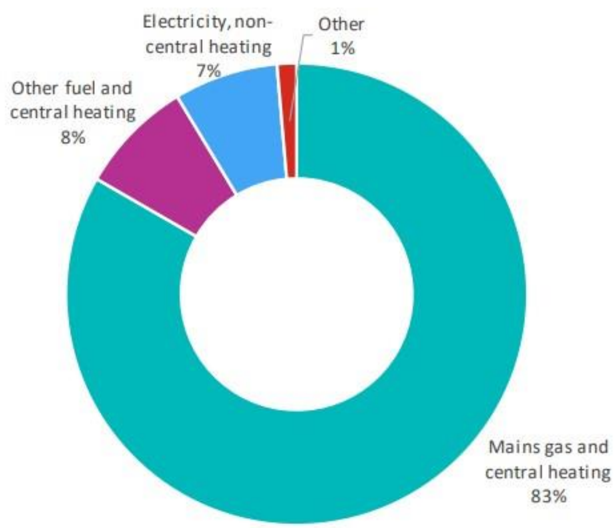


Figure 2. 11: Heating system and fuel type in UK household. (Department for Business, Energy & Industrial Strategy, 2021)

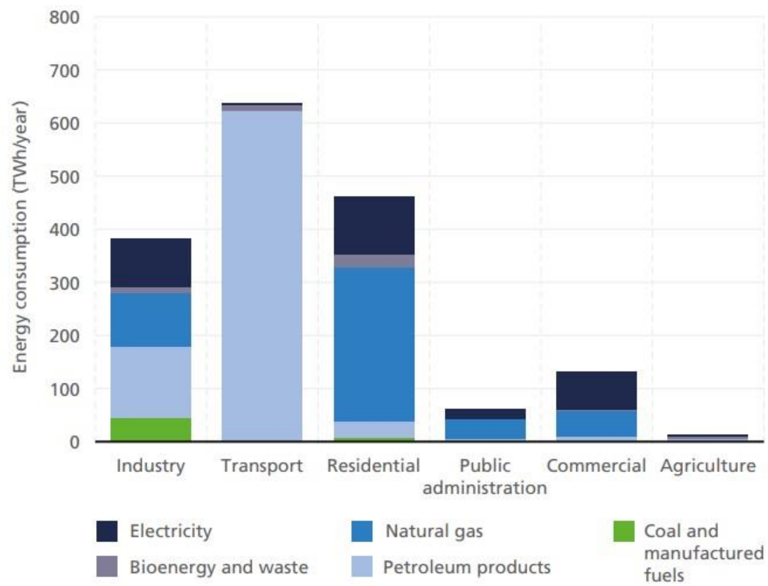


Figure 2. 12: UK final energy consumption by sector and fuel in 2015. (Abad et al,. 2017)

With over 170,000 homes built each year in the UK (Ministry of Housing, 2019), current UK domestic stocks are responsible of 40% of the country's carbon emissions, and most of them are leaky and consume much energy. LEB generally shows better energy performance than a new building (Khatib, 2016) through implementing new laws of the envelope system and improving the energy efficiency in the housing sector can help achieve the national target of zero CO_2 emissions by 2050. and as of June 2019, the UK government announced to be the first economy to pass laws to bring greenhouse gas emissions to net zero by 2050 (Dray, 2021). It is not an easy task, this mean decarbonizing all sectors in the economy, and housing sector one of the most contributor to carbon emission. Therefore, the UK's building sector has been encouraging homeowners to opt for energy-efficient development to save on energy use to reduce the carbon footprint. Efforts to decarbonize the built environment have witnessed a clear spike due to the enforcement of rules for installations using less energy per square metre. The annual housing supply in England was estimated to be 251,000 in 2019, compared to 241,340 in 2018, and the numbers are on the rise based on 2019 housing statistics (Homes England, 2019). The UK government has provided energy performance specifications for newly built and existing dwellings.

2.3.3 Low Energy Building (LEB)

A low-energy building (LEB) is defined as a building that requires low primary energy to operate through the use of envelope insulation and green technologies. An LEB generally shows better energy performance than a new traditional building (Khatib, 2016; Smith et al,. 2016), and potentially reducing energy consumption by 50%–77% when complied with energy efficiency regulations (Torcellini et al., 1999). Another comprehensive definition of LEBs was examined in the study by (Hernandez & Kenny, 2010), who used the annual embodied and operational energy of a building to calculate the overall energy consumed in the form of the whole life cycle to be able to define, net-energy, net-site energy or net-zero energy source. Calculating the embodied and operational carbon in the early stages of design has been recommended by London Energy Transformation Initiatives (LETI) to reduce the overall carbon impact (LETI, 2020).

LEB is a general term used in many countries, which can be confusing sometimes; however, labels and star ratings for a building's energy efficiency are user-friendly and easily identifiable. A typical classification of buildings would involve categories A–G or A, A+, B, and B+; these classifications are indicators to state that these buildings are more efficient than the standard with heating demand equal or less than 30kWh/year (Passivehaus Institute, 2016). In the United States of America (USA), the label "ENERGY STAR" is given to a building that uses 15% lower energy than standard constructions, as defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). In another example, in Austria, a five-star rating is given to buildings with maximum energy efficiency (Jens, 2008). Energy consumption has been the main concern by many countries, and policy makers have introduced regulatory measures to promote energy reduction including the use of renewable energy as a source of primary energy. Primary energy is defined as is the unconverted raw energy in their original form like natural gas or coal and secondary energy is the electricity generated from raw energy like fossil fuel as defined by LETI (2020). In the UK there are number of methods of energy generations, burning fossil fuel mainly from natural gas presents 42% of the total energy used and

9% comes from coal, along with the use of nuclear, renewable energy and imported energy which play small role in energy production (Energy UK, 2016) . In the EU the shift to energy efficiency in building was driven by the need to save energy through strategic policies called EPBD (Energy performance of Building of Buildings Directive) which led to the introduction of nearly Energy Zero Buildings (nZEBs), which is defined as a building with very high energy performance, the nZEBs buildings require very low amount of energy and is sourced by renewable energy from onsite or off site (D'Agostino & Mazzarella, 2018). Based on EPBD member states, the primary energy has to be given in numerical performance indicator which is expressed in kWh/m^2. Each country in the EU has a specific primary energy based on their resources and climate, some countries have tighter energy standards than others and each have the freedom on how they achieve nZEB through any construction techniques. For example in the Oceanic climate like England the primary energy specification is limited to 44 kWh/m^2/year for new building in comparison to similar climate like France they have more flexibility of limiting the primary energy between 40-65 kWh/m^2/year (D'Agostino & Mazzarella, 2018).

2.3.4 Zero Energy Building

Zero-energy buildings (ZEBs) are very similar to LEBs and Passivhaus buildings and have many definitions in the literature. The first definition was based on energy consumption, mainly heating, and later the definition evolved to include the overall mechanical systems of a building, such as heating, domestic hot water (DHW), lighting, and ventilation.

A variation of a ZEB is the zero-carbon home, which requires all CO_2e to be reduced to zero through regulated emissions (heating, cooling, ventilation, and lighting) and unregulated emissions (household appliances; Zero Carbon Hub 2013). The Zero Carbon Hub (ZCH) is a building standard with specifications for three main aspects: (a) maximum energy, expressed in kWh/m^2.year, that would normally be needed to maintain an internal comfort level in terms of temperature and humidity, called the Fabric Energy Efficiency Standard (FEES; see Figure 2.13 for energy specifications based on the archetype); (b) carbon emissions measured in kg/m^2.year; and (c) the allowable solution to compensate for carbon emissions reduction that are difficult to achieve on site. (Papachristou & Firth, 2014).

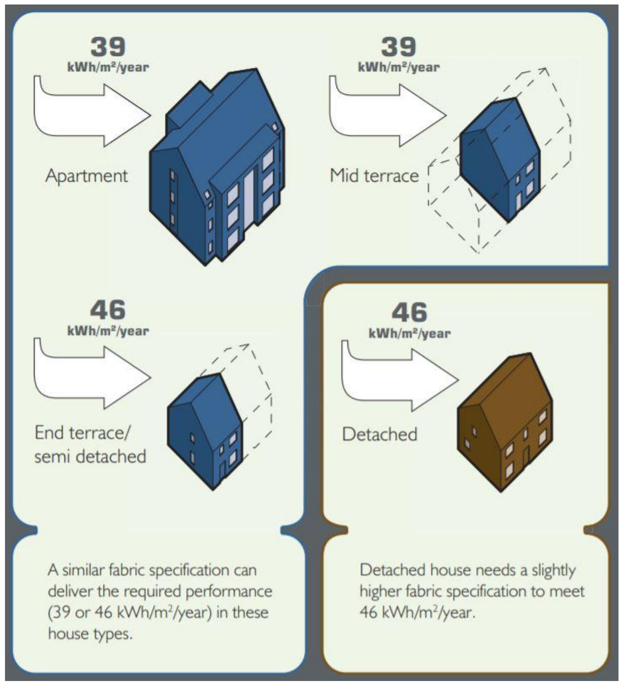


Figure 2. 13: Energy target proposed for Fabric Energy Efficiency Standard (FEES). (Zero carbon hub, 2021)

In comprehensive reviews, Harvey (2013) and Kheiri (2018) examined methods to optimize energy efficiency, considering effective thermal performance as the key to minimizing building energy consumption, and concluded that there are three main optimization criteria: the microclimate of the building envelope, building physics, and thermal comfort.

The following parameters influence the energy consumption of a building according to Kheiri (2018):

I. Its outer layer, including the thickness of the walls, roofs, and floors;
II. Its size and orientation.

III. Its HVAC systems and lighting loads.
IV. The type and size of its glazing system.
V. Selection of appropriate renewable-energy sources; and
VI. The cost-effectiveness of the building and building systems

Another interesting classification that has gained popularity, especially in Europe, is Passive House.

2.3.5 Passive Houses.

Among other building regulations to mitigate the impacts of climate change and global warming, “Passivehaus” standards apply to very specific energy consumption parameters, especially in terms of heating. When compared with other energy-efficient structures, Passivehaus buildings consume almost 70%–90% less energy (Khalfan, 2017; Laustsen, 2008). The concept of Passivehaus was developed in Germany in 1990 by Professor Dr.Wolfgang Feist. Since then, over 60,000 passive houses have been built around the world (2016), with the majority situated in Europe. The standard of Passive House in the UK has also gained interest, with more than 1,000 houses completed and many more in the pipeline (Passivhaus trust, 2016).

A Passivhaus building is one that provides a high level of thermal comfort but consumes minimum energy; this level of comfort is achieved through insulation, heat recovery, and passive use of solar energy. According to the Passivhaus Institute (PHI), five principles should be applied when constructing a Passivhaus building, as displayed in Figure 2.14.

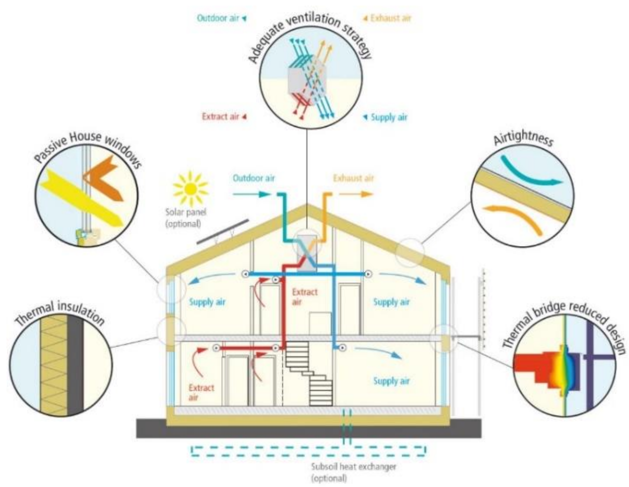


Figure 2. 14: Passive house five main criteria (Passive House Institute, 2015)

The concept is based mainly on scientific and objective methods; its energy target is defined by a clear framework, the restriction imposed on the space heating demand is that it should not exceed (15kWh/m^{2}a), with no predetermined construction methods or building solutions. Passive House includes an assessment tool, the Passive House Planning Package (PHPP), to guide architects, planners, developers, and homeowners on the baselines to construct their own designs based on Passive House specifications (Gonzalo & Rainer, 2014). PHPP is used to estimate a building's airtightness to eliminate droughts, ventilation, heat loss, heating and cooling systems, thermal wall insulation, with a U-value ranging between 0.08 W/m^{2}K and 0.18 W/m^{2}K, with a window of 0.80 W/m^{2}K, a high-performance ventilation unit, energy-efficient household appliances (refer to Table 2.2 for Passive House envelope specifications). Furthermore, another important factor that Passive House incorporates in its design strategies involves thermal-comfort boundaries: The indoor temperature should ideally be 21^{o}C, possibly varying between 18^{o}C and 24^{o}C, and the relative humidity must be between 40% and 70% (Gonzalo & Rainer, 2014; Passivhaus trust, 2016).

Table 2. 2: The Passive house thermal performance standards. (Johnston & Siddall, 2016)

Component Thermal Performance	
Insulation materials	**0.06 - 0.02 W/mK**
Exterior walls	**0.15W/m^{2}K**
Interior insulations	**No Explicit limits**
Roof and terrace construction	**No Explicit limits**
Basement ceiling and ground slabs	**No Explicit limits**
Glazing systems	**Triple glazed/quadruple**
Window frames	**<0.85 W/m^{2}K**

2.4 Modern Methods of Construction (MMC)

Modern methods of construction (MMC) have gained significant popularity in the construction industry over conventional construction using bricks and blocks. Prefabrication, pre-assembly, modularization, and off-site fabrication are all terms used to describe the manufacture and assembly of building components off-site at an earlier stage, instead of the traditional method of on-site construction (Correia et al., 2018). This method was developed in the industry to satisfy the rapid growth in demand for housing and energy reduction in the UK, in accordance with the national agenda of providing affordable housing. MMCs are cost-effective; they control noise pollution and construction waste and reduce construction duration (Hartley & Blagden, 2007).

Building elements are manufactured and assembled in a controlled environment in a factory and later delivered to the construction site when needed. Prefabrication technologies offer several benefits over traditional construction; however, some people are still sceptical about using them. Prefabricated wall systems are frequently used for economic or aesthetic reasons; however, despite the employment of new technologies, they are much underestimated. Once buildings are equipped with the right materials and technologies, high-performance building envelopes can be developed which can reduce the overall energy consumption.

According to (Hwang et al., 2018), MMCs include but are not limited to Prefabricated Prefinished Volumetric Construction (PPVC) and PODS, panelised construction system (PCS), including SIPs, sub-assemblies and components called hybrid systems, and site-based construction.

2.4.1 Prefabricated Prefinished Volumetric Construction (PPVC).

PPVC, also known as modular construction, is a construction method wherein volumetric components (walls, floors, and ceilings) are manufactured and assembled in a credited prefabrication facility and transported to the construction site for installation. These components can be manufactured from most materials, including lightweight gauge steel, timber frame, concrete, and composites (MPA, 2019). The PPVC method is particularly suited for repetitive design features, called POD designs. It facilitates ready rooms, such as bathrooms and kitchens, especially in hotels and student accommodations. Although this method is considered to be efficient and cost-effective, several studies on the use of PPVC have criticized it due to lack of efficiency in project management; for instance, (Azhar et al., 2013) found six main constraints associated with adopting PPVC in the built environment: lack of coordination between designers and developers, site constraints, unavailability of modular components, wrong sizes, low flexibility in changing the design, and inaccurate perceptions of clients.

2.4.2 Panellised Construction System (PCS)

PCS is another method of innovative prefabrication wherein the walls, roofs, and floors are manufactured separately in a factory and delivered to the site for assembly into the three-dimensional structure or to fit with the existing structure (Hwang et al., 2018). Several types of panels using multiple types of materials are manufactured in the factory, such as open panels, closed panels, concrete panels, composite panels, SIPs, infill panels, and curtain panels. In a study conducted in Auckland, New Zealand, (Lopez & Froese, 2016) examined the benefits of using PCS over the traditional construction of residential and commercial buildings in terms of cost- and time-efficiency. They found a 21% decrease in costs across all building types and a 47% reduction in completion time.

In a different study conducted on timber-based wall prefabrication, (Orlowski, 2020) suggests that timber is a better construction material than steel or concrete, since wood is a renewable material and has the ability to store carbon, thus being more sustainable than the other materials. Further, (Hashemi et al., 2020) present an analysis of timber platform building based on a case study in New Zealand, demonstrating that the connections of the installation process might experience damages under design earthquake. Another study (MPA, 2019) states that the second most popular form of construction in the UK is PCS, mainly using SIPs or timber or steel frames. According to this study, out of the 45,000 homes constructed in the UK in 2015, 42% made use of PCS in the main building or in the extension.

A traditional SIP system includes individual panels to form the exterior walls, roofing, and flooring. These individual panels consist of a rigid foam core and are covered with interior sheathing and thermal insulation (Parker, Legg, and Folland 1992). The outer layer is typically made of plywood, cement, metal, fibreglass, or oriented strand board (OSB), and the foam is made of either expanded or extruded polystyrene (Saxton, 2017). SIP techniques have evolved over the past 34 years, with more innovative and rigid systems being in high demand. As the UK's construction industry is driven by innovation and technology, new methods of construction are on the rise. In particular, there are two main factors driving the changes in the industry: emphasis on sustainable constructions and innovations to improve fabric energy efficiency.

2.4.2.1 Magnesium oxide boards SIP (MgO)

As the demand for low carbon emissions and cost- and time-effectiveness has emerged in the market, a new building system has been developed under the prefabrication construction system, called the magnesium oxide (MgO) SIP with reinforcing fibreglass. MgO panels comes in difference sizes and thickness, with U-Values of 0.10 (W/m^2K) (Dragonboard, 2020). According, to Passivhaus standards, MgO SIPs are high-performance with highly insulation building systems that consist of a foam insulation core sandwiched between two layers of MgO boards. Most MgO is mined in China, since 70% of the MgO deposits in the world are in Asia; therefore, most MgO panels are currently sourced from China (Saxton, 2017) (Appendix 1.B). The benefits of MgO sheathing are that MgO boards are resistant to water and mould, suppress fire, provide noise insulation, contain no volatile organic compounds (VOCs), and most important of all, can be manufactured quickly (Rise, 2019; Švajlenka, 2021). The core foam can be made of extruded polystyrene foam (XPS), expanded polystyrene foam (EPS), polyisocyanurate foam, or polyurethane foam, or it can be a composite honeycomb (HSC).

Very few studies have been conducted on the whole life carbon impact of MgO SIP panels in housing projects around the world. Only three such studies have been undertaken in Canada; two papers were based on a life cycle assessment done by (Li & Froese 2016; Li et al., 2018a), the second study involves a smart home in Vancouver, and the third research was conducted by (Lopez and Froese, 2016) on the cost and benefits of panelised MgO SIPs and modular prefabrication. These studies were conducted for specific climatic zones and building regulations pertaining to the respective locations. In this dissertation, I explore the same MMCs in the UK and assess their environmental impact under the UK's building regulations.

2.4.2.2 Case study Vancouver – Canada.

A full-scale prototype house was constructed at University of British Columbia (UBC) in 2016 by AYO House Inc. as an exploration of low-cost, high-performance buildings. This provides limited real case study analysis when investigating the energy consumption usages for future scenarios. The floor area of the house is 150 m^2. The house has two storeys containing three bedrooms and two bathrooms, as shown in Figures 2.15 and 2.16. The skin (foundation walls, ground floor, exterior walls, and roof) was constructed using MgO SIPs.

Figure 2. 15: Vancouver campus, Prototype house at the University of British Columbia. (Li et al. 2018a)

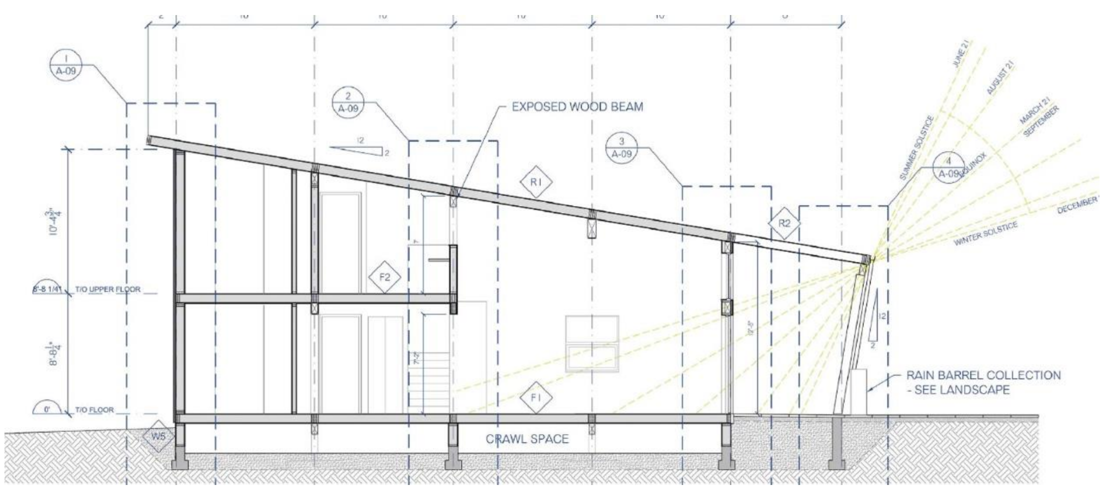


Figure 2. 16: Section of north-south of Prototype house. (Li et al, 2018a)

In terms of environmental impact, the MgO SIP construction produced more carbon emissions than the stick frame construction due to the transportation of MgO sheathing from China and the processing of the OSB, which was added in the life cycle assessment. Further, Lopez & Froese (2016) this study presents a comprehensive analysis of the costs and benefits of the two main construction methods in the prefabricated homes category: panelised and modular. The main goal is to provide a framework of the implications and trade-offs of both construction methods for single family homes, as well as determine which is more cost effective. The methodology consists of a qualitative analysis that includes the overview of the benefits of each construction method over the other, and quantitative analysis which compares the cost of the finished homes per square foot to determine which one is more cost effective. Both analyses are conducted by evaluating two case studies of single-family homes with similar characteristics, one built with panels and the other with modules. The benefits identified for panelised homes have to do with transportation, equipment and machinery, and insulation technology; on the other hand, the benefits for modular homes are related to quality control, on-site work, and trades. The quantitative results showed that the modular construction method is only marginally more cost effective than the panelised construction method under the given circumstances. As a second part of the quantitative analysis, the panel case study was calculated as if it would be built with modules, and the results of both analyses were consistent, but both with the same limitations. Through the proposed method, it is possible to evaluate the cost effectiveness of the two construction methods for single family prefabricated home projects which could serve as a valuable tool for decision making, Lopez & Froese (2016) found that the hypothetical Modular house was marginally more cost-effective than the panelised MgO house in this particular case study.

2.4.3 The impact of climate change on the housing sector in the UK.

The majority of people living in the developed country spend most of their lifetime indoor. Several studies have emphasised the amount of time the people in the UK spend indoors (Schweizer et al., 2007; Vardoulakis et al., 2015), as more than the average UK population spend 96.5% of their time indoor. Also, the climate change directly impacts the indoor environment. With the high rate of occupancy, mitigation measures have been placed in the housing industry in the UK to combat carbon emission without the compromise of thermal comfort.

In the UK, the air temperatures have increased at a steady rate of 0.25°C per decade, with a projection of an increase during summer time of a mean daily maximum temperature (Lowe, et al., 2018 - National Climate Projections, 2018). The UK houses will suffer from overheating due to higher temperature of the heatwave with poor ventilation system and design, which causes building to overheat, especially in the main cities where Urban Heat Island (UHI) effect is prone to intensify—for example, people from London have reportedly suffered from uncomfortable hot homes since 2013 based on the Zero carbon home report. In the UK, the average death between 2013 and 2017 was reported to be around 40,000 people (Natasha Rustemeyer & Mark Howells, 2020), although it was estimated 2000 deaths yearly based on (UKGBC, 2021) report.

The journal by Natasha presented a direct relation between the mortality rate and heatwave. Since the climate change tends to create more heatwaves in the future, an effective and adopted design policy need to be placed such as the implementation of passive or mechanical cooling system in the design to serve the extreme situation. Although the relationship between mortality rate and heatwave was evident in the research, the results presented were mostly associated with vulnerable people; however, these parameters can assist in developing a holistic model that is fit for the future. The mitigation measures of improving the building design to meet the efficiency standards, such as efficient mechanical systems for adequate ventilation, passive cooling, and airtight envelope, can reduce the environmental impact and provide thermal comfort. In 2014, the total carbon foot print in the UK was reported at 821 $MtCO_2e$, and 42% of that was from the built environment and 22% from EC and OC (UKGBC, 2021). Adaptation and mitigation have been implemented in the built environment. There is a collective effort from all sectors in the economy to reduce carbon emission, especially in the building sector since there are many opportunities of reduction than other industry. In the built environment, building regulations which have been studied require a rigid implementation to reduce the GHG.

The main cause of climate change is the excess amount of CO_2e trapped in the atmosphere caused mainly by burning fossil fuel, contributing significantly to heatwaves, drought, and flooding. An energy strategy of a total reduction of energy consumption in building can also reduce the dependency of importing energy and promote local investment in sourcing the extra energy requirement from green solutions. Applying these methods of reduction would result in two major environmental effect: a reduction in GHG and fossil fuel pollution. There are multiple efforts to enforce the energy efficiency in building using building regulations, rules, and certifications. Given the long-span life of buildings, energy used in residential building consumes the most, particularly space heating/cooling, as they comprise almost 75% of total building energy demand.

Hence, building codes regulated the energy efficiency requirements based on the building function. In the case of residential building are sets of building elements that once improved to the current energy efficiency standards that contributed significantly to the overall energy reduction in the building. In a study conducted by (Jens 2008) and where building envelope becomes the parameter in energy saving, these measures present an energy specification for classified as energy efficiency building, they specifying the U-values of walls, roof, floors and window and calculated based on ASHRAE as follows :

$$U_{overall\ value} = U_{ceiling} + U_{wall} + U_{floor} + 0.2 * U_{window}.$$

The strictest overall U-value was found in Sweden, where the overall U-value was close to 0.70, followed by Denmark, where the overall U-value was 0.77. When compared to Passivhaus building regulations, the total U-value has half of this value, which is closer to 0.50. Conversely, based on the ASHRAE U-value calculated as stated above, the MgO SIP's overall U-Value calculation had even lower values than the strictest countries in Europe. The SIPs House's overall value was close to 0.60, making it the closest model to Passivhaus building regulations.

Furthermore, the path to combat the carbon reduction in the residential building was not limited to the thermal productivity of the envelope but has also investigated the possibilities of achieving even lower energy results that are compatible with Passivhaus building regulations, such as the Zero net energy building and Zero carbon building. The main difference between them is that the Zero carbon building produces its own energy using clean technology to produce electricity to supply its demand, and the Net Zero building could rely on fossil fuel for energy use with the ability to offsite them creating neutral carbon. In recent years, there has been more emphasis on following zero carbon building regulations, as they have examined the most efficient measures to reduce carbon emissions to zero through the following (Laustsen, 2008):

i. Reduce energy demand through design.
ii. Reduce the need for cooling by shading or another passive design.
iii. Supply homes with highly efficient mechanics and home appliances.
iv. Supply the remaining energy requirement through renewable resources.

Zero carbon homes (London Environment Strategy, 2020) also suggest the use of smart appliances and battery storage for renewable energy, along with the use of efficient building materials to improve overall energy performance. To understand the future behaviour of the UK residential sector, an investigation of the MgO SIPs House was conducted in the three timelines of 2030, 2050, and 2080.

Moreover, based on the literature, it is evident that the building environment, especially the housing sector, consumes much energy, and the road to reducing carbon is by applying energy measures to the building. Building codes that regulate energy consumption and envelope specifications, along with encouragement to use renewable energy, have shaped a new typology in the building sector. These design parameters come with many obstacles, especially the existing building, where reservation and building conditions are far more complicated to upgrade, but in recent years, the design concept of retrofitting has become more popular in the country since there are more than 29 million existing homes in the UK that need to be energy efficient, and based on the carbon emission reduction plan of 2050, all residential buildings new and old must meet the carbon budget of zero carbon. Based on the current demand for building new homes, another challenge is faced by the industry, where they have to deliver faster home, but with energy efficiency standards. The building regulations are a method in which the government can identify how much energy each household has; however, with no specific guidance to the type of building structure, this provides a more challenging task to choose from. In this research, the SIPs Houses were tested in the current weather scenarios and in the future, and in both timelines, the thermal properties of the envelope and energy consumption were examined carefully, and the results demonstrated a promising energy model of a residential building under the UK weather climate.

2.5 Summary

The effort to reach better performance standard in the built environment is the current notion to combat the rise of climate change, with current trend of the housing stock and simultaneously meeting the national agenda to meeting net zero by 2050 a collaborative work has been advised. To fulfil the government target of nZEB/ZC by 2050, a series of efforts and collaborations need to be initiated like the refurbishment of the existing housing stock to reach better performance rate. The importance of addressing the current energy situation and following the carbon road map for the UK is directly related to the context of this research. A clear understanding of energy efficiency in the housing sector through using MgO SIPs as an MMC will enable the transition from the traditional method of dwelling construction to innovative building methods and sustainable development.

Builders, designers, and homeowners will face several challenges in meeting the net-zero requirement if they do not adapt to the new construction regulations; thus, they need to decide whether or not MgO SIPs construction would be the right solution to meet the requirement. The objective must be to make new homes self-sustaining through minimizing energy consumption and limiting the burning of fossil fuels for energy through adopting renewable energy sources instead.

A real-world case study of an MgO SIP house will be beneficial in assessing the carbon footprint of these modern innovative panels, as limited information is available regarding the construction of MgO SIPs houses in the UK. It will also help end users make better choices in the initial stage of home design. If MgO SIPs indeed prove to be the best envelope for houses, they will transform the construction industry and assist the government in reaching its net-zero carbon emissions target by 2050. In turn, government incentives for using MgO SIPs in construction can support the manufacture of these panels to reduce carbon emissions.

The following chapters of this dissertation focus on the research method selected for this study, data collection methods, thermal and energy monitoring measures and tools, thermal model creation in a simulation programme, and validation. Further, a comprehensive discussion on model optimization is presented. In order to identify how the key design features of and materials used in the house contribute to its energy performance and carbon emission, the case is compared with nZEB and net-zero carbon building regulations and Passivhaus standards and analogies are drawn. Furthermore, energy simulation tools are used to identify parametric modifications and solutions to optimize the model in terms of comfort, energy efficiency, and carbon reduction to meet the national target of net-zero carbon emissions by 2050.

Chapter three: Research Methodology

3.1 Overview

The present chapter explains the research methodology adopted to test the research hypothesis and answer the research questions. Thus, it outlines and discusses the research framework, including the rationale for the research method selected, selection of a case study and weather data files used, construction methods and materials used in the energy simulation program to evaluate the nZEB/NZC standards under the current and future weather scenarios. Moreover, the chapter discusses the data collection procedures and measuring tools used to evaluate and validate the process. Finally, it provides a description of parametric analysis used in the research to improve the overall energy and thermal performance in the current and future weather three timelines.

3.2 Research method.

3.2.1 General research framework

This section aims to describe the research method used throughout this study and outlines the strategy integrated in every section of the research. This research follows the quantitative approach paradigm because most theory testing was based on numerical data of operational research and or system analysis from a whole building energy simulation program that provides energy indicators such as energy supply and demand, thermal performance that are accurate and reliable measures(Crawley et al. 2006; Dominković et al. 2022). (Please refer to Figure 3.1)

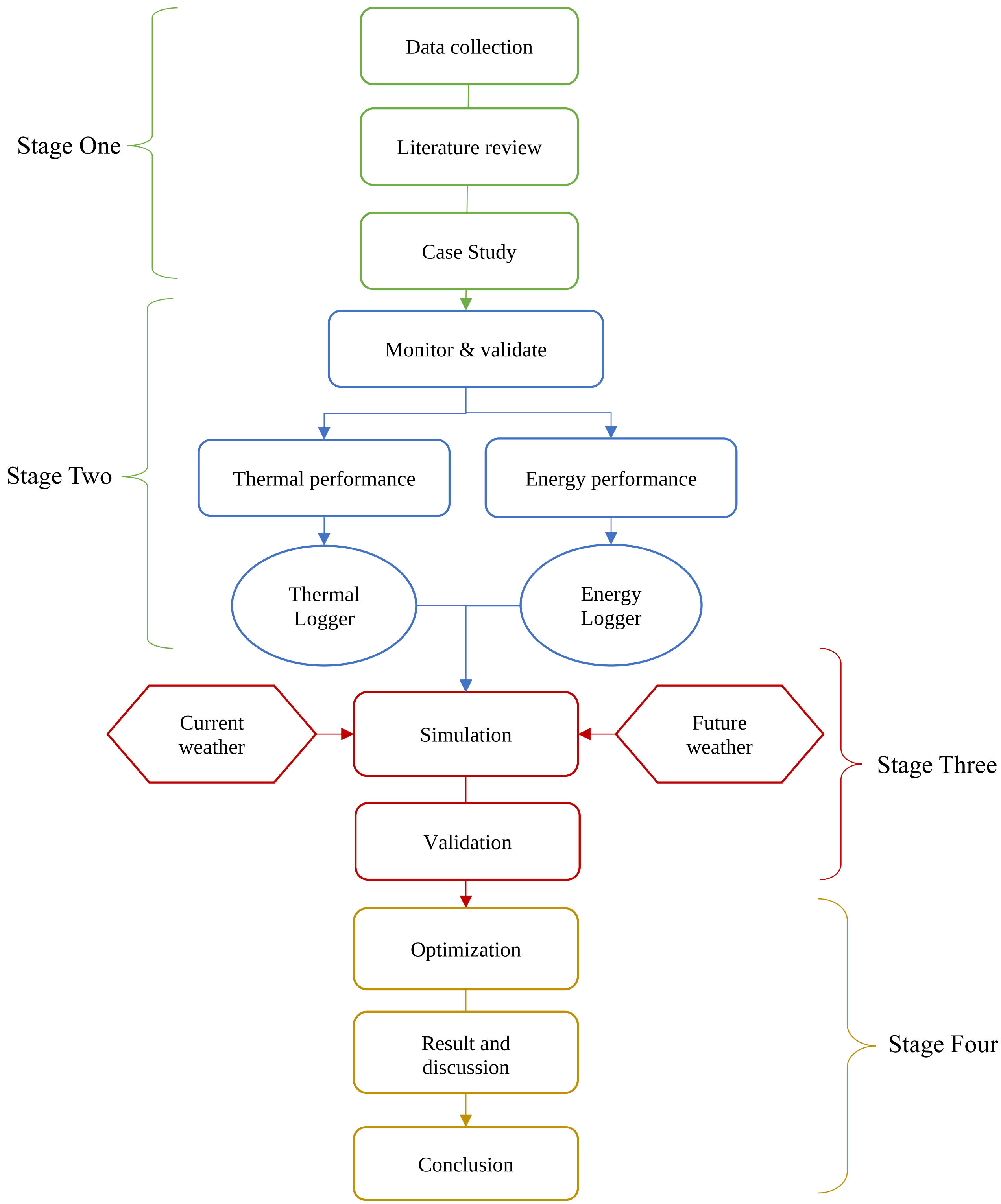


Figure 3. 1: Overarching general methodology of the research

There are several research limitations and disadvantages associated with choosing a qualitative research paradigm, such as not being able to control the variables, which the author will discuss further in chapter 4. Furthermore, most of the research investigation tool was based on a thermal simulation program to assess the performance of the case study against the nZEB/NZC energy requirement.

3.3 Research tools and methods

The main research methodology adopted for this research was based on a computer-based simulation program, DesignBuilder, which produces numeral outputs that are related to assessing the nZEB/NZC standards and regulations in relation to the case study. The research method was created on compound measures and steps by selecting the case study; selecting reliable on-site measurements tools, thermal and energy simulations; quantifying the energy uses of the case study; evaluating the current and future weather scenario; and finally, model optimisation.

The research steps and method selection are as follows:

1. Selecting an existing case study house made with an innovative building material as part of MMC located in the Heswall, Northwest England.
2. Selecting suitable weather files for the exact location from nearby stations.
3. Selecting suitable on-site measuring tools to record the thermal and energy data.
4. Creating a 3D thermal model in DB by selecting the location, orientation, building material, mechanics of the house and occupant schedule.
5. Monitoring energy consumption through an on-site measuring tool and recording indoor and outdoor temperature and relative humidity.
6. Assessing the low-energy building standards in the UK, including nZEB/NZ, and Passivhaus, in the current and future timelines.
7. Simulating the model under future weather scenarios based on climate change.
8. Conducting a parametric study for the base case, referred to as the SIPs House, to identify the main components of energy consumption and create an optimum model based on the parametric recommendations.

3.3.1 Building simulation tool

Computer-based modelling is an essential method to evaluate the overall performance of a building based on the method of construction and material used because this is an important step in abating carbon emissions in the country. As stated above, there is an urgent need to reduce CO_2e from the built environment based on the UK's national agenda and current statistics. Furthermore, to assess the efficiency of the built environment, many virtual and manual tools have been used. Since developers often model the thermal and energy performance of buildings to meet long-term energy targets and building efficiency by estimating the annual energy consumption and monitoring the indoor thermal comfort, this process leads to an assessment of the study boundaries, which includes monitoring heating demands that are provided by the mechanical plants and the delivery of natural ventilation to maintain an adequate level of indoor comfort (COPSE, 2012). Adopting thermal modelling allows designers across all disciplinaries to benefit from the predicted results and use them in their interpretation.

Building Energy Modelling (BEM) is a tool for evaluating the overall energy and thermal performance of a building. The dynamic simulation is based on algorithm modelling of the heat transfer process. The development of BEM focusses on performance analysis, which is based on the energy used, energy cost, temperature and relative humidity, and these indicators are the products of server inputs. Therefore, the steps to develop a model in BEM require specification inputs, such as the following: 1) the building's construction data and thermophysical properties, 2) exact orientation of the building, 3) absolute location, 4) HVAC system input and heat plants, 5) occupancy and household operational schedule and 6) a compatible weather file (Harish & Kumar, 2016). In the effort to minimise carbon emissions and test the efficiency of a building's fabric, hundreds of BEM tools and software programs have been developed by individuals and companies that provide users with additional building performance indicators, such as indoor thermal comfort and carbon emissions (Abo Issa, 2018; Crawley et al., 2006).

Over the past two decades there has been a growing interest in the field of BEM among researchers, a research by Dominković et al. (2022) analysed 12,182 publications from around the world, the research was based on location, type of study in the field of BEM, type of journals, number of institute and number of collaborations. The result indicated that China and Denmark have the highest slop of number of publications and USA and UK has the highest number of collaboration work, which indicate the importance of the study in different disciplines such as energy saving, engineering, economics, and environmental science.

Furthermore, one of the most recognised energy modelling tools is EnergyPlus. EnergyPlus is a building energy simulation program to model heating, cooling, natural ventilation, and lighting. It builds on the most popular features and capabilities of BLAST and DOE-2 and is integrated in the user-friendly graphical interface of the DB, a program that is commonly used for energy simulation and is licensed by the University of Liverpool. The program provides important information at different stages of design to evaluate the materials used and their impact on the design intended. Computer-based modelling and simulation is the best practice not only in calculating the current operational energy and evaluating the overall thermal comfort but also in providing future prediction of the building performance once it is combined with future weather files. Nonetheless, there are plenty of discrepancies between the simulated result and existing performance of a building, which is called a performance gap, and this means that there will certainly be discrepancies between the modelled energy demand and actual measured consumption of energy, such as electricity or gas.

Using energy simulation tools presents certain limitations and challenges, especially in simulating energy demand calculation. The post-occupancy energy calculation in the simulated model has a program-specific algorithm that provides specific results based on the input by the user rather than real data. Moreover, in previous studies by Askamiji (2015) & Bertagnolio (2012), the researchers investigated the discrepancies between simulations and true results in a building; they estimated and presented the boundary gap, which must fall between 10% and 30% for the results to be valid. The uncertainties can be reduced if a reliable tool is selected along with methods to regulate the boundary of forecasted outcomes. Designers and architects have been using BEM tools to help them develop the most effective and energy efficient building design, and the rise of popularity of such tools has forced the industry to continue developing and improving the BEM tools for the end user. Furthermore, after the introduction of building ratings like BREEAM and LEED, many designers and engineers have found the BEM tools useful to predict, modify and execute designs based on the new building regulations. According to Attia & Carlucci, (2015), eQuest, DB and IES-VE are the programs most commonly used by architects and designers; each delivers specific performance outcomes based on the design requirements. In the same research, a survey was conducted where engineers from different disciplines had to select the best tool to deliver accuracy and ability to simulate detailed and complex building components. The results indicated that DB is the best to work with (see Figure 3.2).

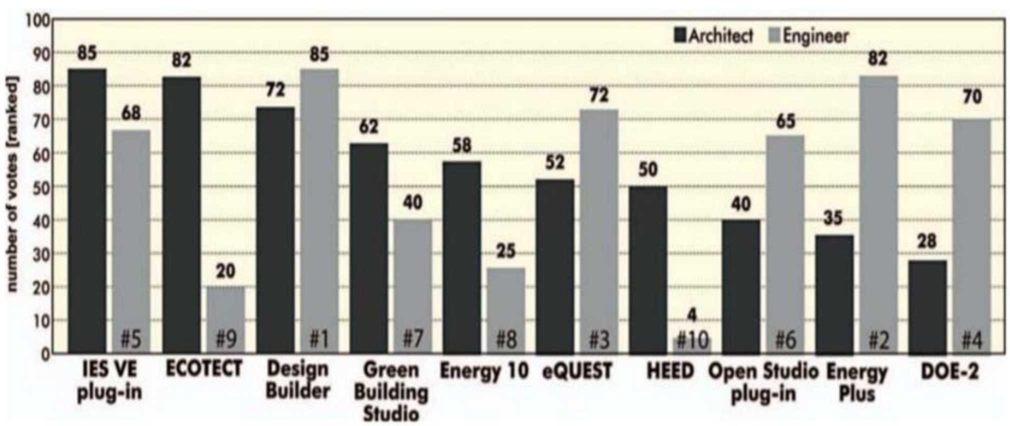


Figure 3. 2: Design builder ranked #1 among 10 BEM tools according to architects and engineers' votes. Source (Attia., et al,. 2015)

DesignBuilder is an integrated simulation tool that was developed in the UK that employs the EnergyPlus simulation engine; the EnergyPlus was developed by the US Department of Energy, and it is widely accepted and reliable for thermal and energy simulation (Abo Issa, 2018). DB has been selected as the most advanced building simulator in the industry because of its user-friendly interface, metrological database and sophisticated model to evaluate energy supply based on internal heat gain and external solar supply. The software can also generate the heating and cooling demand throughout the year, separating summer and winter design preferences. These are the evaluation tools this research required to enable the assessment of the case study model (Tronchin & Fabbri, 2008). Furthermore, the program can evaluate the future performance of the case study house and eradicate any performance gap because of its ability to generate reliable data; the program precision analysis is backed by a level of detail that is required as an input, for example, the schedule and occupancy option. This allows the user to accomplish the following: 1) produce an accurate model, 2) account for seasonal conditions, 3) retrieve flexible of results, 4) produces hourly and sub-hourly results and 5) simulate simple and advanced mechanical systems (Abo Issa, 2018; Giordano et al., 2015).

Because of its advantages, the DB program was selected for this research to produce a virtual model (3D) and simulations. DB has commonly been used among researchers at the University of Liverpool; the software program was introduced in the university to provide researchers with introductory learning exercises along with a DB platform that provides an ongoing learning hub. In addition, the online learning forums and face-to-face option on campus allowed an easy transition to learn the program and implement in the research. Therefore, the main investigation approach for this research is based on 3D thermal dynamic simulation to assess the current and future performance of the case study under the nZEB/NZC standard. The research method is built on complex and interrelated steps that began with finding the gap in the literature review, selecting the ideal case study, monitoring thermal and energy usage, simulating the results to validate the model, running future weather scenarios, and finally, optimising the current base case.

3.3 The selection of an existing case study house

To identify whether MgO SIPs are capable of meeting nZEB/NZC requirements under the climate change agenda, a single detached house was selected in Heswall, Northwest England, as shown in Figure 3.4. The house is a two-storey building built in 2016, and it was constructed using MgO SIPs; therefore, the SIPs

House was selected to investigate the overall fabric performance under the current and future weather scenarios. The SIPs House was selected for investigation by the DB to answer the research main question and justify the research hypothesis. MgO SIPs represent an innovative, advanced building material in the SIPs industry; one of the main manufacturers in the United Kingdom is Dragonboards Ltd., it is a small to medium-sized enterprise based in Northwest of England, and it is the supplier of SIPs panels across Scandinavia, France, Ireland, the United Kingdom, the Middle East and the Far East. To replicate the same house in the 3D thermal modelling program, several building criteria were selected to ensure accuracy and persistence in the design, including building size and architecture details, location, orientation, occupancy rate and occupancy profile.

3.3.1 The MgO SIPs House

In this research, the case study is referred to as the SIPs House. The SIPs House was built using MMC, and the entire house was built by MgO SIPs, including the roof, exterior and interior walls, and floor. Other materials, such as steel, glass, aluminium, insulation, glulam and uPVC, have also been used in this method of construction (see Figures 3.3, 3.4 and 3.5 for location and building specifications). The house has two floors; the ground floor consists of an office, utility room and open plan kitchen and family room, whereas the second floor has a large master bedroom with bathroom. The house is occupied by retired couple and has a total floor area of 92 m^2. Details are given in Table 3.1.

Table 3. 1: SIPs House building specification.

Building specification	**SIPs House**
Gross floor area	$92m^2$
Building orientation	Entrance from East and West elevations and majority of glazing is facing south
Occupancy density (m^2/ # people)	46
Year of built	2016
Floor	2
Building materials	MgO SIPs

The main reason the SIPs House was selected for the research was to evaluate the construction materials used in the house by testing the research hypothesis, which is that the SIPs House's method of construction is sustainable and can meet the nZEB/NZC standards by 2050. The evaluation process involves testing the fabric efficiency rate under current and future weather scenarios. The second reason for selecting this house was the availability of the house to conduct thermal and energy performance tests via on-site and off-site measuring tools.

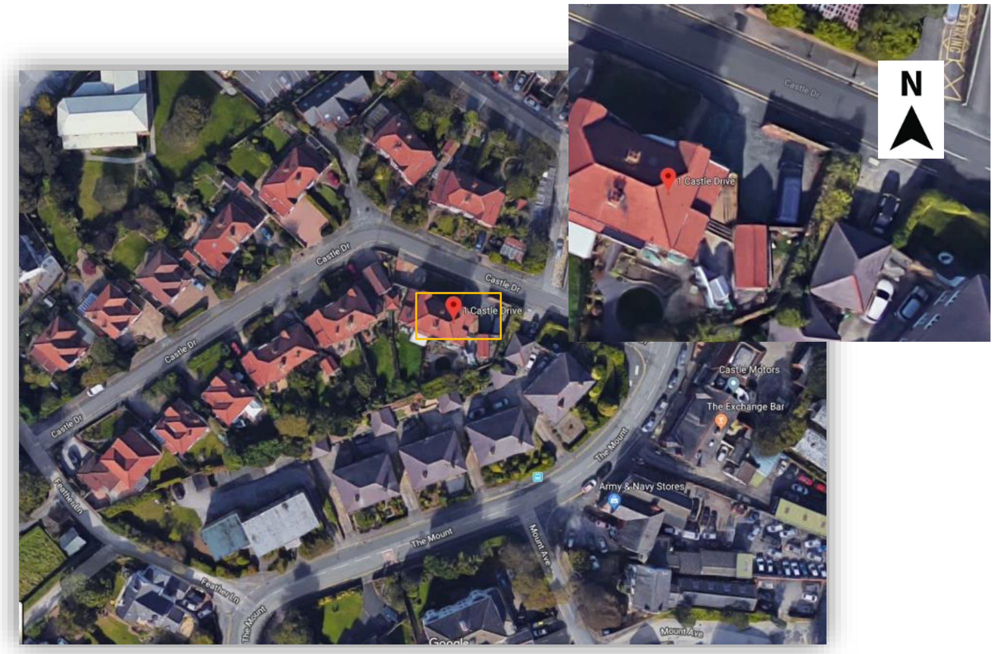


Figure 3. 3: SIPs House aerial location within the Heswall suburb area.(Google map)

Figure 3. 4: Front elevation photograph of the SIPs House.(by Author)

Figure 3. 5: Floor plans, elevations, and section of the SIPs House.(by Author)

3.3.2 Selecting suitable weather data

In this research, to analyse the energy consumption in the current and future weather scenarios, it is vital to obtain the climate conditions of the building, which consist of outdoor air temperature (referred to as dry bulb temperature) and relative humidity rate based on geographical location. In terms of its location, Heswall is a small town in Wirral in the county of Merseyside with a latitude of 53.32 North and longitude of 3.09 West (see Figure 3.6).

Figure 3. 6: Location of Heswall town

Predicting building performance in terms of energy consumption and thermal comfort has become increasingly important in the built environment for projecting and planning purposes (Mark et al., 2008). Building Performance Simulation (BPS) is an integral part of assessing and planning building performance, and most engineers in the United Kingdom use BPS tools, such as DB and Integrated Environmental Solutions (IES). The weather files are available in most of the programming tools, they provide common weather files of almost every metropolitan city around the world; however, it should be noted that they do not cover all cities, which makes it challenging to find every location. In addition, the weather data provide important information about the climate conditions that affect the energy and comfort level of the indoor environment. The weather parameters has multiple variables such as air temperature, solar irradiance, cloud cover, precipitation, wind speed and more (Cox et al., 2015). The availability of weather climate information is useful for estimating future energy consumption at a given location; therefore, it is necessary to obtain the corresponding weather files of Heswall city.

BPS tools require site-specific hourly weather data to perform accurate building analysis in the simulation phase. Weather files represent observation of temperature and relative humidity at any given location. The set of data also includes dry bulb, web bulb, solar radiation, wind speed and wind direction. There are weather file formats designed for each region; for instance, the International Weather Year for Energy Calculation (IWYEC) developed by ASHRAE is commonly used in the United States, and the Test Reference Year (TRY) which was developed by European Commission and Design Summer Year (DSY) developed by CIBSE weather data are both are commonly used in United Kingdom and Europe. These files do not present the average data of a specific time in year; rather, they give a sample of real weather data (Cox et al., 2015).

The most commonly used weather file is EnergyPlus Weather (EPW) Data and Typical Metrological Year (TMY3). The files can be downloaded from several websites; they are available free of charge from the EnergyPlus website or can be accessed via commercial websites like *Meteonorm* (Meteonorm, 2020). *Meteonorm* is an advanced metrological weather file generator; it generates accurate and reliable weather files of any given location, with a database of more than 8000 stations around the world and monthly, daily, hourly and minute-level time intervals (Meteonorm, 2020).

The future weather data prediction in *Meteonorm* is based on the published Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES; IPCC, 2000). The emission scenarios in the report are grouped into the three following categories: B1, low emission; A1B, medium emission; and A2, high emission; (Gerald A et al., 2007). For example, A1B includes the following criteria: 1) rapid economic growth, 2) a global population that reaches 9 billion in 2050 and then gradually declines, 3) the quick spread of new and efficient technologies, 4) a convergent world where income and way of life converge between regions, 5) extensive social and cultural interactions and 6) A balanced emphasis on all energy sources (IPCC, 2000). Which scenario to use for the future is a contentious issue, and some have argued that using the worst-case scenario should be considered when designing resilient development fit for the future harshest weather conditions (Gupta and Gregg, 2012). In contrast, others have suggested that the worst case may not happen,and investing in the built environment for the worst case might be unnecessary; therefore, the use of the average projection will result in more feasible development. UKCP09 recommends that all three emission scenarios be considered (B1, A1B and A2).

This research uses the following weather files to test the research hypothesis:

1. Current weather file extracted from the Meteonorm program.
2. Future weather scenarios for 2030, 2050 and 2080 with A1B (the balanced approach).

Meteonorm software version 7.0 was used to acquire a present-day weather file and future weather files in EPW format, and four timeline's slices were selected under A1B medium emission for the future (2019, 2030, 2050 and 2080) and the current year (2018). Meteonorm typically generates weather files in TRY format, which can later be converted to EPW as DB-readable files. The files were converted using Elements software, which is available online for free under Bigladder. Elements is an open source software tool used to create and edit weather files (Elements, 2021). Another reliable software program was used in this research to visually represent the data and analyse the current and future weather scenarios of Heswall, which was the Climate Consultant 6.0 software.

Climate Consultant 6.0 is a graphical-based visual tool developed by the University of California, Los Angeles (UCLA) Energy Design Tools Group. It is readily available for free download through the UCLA website. Climate Consultant provides a visual representation of an annual 8760 hours of climate data in EPW format. Similar approaches were used by (Abuhussain, 2020; Khalfan, 2017) to obtain the current and future weather data for a given city. The Climate Consultant tool also provides psychometric data to examine indoor comfort level with a representation of design guidance on how to obtain indoor thermal comfort. In this study, the program is used to visually represent the current weather of Heswall, which indicates the summer and winter high and low temperatures (see Appendix 1.C for current and future weather files). The current and future weather files were generated in Metronome and later converted to EPW format via elements software for use in Climate Consultant, and the data were used to project 2020, 2030, 2050 and 2080 climate change scenarios.

Another future weather study was intended to be conducted in this research to understand the high and low probabilities of climate change effect using the PROMETHEUS project. The project aids in releasing future weather files for more than 45 locations and two emission scenarios in the United Kingdom (previously only three cities in the United Kingdom), which can be used to predict how built environments will perform in the future (Robinson, 2021). The hourly weather data of DSY and TRY are available under low, medium, and high emission scenarios with different probabilities of occurring represented in percentiles of 10, 33, 50, 66 and 90. Because of the lack of availability of Heswall future weather files in the program and the closest city was Liverpool, the weather files for Liverpool were initially used to conduct the future weather studies. However, it was found that there are differences between the humidity and temperature between the city of Liverpool and Heswall because of geographical location of both cities, the results indicated that the temperature of Liverpool were presented higher than Heswall as presented in Figure 3.7 for the whole year and Figure 3.8 and 3.9 present the hourly temperature and RH% on 17 December 2018, it was found that the daily temperature differed between 2.2^{o}C 3.1^{o}C and in midday hour the difference in temperature was reported 5^{o}C higher in Liverpool than Heswall, also the maximum temperature reported in Liverpool was 6.74^{o}C and Heswall 5.1^{o}C on the same date. The minimum temperatures between two cities had a difference of 1^{o}C, also the monthly mean temperature present a difference of around 2^{o}C as presented in Table

Table 3. 2: Monthly average temperature of Liverpool and Heswall

	Mean temperature °C	
Month	Liverpool	Heswall
January	4.18	3.2
February	2.7	3.4
March	5.7	4
April	8.3	5.7
May	11.5	9.6
June	14.3	11
July	15.7	13.1
August	15.72	13.5
September	13.58	12.2
October	10.2	8
November	5.7	6
December	4.13	3.8

The RH% in Both cities reported a difference of around 12% on the same day with maximum RH% reported of 99% in Liverpool and 87% in Heswall, and the daily mean of RH% was 91% for Liverpool and 74% for Heswall. therefore, it was decided not to conduct this study any further. These discrepancies will be relevant in the outdoor temperature validation process and indoor, as a result, the current weather files of Heswall from Meteonorm software version 7 were used to analyse the building performance and thermal comfort in the DesignBuilder, and the future scenario modelling will be conducted to evaluate likely future performance.

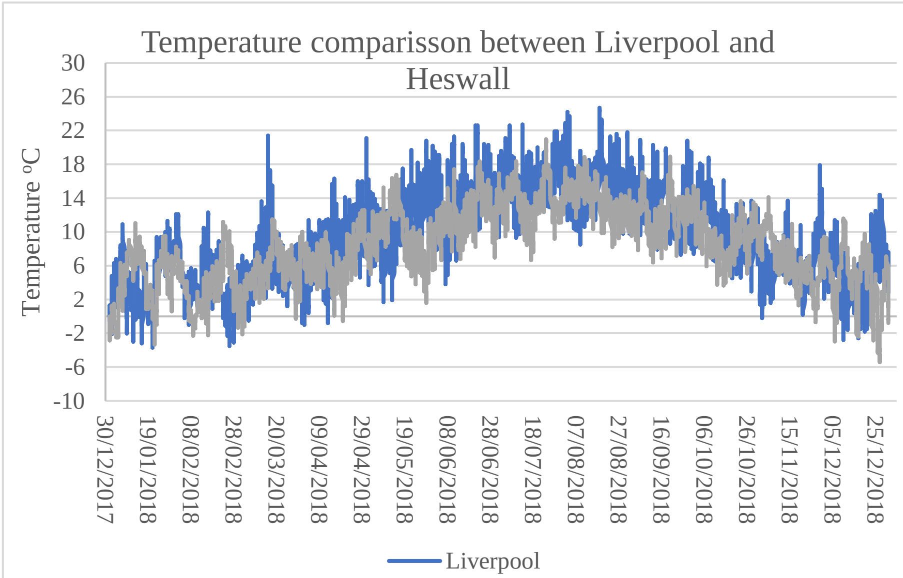


Figure 3. 7: Liverpool and Heswall hourly temperature comparison.

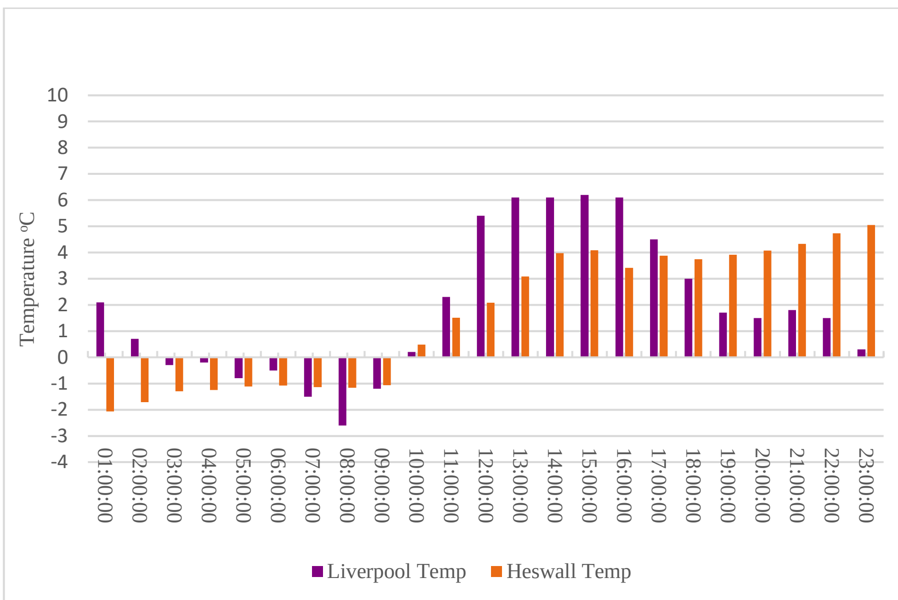


Figure 3. 8: Hourly temperature of Liverpool and Heswall on 17 Dec 2018.

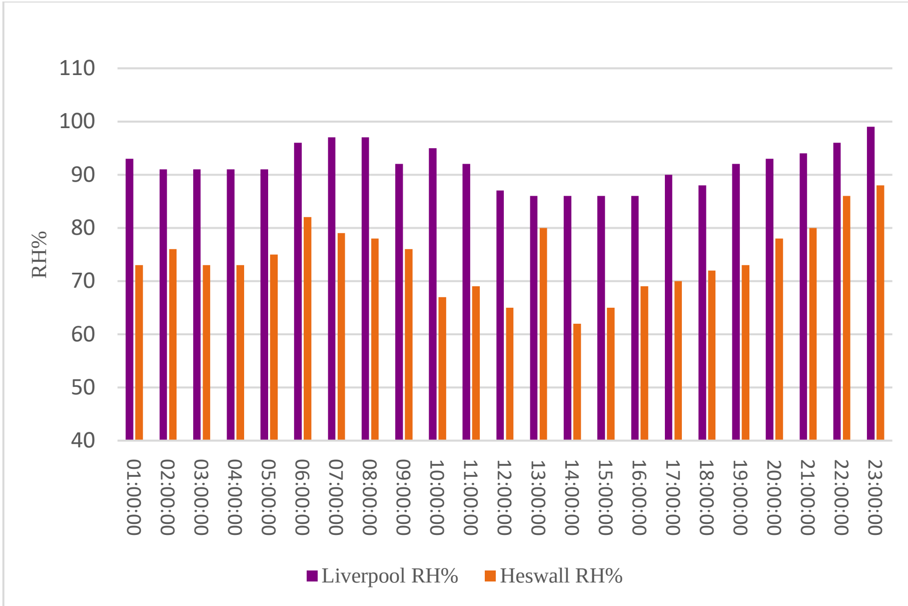


Figure 3. 9: Daily relative humidity rate of Liverpool and Heswall on 17 Dec 2018.

3.4 Monitoring system

On-site measuring tools can bridge the performance gap by providing detailed thermal and operational data that can be utilised to assess an existing building or plan for future improvement (Mahdavi & Taheri, 2017). With the current norm of industry to investigate energy performance, the relatively low prices of measuring tools assist wider investigation by designers and researchers (Santin, 2011). Furthermore, the performance of a building can be measured using data loggers that transmit the required data through the internet via Wi-Fi connection and energy loggers that are connected directly to the building electrical meter. For this research, energy performance and indoor thermal comfort were investigated. The energy performance consumption was obtained from the main meter in the SIPs House via a Wi-Fi transmitter, and the indoor thermal comfort was investigated through on-site monitoring and three standard comfort models.

3.4.1 Data logger: Temperature and RH% data logger.

With rapid development in electronics hardware, on-site and offsite measuring tools have become more available and easily accessible by many. In this research, the author has used Lascar EL-Wi-Fi loggers, with EL-Wi-Fi-TH temperature and relative humidity sensors as indoor data loggers (see Figure 3.6). They can measure temperature in a range of -20°C to +60°C and relative humidity (RH) in a range of 0% to 100%. The loggers have an accuracy level of ±0.3°C (-40°C-80°C) and ±2% RH (20%–80% RH) and any recording above 90%RH will result a change up to -5%RH. Data are uploaded periodically every half an hour using the standard Wi-Fi network to the Easy Log cloud website the sensors were powered by battery and it can be recharged via a PC, USB +5V wall adapter or portable USB battery pack (Filesthrutheair, 2018). Moreover, while the building's appliances switched off during winter hourly temperature calibration was conducted between the indoor temperature and Design builder model by using the data loggers at hourly interval. In this study, the data loggers were placed in in four rooms approximately 1.2 metre high, away from direct heat and direct sunlight, as recommended by the manufacturer. Moreover, free-standing sensors were placed in kitchen/living room, office room, master bedroom and bathroom. The location of each sensor is presented in Figure 3.7, and six months of data recording presented in Figure 3.12. The external data logger was placed in the backyard under the decorative stone wall shelter away from the direct sunlight and rain. TinyTag Plus2 with reading between -40°C to +85°C, it was selected to measure the air temperature and RH% for the outdoor weather condition on every half an hour interval, the logger is powered by lithium battery that can last up to one year and the data were stored in the USB (See Figure 3.7 and 3.8). Moreover, The website provides csv file formats for reading the recorded data, and the author converted the data into excel documents (xlsx) format.

Figure 3. 10: EL-WiFi-TH WiFi Temperature & Humidity Sensor model.

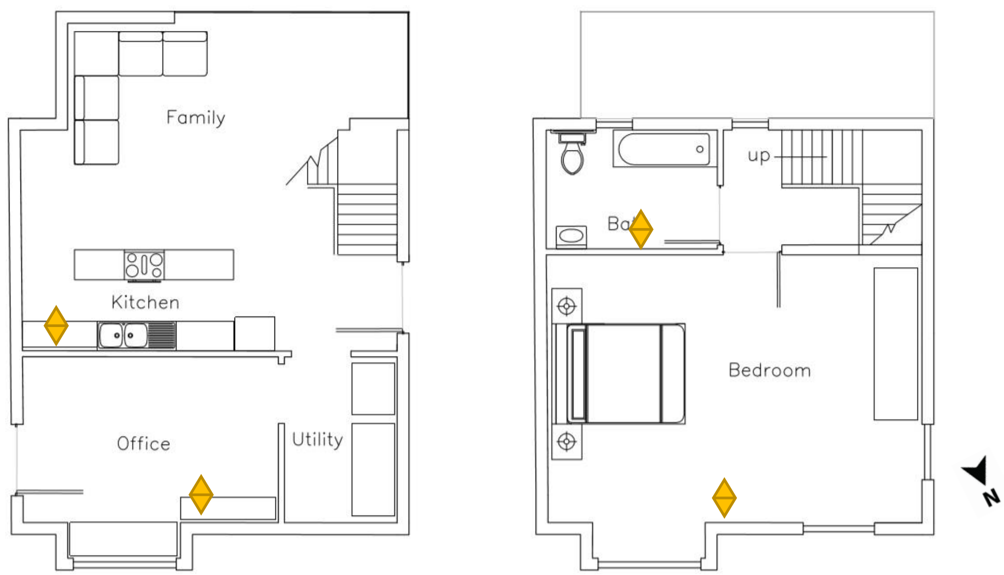


Figure 3. 11: Placement of data loggers in each room of the SIPs House (by Author)

◆ = The Data logger placements

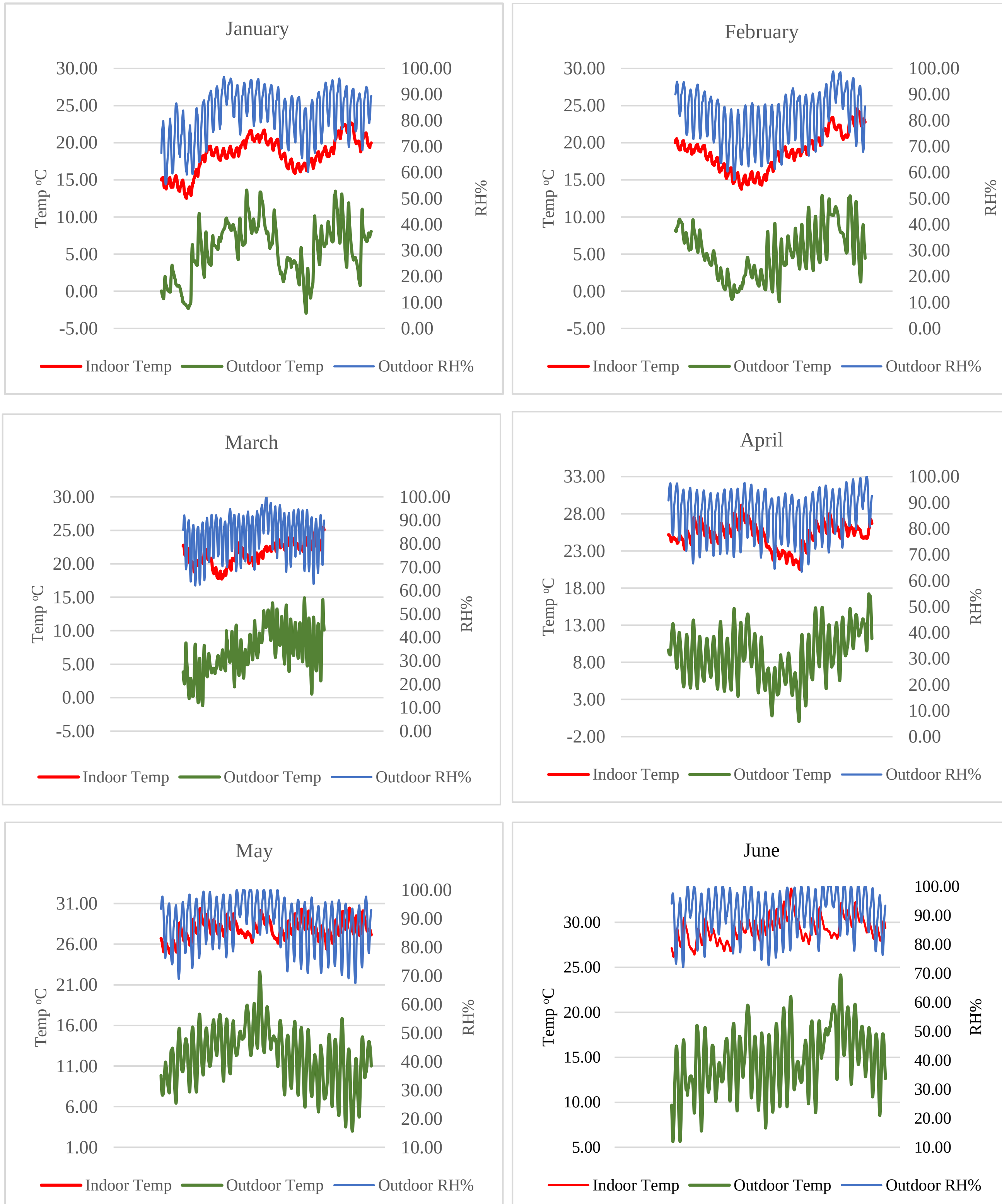


Figure 3. 12: Six months temperature and RH% recordings of indoor and outdoor.

A simple comparison of logger precision was carried out during the wintertime when the house’s appliances switched off, all loggers were placed within the same environmental condition to avoid any discrepancies, and this comparison indicated that the data loggers appear to present close accuracy similar readings to one another (see Figure 3.13).

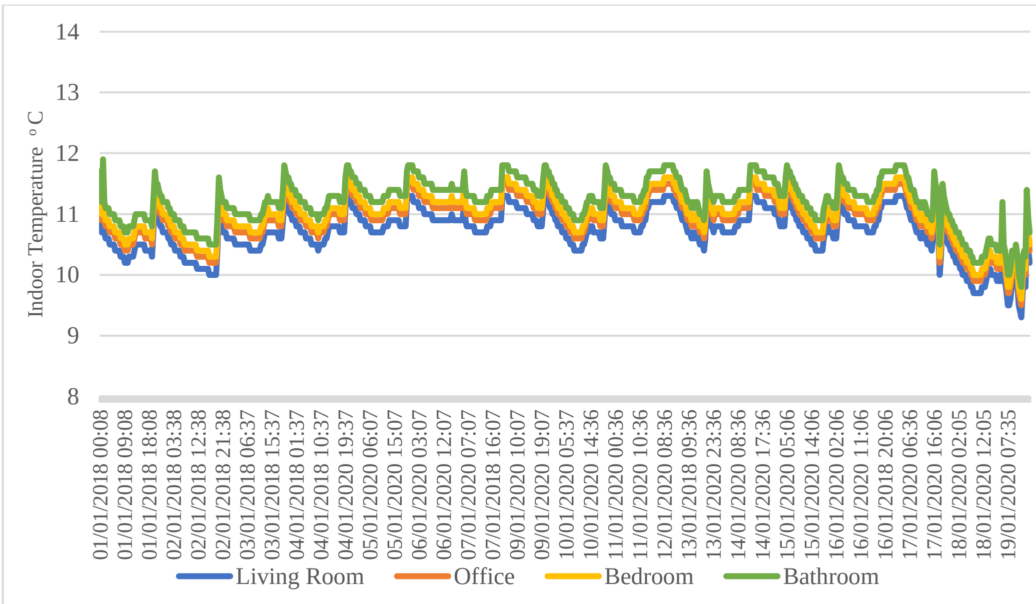


Figure 3. 13: Temperature data logger calibration

Figure 3. 14: Outdoor data logger (TinyTag)

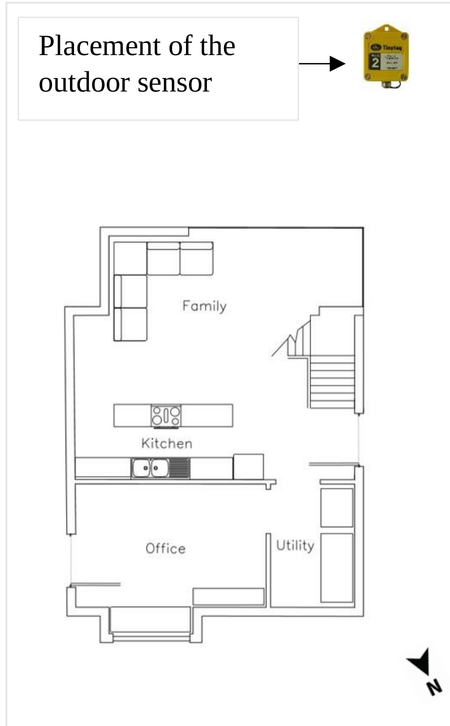


Figure 3. 15: Data logger placement outside the SIP House.

3.4.2 Energy logger – Efergy energy

The results of energy recording over a period can quantify the energy used by the building because it is one of the indicators to building efficiency. Energy monitoring also predominantly focusses on the energy consumption issues surrounding the physical properties of buildings, such as the building envelope and thermal comfort (Shiel et al, 2018). The energy output can evaluate the energy consumption based on the fabric properties and the level of durability of the construction materials to maintain a certain amount of thermal comfort at a given level of energy consumption. Therefore, energy monitoring is a crucial part of this research and requires detailed analysis of the usage by physical monitoring of the electricity supply. In this study, the energy use of the SIPs House was calculated via an energy sensor called Efergy (see Figures 3.10 and 3.11)

Figure 3. 16: Energy efergy sensor

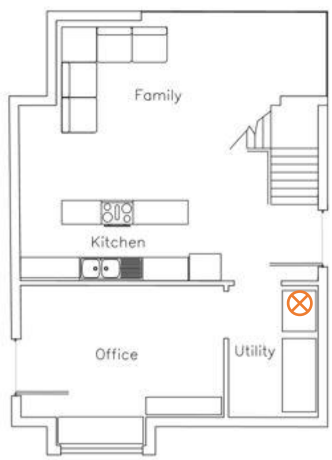


Figure 3. 17: The physical location of the energy sensor in the house on the ground floor

⊗ = The Data logger placement

The energy logger is connected to the main electric supply of the house, which means the energy sensor can only measure the total amount of electricity used by the SIPs House. As there is no disaggregation of the data received, it possible to sub-meter all electricity consuming elements in the house, but due to their physical placements it was difficult to place them, and it will cause a lot of disruption to the end user if changes were made to place them. The SIPs House is completely powered by electricity, a grid connected with no gas supply. The next section discusses the thermal comfort of the SIPs House, and its relation to energy saving is discussed in detail in chapter six.

3.5 Thermal comfort

Thermal comfort has always been the focal point in energy efficiency homes. It is defined as the '*set of mind which expresses the satisfaction of air temperature in an environment*' (ASHRAE, 2017; Ferrari & Zanotto, 2012; Taleghani et al., 2013). The Indoor temperature of houses in the UK have been reportedly increasing during the summer and creating increase concern in the built environment. Specially that the UK has been experiencing heat waves which can cause life threating caused by high indoor temperature (Tabatabaei et al., 2015). With a growth response to climate change and the need to mitigate the rise of CO2 emissions, the UK government has implemented building regulations to meet the national agenda of NZ by 2050. The enforcement of building regulations has led to creating building that are highly insulated to prevent heat loss and save energy since improving building fabric standards is the key to reduce carbon emission, but at the same time they are prone to suffer from overheating without proper ventilation system. Overheating is a major concern in modern construction, and long-term monitoring study is a tool to identify wither or not the use of modern method of construction like the MgO SIPs are suitable for future or not. Several guidelines have been establish including CIBSE guide A, Schneider thermal model and Passivehaus summer comfort design, they have set boundaries of overheating in residential buildings, for example CIBSE guidance has temperature limitation in different zones in the house, and Passivehaus summer comfort design has temperature boundaries based on the total number of uncomfortable hours in a year and lastly Schneider thermal model presents a temperature and RH% threshold. Therefore, thermal simulation modelling and on-site data measures, such as provided in the SIPs House, can identify the overheating parameters and risk associated with highly insulated walls (Haddad et al., 2017). In this research, Schneider thermal model and Passivehaus summer comfort design was selected to assess the overall thermal comfort of the SIPs House.

3.5.1 Passivhaus summer comfort design (Overheating)

In the context of climate change and global warming, indoor thermal comfort has been a key problem in nZEB/NZC buildings. Although energy standards and benchmarks have been developed to evaluate the summer comfort level, the outcome is still debatable (Dartevelle et al., 2021). In addition, in recent years, a growing body of evidence related to overheating during summer in energy efficient buildings has emerged as a result of the pressure to meet the current climate change agenda, where all buildings need to have an airtight envelope to reduce the primary energy demand. This phenomenon is especially evident in new airtight buildings like nZEB/NZC and Passivhaus (Fletcher et al., 2017); this is because the main goal of creating airtight buildings is achieved by increasing the wall insulation level to reduce heat loss, and consequently, reduce carbon emissions. Since the SIPs House was designed to be an energy-efficient dwelling with an airtight envelope, it was necessary to assess the fabric performance during the summer using the Passivhaus summer comfort design because it provides detailed numerical boundaries to evaluate thermal comfort.

The Passive House Planning Package (PHPP) for summer thermal comfort sets out a maximum temperature threshold and its frequency over 1 year, providing the amount of total uncomfortable hours in ratio format over 365 days, where $T > 25°C$ (= Tmax) for more than 10% annual occupied hours. Whereas meeting the 10% target is mandatory to achieve the Passivhaus certification, the guidelines recommend that the frequency of overheating should not exceed 5% to guarantee high summer comfort in a changing climate (Hopfe & McLeod, 2015; Passivehaus Trust, 2016).

3.5.2 Climate Consultant software

Climate Consultant is free software developed by UCLA, and *Climate Consultant* 6.0 is the latest release version (previous version 3.0), which is compatible with Microsoft and Mac OS computers. The program can read EPW files, and it reads 8760h/year from almost all the weather stations around the world. Moreover, it provides graphic climate details for a given station and design suggestions based on the location's weather conditions. Thus, many researchers have used this software; (Khalfan, 2017) implemented *Climate Consultant* strategies in research on the hot climate of Qatar, whereas (Milne et al., 2006) used similar study method in the cold climate of Cleveland in the United States to perform weather analysis for a residential building. *Climate Consultant* provides a list of climate variables, such as the temperature range, relative humidity, wind direction and solar radiation, and on top of this, it provides the user with graphical charts called psychrometric charts, which are useful for comparing the weather conditions with the comfort level. The Graph in (Appendix 1.D) presents a list of design strategies based on the location given in a chart format. Based on the psychrometric design, any building in Heswall can achieve a level of 100% comfort if the displayed design strategies are applied.

In the displayed graph, the design strategies are given a percentage representing the total comfort level, and the factor contributing most to thermal comfort is the heating demand, where it contributes 60.7% to the total thermal comfort in a year. The internal heat gain of lights, people and appliances contribute 32.4%, which counts for 2834 hours in a year. One of the strategies to effectively and passively reduce heating demand would be a passive solar design strategy. Placing all glass windows to the south is suggested to maximise the sun exposure during winter and provide overhang in the summer to prevent overheating. Passive heating involves 2834 hours per year that a house can passively benefit from. *Climate Consultant* suggests in a cold climate zone if a building was provided heating and reduced the consumption of heating through passive solar gain and internal heat gain, 100% comfortable hours could be achieved.

The focus of this chapter is to give the results for the total energy performance of the SIPs construction in the case study, and the thermal comfort analysis is a supplemental tool to assess the envelope performance. Therefore, investigating the level of comfort in the SIPs House was necessary to link it to the envelope performance under the current and future weather scenarios and determine how they behave differently. A detailed analysis is presented in the next chapter, the Discussion chapter. The next section presents the results of the envelope performance based on DB simulations.

In this study, thermal comfort measurements are obtained by monitoring indoor and outdoor temperature and indoor RH%. The scope of the research defines the parametric boundaries in terms of the duration and time of spot recording. The outdoor variables are dry bulb, air temperature, wind speed, relative humidity, solar radiation, and perception. The variables are recorded by outdoor fitted sensors and manually placed in a safe location at the backyard under a decorative wall, because they can be prone to damage in harsh weather conditions. Moreover, questionnaires and surveys are found to be usual tools to assist in the thermal comfort evaluation when possible; however, in this research, most data depended on the data loggers and monitoring measures because the main scope of the research comprised energy usage. Given the timeframe of this study, conducting a comprehensive thermal analysis would not have been possible.

In this study, the monitoring phase was divided into two periods. The first monitoring period lasted from April 2017 to March 2018, but the data were deleted due to technical problems in the SIPs House; this caused major delays in the validation process of the house. The second monitoring period begun in mid-2018 and continued until February 2020. The data from the loggers were able to provide synchronised readings of the temperature and relative humidity in each room. The placement of the sensors is crucial for recording accurate measurements, and based on (Santin, 2011), the best placement is by hanging them somewhere away from any surface that could jeopardise the actual readings. However, the owners of the house did not want to hang the loggers from the ceiling, preferring to keep them on a top shelf in each room for visibility ussie. The next section discusses the energy standards in nZEB/NZC building, such as the energy requirements presented in kWh/m^2/year, the envelope efficiency requirements and other energy generation benchmarks. Moreover, it sheds light on other energy efficiency standards in the United Kingdom, including ZCH and Passivhaus building standards.

3.3.4 Assessing the nZEB/NZC energy and other low energy standards in the United Kingdom.

Once the indoor measurements are in place, and data collected satisfied the duration period of the course, the dataset collected on a daily basis can create a baseline for the energy consumption in the SIPs House, so that the real monthly energy consumption of the house is clarified. This process is crucial for assessing the energy performance of the SIPs house under the current and future climate change scenarios. Once the 12 months of electricity consumption in kWh/m^2/year was established, the results were assessed against the current nZEB/NZC energy requirement implemented by the UK government, which aims to decarbonise heating systems and power in residential sector through strategic building regulations as defined by Department for Business, Energy & Industrial Strategy (2021) and LETI, (2020) for residential building and compare the results with other similar low energy building standards in the United Kingdom, such as the ZCH and Passivhaus. As presented in Table 3.2, a comparison between the three major energy efficient buildings is displayed in the form of energy and fabric requirements. The table presents the numerical values of each standard and the minimum or maximum allowances to be classified in these labels. The numerical boundaries are crucial for this research because they set the current and future energy and fabric standards of energy efficiency building like the nZEB/NZC and Passivhaus. As a result, the research will be evaluated under the context of the three major energy efficiency building standards—the nZEB/NZC, ZCH and Passivhaus.

Table 3. 3: Energy standard requirements

Requirements	nZEB/NZC (European Commission 2012; LETI 2020)	ZCH (LETI 2020)	Passivhaus (Passive House Institute, 2015)
Energy (kWh/m^2/yr.)	44	35 (Heating 15)	<120 (Heating <15)
Fabric U-Value (W/m2. K)			
Walls	0.18	0.13–0.15	0.15
Windows	1.3	0.80	0.80
Roof	0.16	0.10–0.12	0.15
Floor	0.18	0.10–0.12	0.15
Renewable energy	Partially and/or fully covering the energy requirement'	100% of the energy demand' covered by onsite	Not required

Once the results from the on-site measurements were ready for evaluation, they were compared with nZEB/NZC standards, and the aim of the research is identified by answering the main question of whether the SIPs house is capable of meeting the nZEB/NZC standards by 2050.

3.3.5 Parametric analysis

DB has a feature called parametric analysis. The parametric tab in DB allows the user to define the design criteria and modify them by changing the size, type, model or even the whole design against parametric outputs like the carbon emission or electricity usage (refer to Figure 3.18). For example, energy consumption can be used as study point, it can be measured by adjusting the parameter of the window glazing type. The ultimate type can be defined by the least energy consumption against other options available in DB library. The parametric analysis was used in this thesis to identify the lowest energy consumption by improving the parameters. The process is useful at a conceptual design stage in terms of understanding how a building is affected by design criteria. DB generates a list of iterations to show the response of changing building design to the inputs parameters, such as carbon emission, comfort and the electric load (DesignBuilder, 2020). The building envelope was assessed experimentally, including the exterior walls, roof, ground floor and windows.

Energy evaluation and assessment from the on-site measuring tools were used to identify the total energy consumption for the base year and the results were compared to the actual utility bill of 2018. It was found that the base year energy consumption was below that of the average UK household, according to (Ofgem, 2022) the average UK household with around 2.4 people living in, uses around 3000 kWh of electricity and 12,000 of gas respectively, and further investigation was carried out. In terms of energy consumption, the assessment required a detailed study of each component in the house and how much energy is needed to maintain thermal comfort throughout the year.

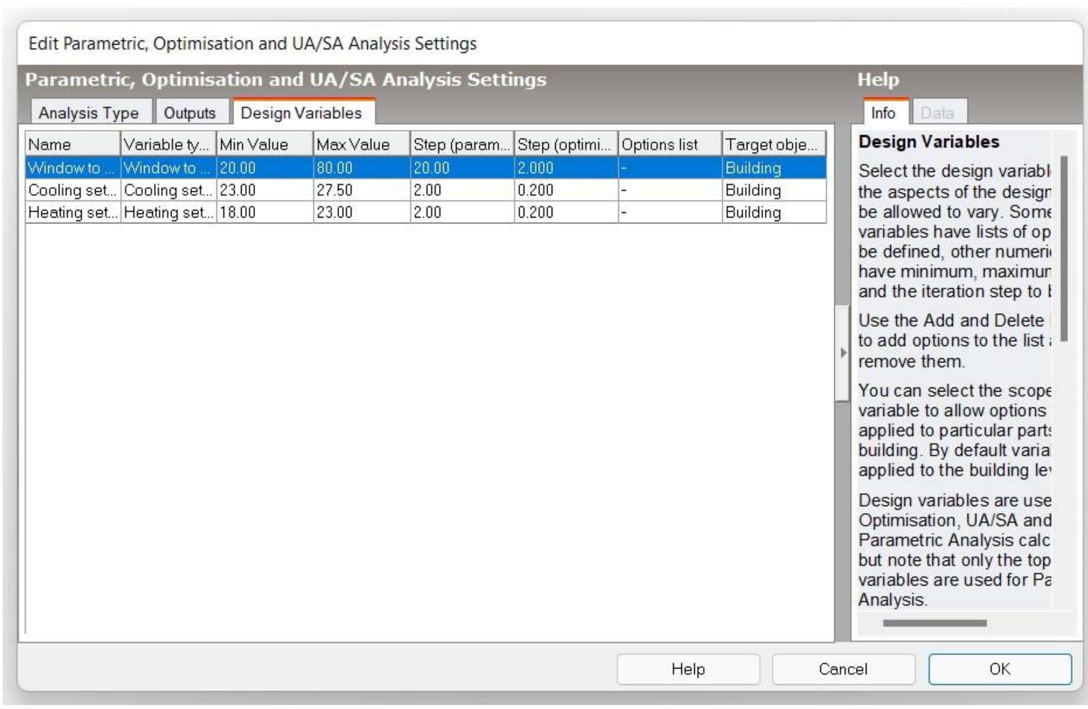


Figure 3. 18: Parametric analysis inputs process in DB

The parametric study was conducted in this research to measure total energy savings because energy reduction is the focus of the national agenda, and the aim of this research is to assess the energy performance of the SIPs House under current and future weather scenarios. The total energy used was the key element considered in investigating the energy consumption in the case study; difference modification was tested in the envelope to test energy saving, The total energy used was the key element considered in investigating the energy consumption in the case study; the number of simulation was conducted based on five dependent and four independent variables, and each was simulated six times, which concluded 72 total simulations in this research.

for example, the process involved, modifying one parameter against other parameters where every other aspect of the base building configuration remain unchanged. Such as, the exterior wall insulation including (MgO sheathing) thickness was increased by 10%-60% incrementally to reach ultimate energy saving results, and at the same time other parametric variables remain the unchanged at the building level, including (roof, walls and floor) which were left unchanged, Also, site orientation, and glazing types were used in the parametric analysis, the primary goal of this section was to investigate and test the ability of the exiting construction material and building mechanics to reduce heating demand and save energy. Each parameter was tested individually while keeping the other parameters constant at the building configuration base case level. Each simulation was conducted in the current and future weather scenarios to assess the ability to save energy through a reduction in heating requirements under current and future weather scenarios. Moreover, the parametric analysis was conducted in terms of future weather scenarios, and an optimum model was designed to achieve net zero carbon emission. The results are discussed in chapter five. The next chapter discusses the creation of the 3D model of the SIPs House in DB, including importing the current weather files, construction materials inputs, heating/DHW and occupant profiles. It also considers the model making and validation process and assesses the performance gap between the recorded and simulated data; finally, it clarifies model normalising through the long-term monitoring process.

Chapter Four: Simulated energy performance and parametric analysis of the case study building

4.1 Overview

This chapter focusses on the steps of developing the energy simulation program (DB). This is done in two main parts. Figures 4.1, depicts the stages of model making and validation. The chapter discusses the development and making of the model in the simulation program, which requires input data from the architectural drawing; site visits to allocate home appliances, including the HVAC systems; and the construction materials used. It this initial stage, allocating the on-site monitoring devices (data loggers) is vital to the study of the building's thermal and comfort behaviour; therefore, six data loggers have been placed indoors and outdoors to monitor the SIPs House performance. Once the model is created in the BIM software (DB), the next stage is to validate the performance of the case study using the measured data obtained from the data loggers and compared them with predicted outputs.

The model making and validation process began with stage three and different parameters were conducted and studied during the simulation process. This began with several inputs from 3D architectural drawings, building orientation, materials specifications, heating and ventilating systems. DB can offer a great range of building materials and mechanical inputs in its library, which is a necessary to enable the program to create a model that replicates a reality. The model provides a simplified illustration of the SIPs House. Stage two described the process of the validation phase. It started when recorded field measurements were used to validate the DB model outputs. This method of comparing real data with the simulated model is called validation. The DB program has been proven to be one of the best energy performance simulation programs in several case studies. Model creation is an important part of model development; once the model is created, it gives the user the confidence to depend on the results and modify them in the simulation phase to create best-case scenarios. Computer simulation programs are the best method to assess the operational energy for current and future design (Oduyemi & Okoroh, 2016; Visitsak & Haberl, 2021a, 2021; Wong & Fan, 2013b); they help designers to predict energy consumption in buildings and assess the building design. They also calculate energy generated from solar panels in the building and analyse the outcome for energy savings. At the same time, discrepancies can occur between the recorded data and simulation data, and these are called performance gaps; however DB has the ability to reduce the discrepancies by filling these gaps, as explained in by Pour, (2017), this issue is discussed in further detail below.

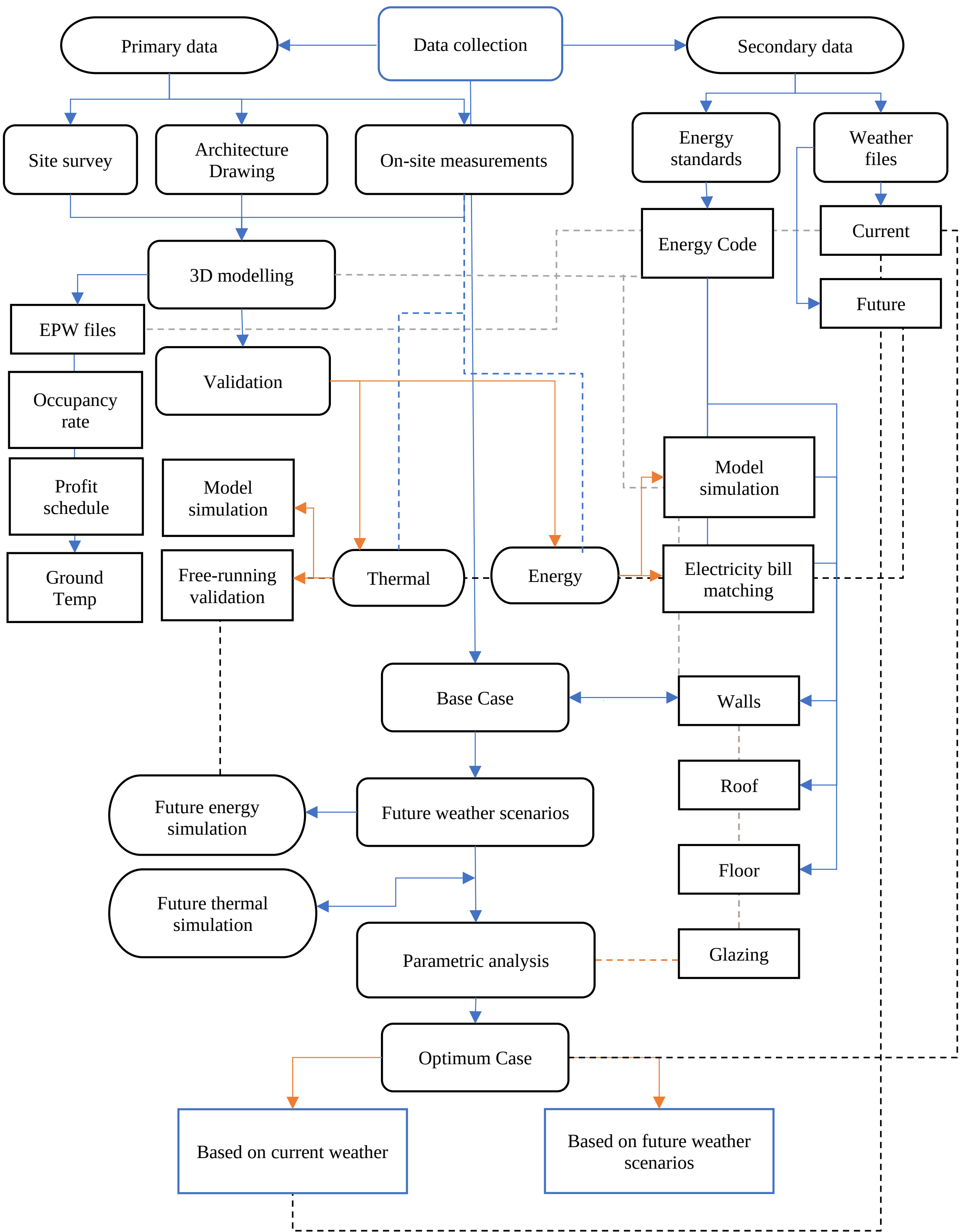


Figure 4. 1: Stage three, Simulation hierarchy

4.2 Input parameters for simulation.6

4.2.1 Architectural drawing

The DB program can support various models of 3D or 2D geometry files, such as from the AutoCAD or Revit programs using the IBM format. The author of this research has used the 2D geometry files from AutoCAD and imported the drawings into DB to create a 3D geometry shape as a replica of the case study. The SIPs House was modelled in DB as shown in Figure 4.2 the model was drawn from the architectural drawing (given by the owner to the author). The drawings were hand drawn, and the author had to create an AutoCAD DXF format to be able to import them into DB. Once the drawings were imported, the building outlines were traced in DB to create blocks and zones; this was done with precise measurements to create the right volumes and heights in each room. The model almost exactly replicated the dimensions of the house in terms of wall thickness; these dimensions of the windows and doors; room sizes and heights; and orientation. The orientation of the house is along a north/east axis with major curtain walls facing south. (See Appendix 1. E) gives detailed photographs of the house.

Figure 4. 2: DB model of the SIPs House

4.2.3 Fabric and construction materials

The modelled house (SIPs House) was constructed with MgO SIPs throughout. Each material requires a defined buildering material component with thermophysical property of every layer. DB has a vast library of construction materials; however, MgO SIPs are well known material, but not much research has been done to investigate their overall potential usages in the built environment as an innovative method of construction. As a result, the author had to create new layers in DB, as shown in Tables 4.2–4.5 and 4.6 and figure 4.4-4.5. To obtain accurate construction materials with thermophysical specifications, the DB and environmental product declaration (EPD) of each component used in the building were investigated carefully in this research to ensure that the information pertaining to the thermal properties of the construction materials was accurate. Thermal calculation for creating new layer in DB is displayed in Figure 4.3, and the construction materials are listed in Table 4.1.

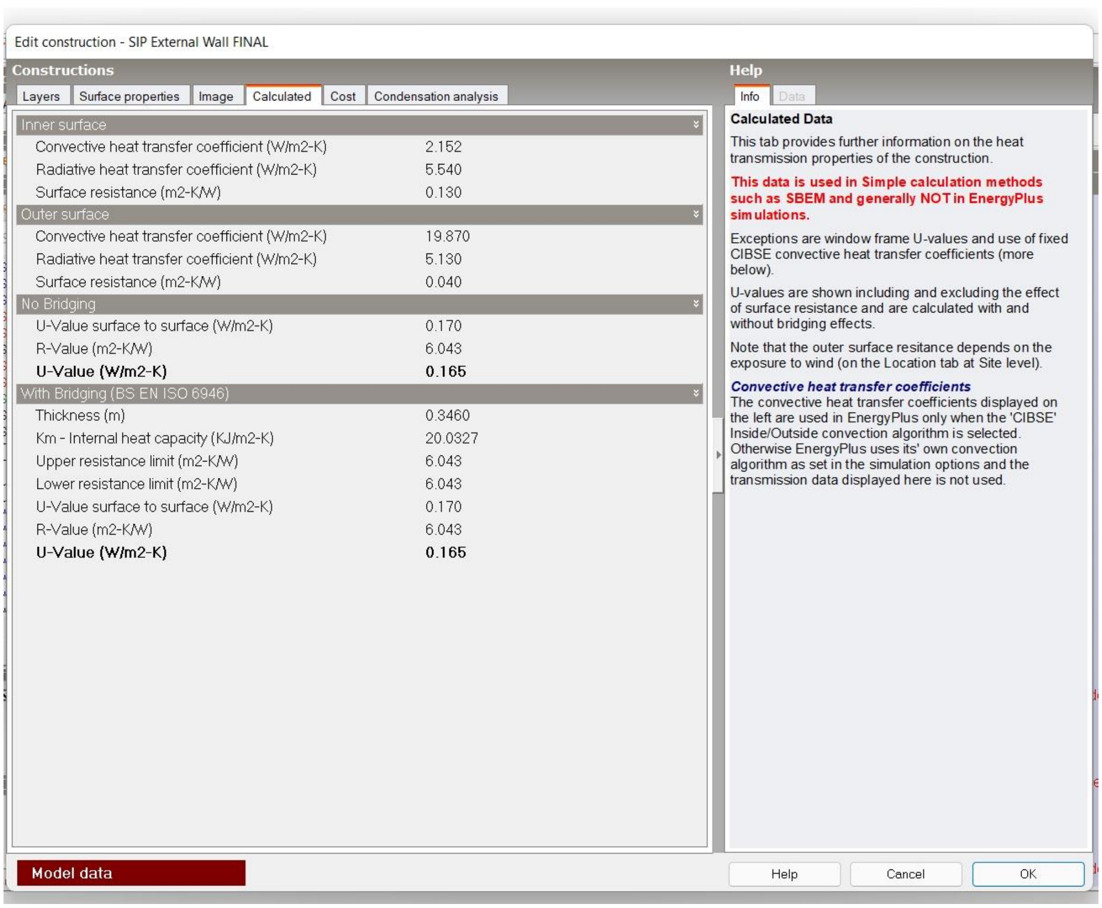


Figure 4. 3: Thermal calculation in DB of creating new component of external SIP wall

Table 4. 1: Construction material detail of SIPs House

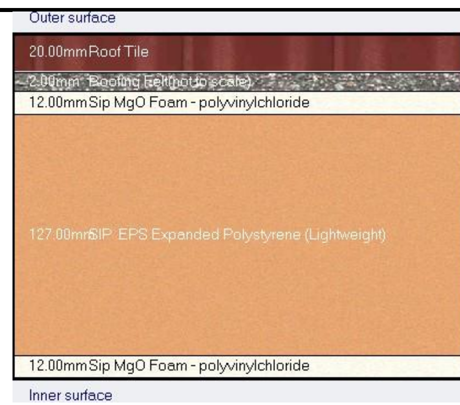
Element	**Construction materials**	**U-value (Wm^2K)**	**R-Value (m^2-KW)**	**Section**
Exterior wall	MgO SIP	0.165	6.06	
Ground floor	Concrete slab and MgO SIP	0.126	7.9	
Pitched Roof	MgO SIP	0.195	5.1	

Table 4. 2: Exterior wall fabric details: Design builder library

Layers	**6 Layers**
Outermost layer 1	Marley Cedral - Fiber cement
Layer 2	Prilux Silicon base render
Layer 3	MgO SIP
Layer 4	EPS
Layer 5	MgO SIP
Innermost Layer 6	Gypsum Plastering
U- Value (Wm^2K)	0.165
Thickness mm	0.346

Table 4. 3: Roof fabric details; Design builder library

Layers	**5 Layers**
Outermost layer 1	Roof tiles
Layer 2	Roofing felt
Layer 3	MgO SIP
Layer 4	EPS
Layer 5	MgO SIP
U- Value (Wm^2K)	0.195
Thickness mm	0.173

Table 4. 4: Ground fabric details; Design builder library

Layers	**5 Layers**
Outermost layer 1	Plywood
Layer 2	Underlay Cellular rubber
Layer 3	MgO SIP
Layer 4	Sand and Gravel
Layer 5	Aerated Concrete slab
U- Value (Wm^2K)	0.126
Thickness mm	0.600

Table 4. 5: Window details; Design builder library

Layers	**3 Layers**
layer 1	Clear 3 mm
Air	Air 6MM
Layer 2	Clear 3 mm
Air	Air 6MM
Layer 3	Clear 3 mm
U- Value (W/m^2K)	0.95

The MgO SIP is not in DB database and therefore a new element was added using the following material properties for the MgO SIP (See Table 4.6):

Table 4. 6: MgO material properties.

MgO material properties	
Thermal conductivity	0.0350 W/mK
Density	37 kg/m^3
Specific Heat Capacity	1470 J/kgK

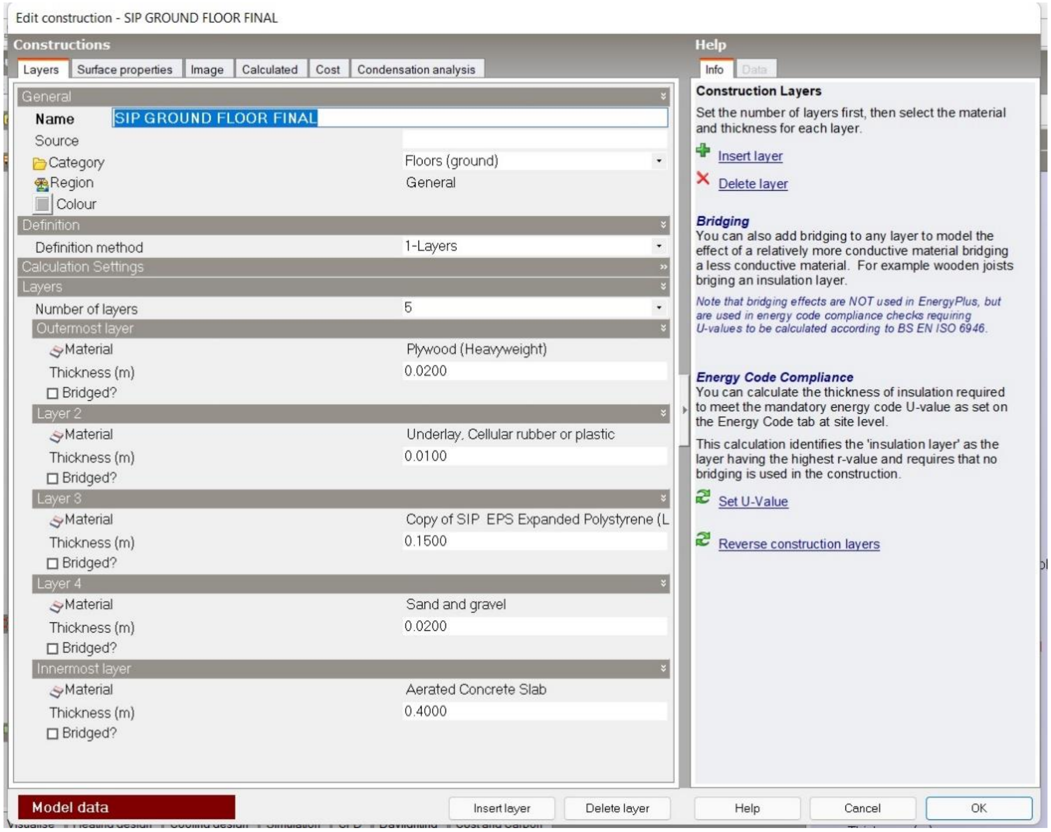


Figure 4. 4: Creating new construction material in DB's library.

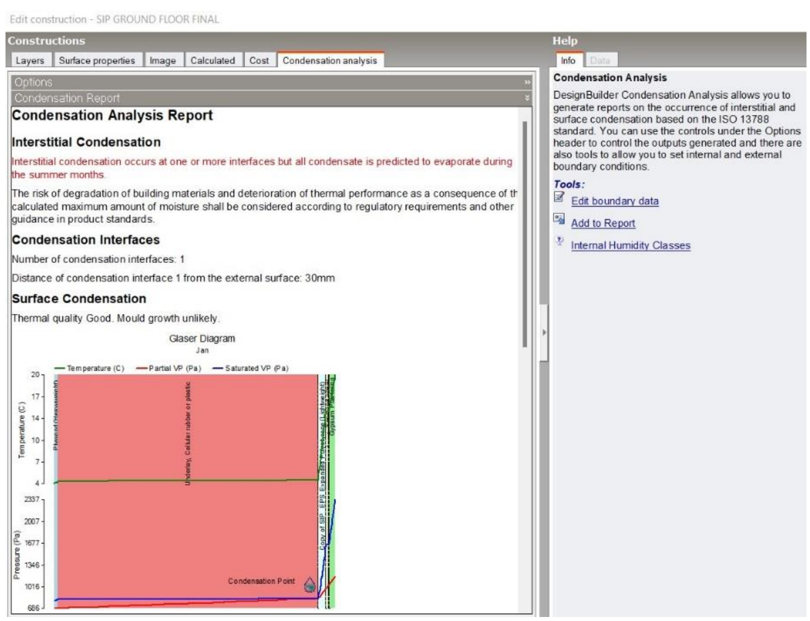


Figure 4. 5: An image of a new construction material surface analysis.

4.2.4 Site visit and survey.

Once the model was created in DB with all the parameters—including creating a new fabric as a component, orientation of the house and allocation of all the openings—a site visit and building survey were conducted as important parts of the validation. These steps provide further details that architectural drawing lacks. A walkthrough of the building to understand the functionality of each room was initially conducted to allocate the right equipment in the zoning section in DB to be able to calculate the heat load. It was also important to define the real size and materials of the opening exactly in DB. In addition, the type of heating and ventilation systems, along with appliances and their designated location, had to be determined. The main objective of the survey was to further understand the building functionality and how it was mechanically supplied.

4.2.5 Heating, ventilation and air conditioning systems and appliances.

The on-site survey aimed to collect inventories of the mechanics and appliances and ensure the right equipment was selected in DB. It was found that space heating and hot water are provided via a 300 L Daikin EKHWP300B hot water storage tank (thermal store) fitted with a 3-kW electric immersion heater, Hot water from the thermal store is pumped via pipework to a post-heater (Figure 4.6), which creates hot air that is circulated to each room of the house, the same water is used for domestic hot water uses in the kitchen and bathroom. Furthermore, when heating is not enough, additional heating is provided by a post-heater which creates warm air that circulated to each room of the house. In addition, the post heater is controlled by a thermostat in the bedroom and a special controller which measures the air temperature and displays heater when there is no air flow. (See appendix 1.F for HVAC).

Figure 4. 6: Electric post heater (Paul Heat Recovery Scotland, 2016)

In addition to the thermal store, a Mechanical Ventilation with Heat Recovery (MVHR) system is used to provide fresh air, extract stale air (while recovering heat) and any necessary additional heat is provided by the post heater. A secondary supply of space heating is provided through a separate 5kW Mitsubishi Ecodan Air-Source Heat Pump (ASHP), located on the ground floor in the kitchen/living room area, the ASHP is separate unit serves the living room and not ducted or piped to other zones. Also, according to the occupants, the ASHP is used infrequently. Once this information was entered into DB along with the schedule, the program could determine the current and future energy consumption, and the DB results could be compared with the measured ones. The results indicated a synergy between the predicted measures and real measures through the monthly electricity bills of the SIPs House, which is defined as the model calibration.

The mechanical system of the SIPs House was created in DB, as the system was not common, it was required to create detailed HVAC system to create similar heating and DHW system that matches the real case. A) hot water thermal store is charged-up (heated) by an electrical immersion heater element (3 kW power) and this runs for typically 3 hours per day (9 kWh per day to charge the thermal store. B) This hot water store provides both domestic hot water (DHW, for baths, taps, etc.) and warms air space heating via a Post Heater, the Post Heater is supplied with hot water via pipework from the thermal store and this provides heat to warm the air in the mechanical ventilation and heat recovery (MVHR) system. As the MVHR gets some of its heat from recovering the heat from within the building then the post heater only needs to run as a top-up to the recovered heat (most likely to happen on colder days). In DB, electric source water heater called (DHW Instantaneous electric) and AHU

(CAV) with heat recovery called DOAS preheat HR was selected to create detailed. (See Figure 4.7 and 4.8)

Once this information was entered into DB along with the schedule, the program could determine the current and future energy consumption, and the DB results could be compared with the measured ones. The results indicated a synergy between the predicted measures and real measures through the monthly electricity bills of the SIPs House, which is defined as the model calibrating phase.

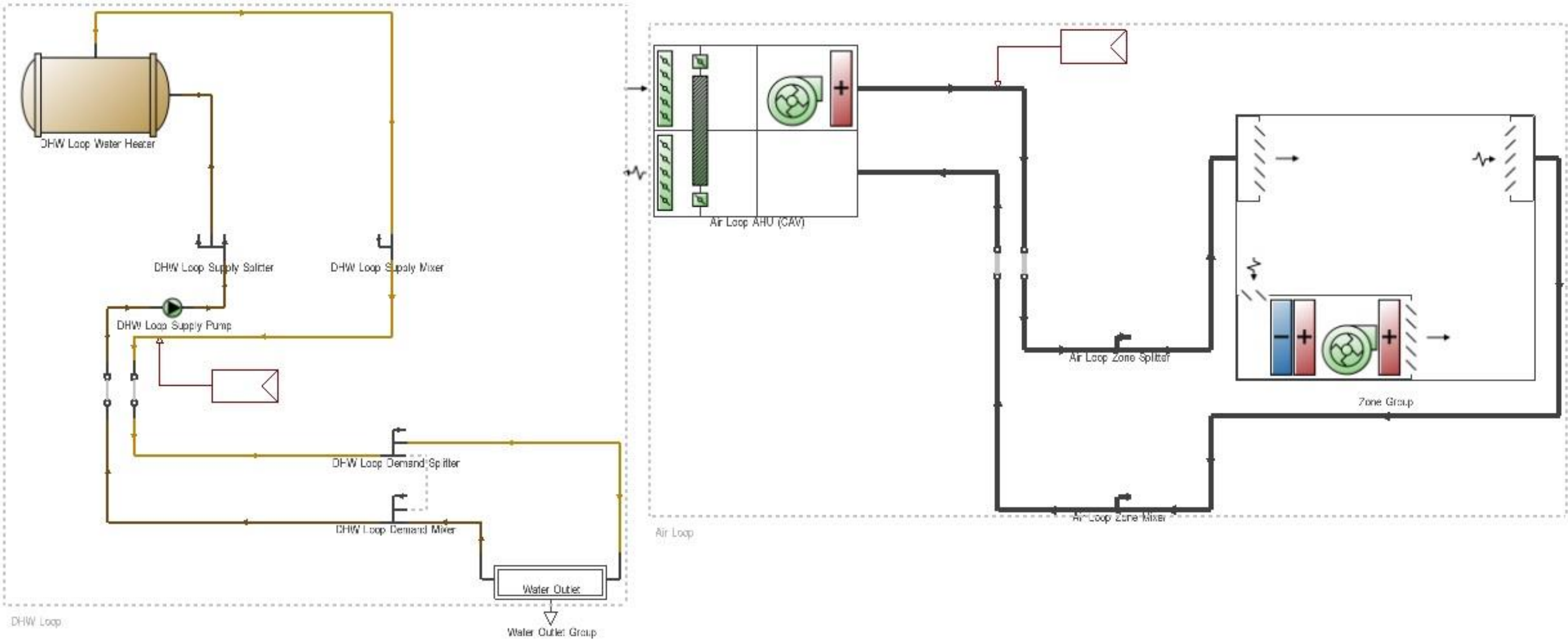


Figure 4. 7:DB detailed HVAC and DHW system of the SIPs House

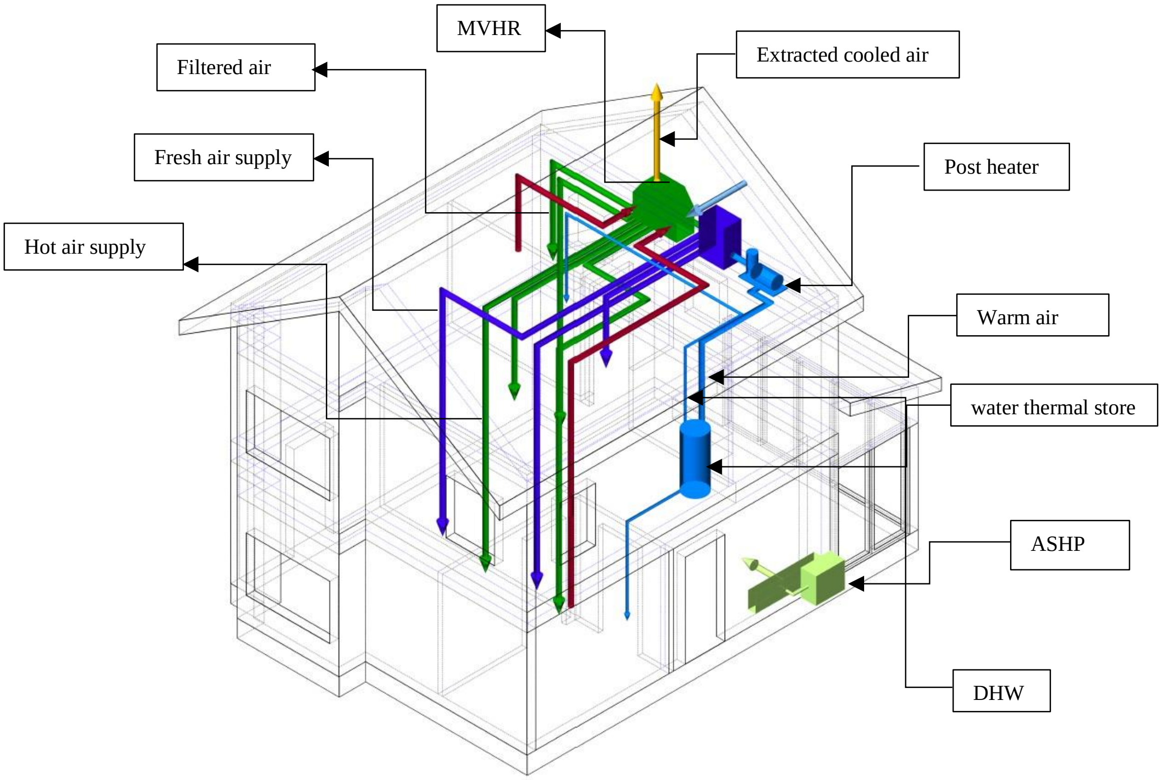


Figure 4. 8: Schematic of the mechanics of the SIPs House.

4.3 Model making and verification

Model validation is the most important step in model development. The validation stage gives the assurance that the 3d model created in the simulation program is a replica of the real model, and this gives the research the abundance of possibilities to create new data and simulations for current or future weather files.

4.3.1 Onsite management

For this research, a wireless data logging and monitoring system was installed in the SIPs House by the author for a period of 12 months. The measurement tools were selected based on the required data from the SIPs House in terms of indoor thermal comfort by recording temperature and relative humidity; indoor and outdoor data recordings at every at 30-minute intervals.

The monitoring period provided the following data:

1. Internal temperature and relative humidity recorded by data loggers placed on shelves in each room at 30-minutes interval.
2. External temperature and humidity recorded by an external data logger was placed outdoor near a decorative wall in the backyard away from direct sun/wind and rain and at 30-minutes interval, data were transformed via USB. Electricity recorded by an energy logger mounted to the main electricity supply in the utility room at 30-minutes interval. And site survey was conducted to identify and estimate the electricity consumption per appliance since sub-metering was not possible.

4.3.2 Temperature and Relative Humidity calibration between recorded temperature and DesignBuilder simulation outputs

The temperature and relative humidity data were collected from a website called filesthrutheair (Filesthrutheair, 2019). The indoor measured temperature was compared to the predicted temperature, (as shown in Figure 4.9–4.12). A sample summer month was selected which is August. The data recorded from the indoor loggers were further analysed to understand the monthly averages, maximum and minimum temperature, and RH%. Furthermore, the maximum temperature recorded that are 30C^{o} or higher which are recorded during the summer months are unusual and likely to be local effect, however the frequency and duration of these peaks are low as the average temperature is good match to Met office see Table 4.6 for outdoor temperature and RH% recorded every 30 minutes please refer to Figure 4.13. Moreover, the author compared the recorded temperature and relative humidity to DB simulations to compare. The results of the predicted and measured temperature presented a slight difference in the simulated result, as there are many reasons for data discrepancy that could influence the results, such as sensor accuracy, influence of radiation of local surface temperature or due to human factor, this anomaly of recording needs to be considered while comparing the real and predicted data; the location of the loggers affected the recordings somewhat because hot air tends to rise, and they were placed on shelves. The recording showed warmer results than simulated, which was presented in each room's recording. Nonetheless, the logging dataset presented an acceptable variation between predicted and measured temperature and relative humidity; the highest variation was recorded in the bathroom, at 5% difference; in the kitchen, it was around 3%. The bedroom recorded an average variation of 4%, and the office showed 3.6% variation.

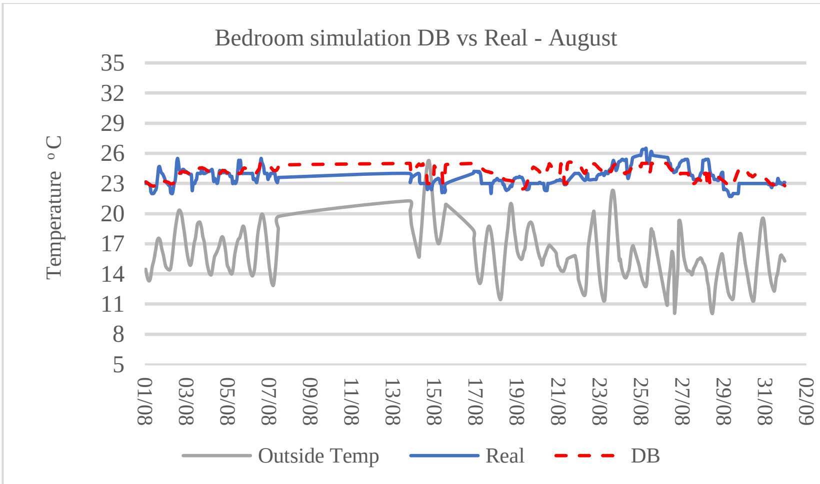


Figure 4. 9:Bedroom simulated temperature results vs recorded

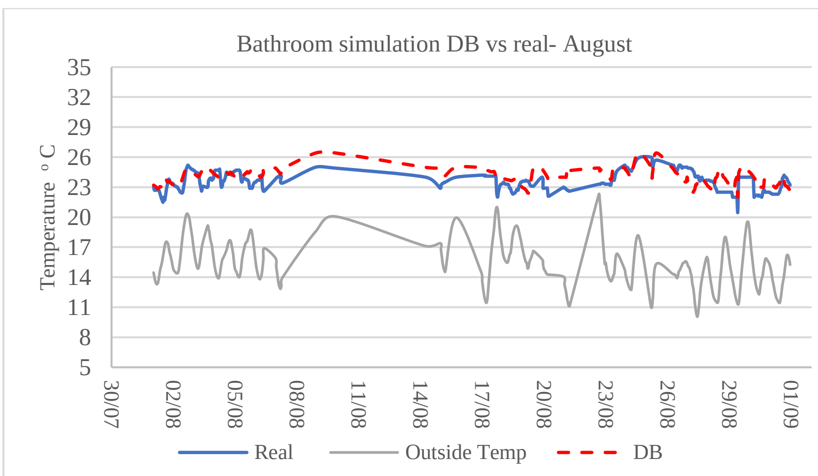


Figure 4. 10: Bathroom simulated temperature vs recorded

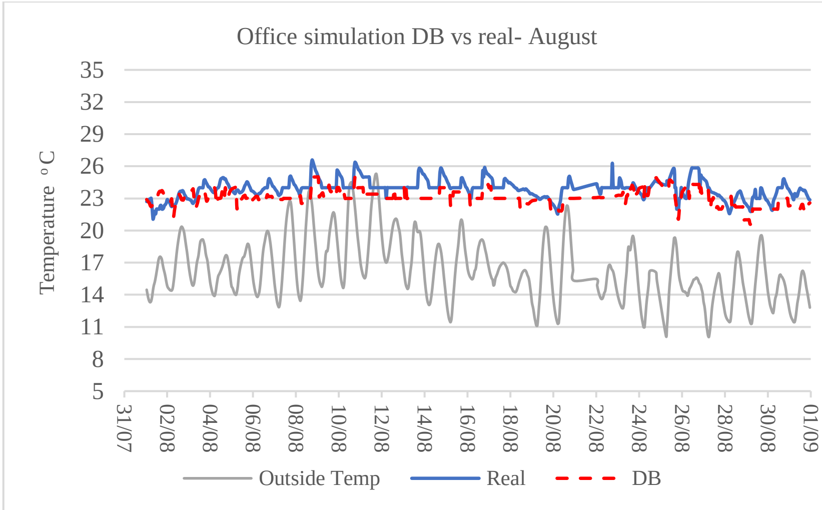


Figure 4. 11: Office simulated temperature vs recorded

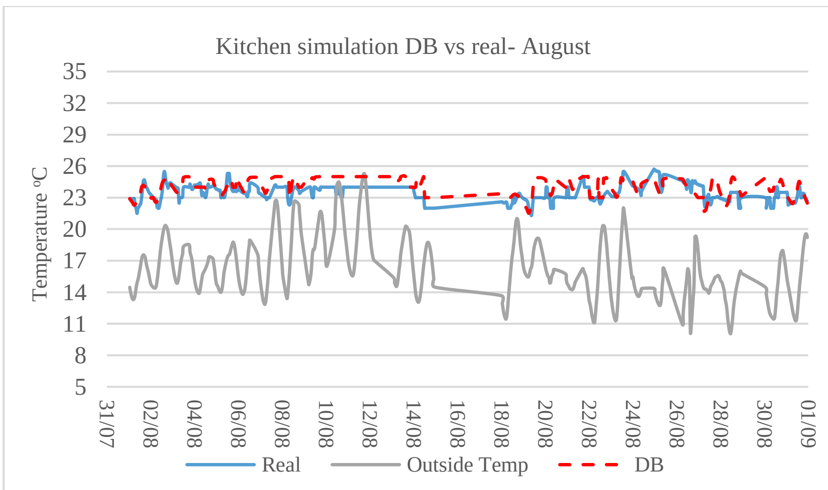


Figure 4. 12: Kitchen simulated temperature vs recorded.

Table 4. 7: Recorded Average monthly outdoor temperature and RH% in 2018.

Recorded 2018	Ave Temp	Ave RH%	Max Temp	Min Temp	Max RH%	Min RH%
January	5	82	11	2.1	95	62
February	7	78	17	-1	93	48
March	6	82	15.3	2.2	98	44.1
April	10	80	30	1.9	100	40.6
May	16	68	33	4.8	92	31
June	19	65	39	12.1	90	35.5
July	20	66	38	13.6	92	25.6
August	17	74	33	12.3	91	42.9
September	15	77	23.5	9.4	90.4	42.9
October	11	82	18	2	94	50.9
November	8	88	12.7	0.9	97	71
December	7	91	12	1.7	99	73

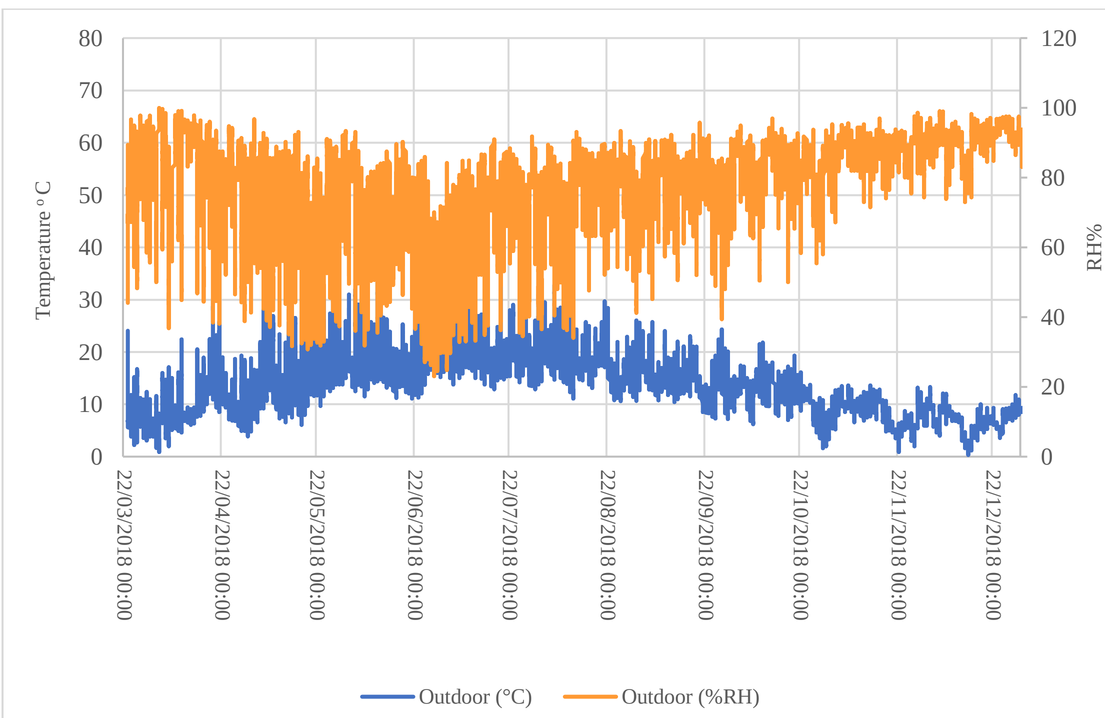


Figure 4. 13: Outdoor temperature and RH% recorded every half an hour in 2018.

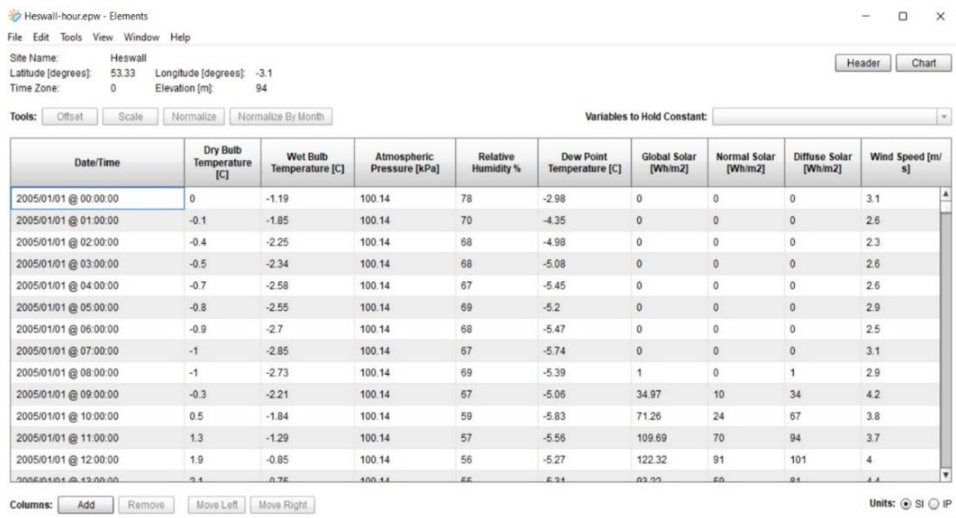
4.3.3 The recorded and modified outdoor temperature and RH%

This section discusses the accurate method of reporting weather conditions based on exact location. Weather files from a weather station provide weather station provides a record of weather data for that site and generally to a high standard of data quality and sensor accuracy but the use of on-site measures enabled the author to record precise weather conditions intended particularly for this research. Initially, weather files from Heswall were extracted from the Meteonorm weather station in EPW format; the current weather files and the future weather files of the three time-lines of 2030, 50 and 2080 were generated in Meteonorm, later the files were important in the Elements tool to modify the weather conditions inputs by using the recorded data onsite. Once the files in elements were modified, they were imported in DB for simulation.

Figure 4.14 displays the software platform, which is similar to the Excel sheet format, where the weather condition of Heswall was imported from the weather station and these weather conditions included the hourly dry bulb, RH%, wind speed and more.

The software is designed to enable modification in the platform once the data are imported; hence, the author of this research had to use (Elements) to create a new set of weather conditions that would be more accurate for the SIPs House's specific location. Building energy simulation requires specific weather data to be able to run accurate energy performance simulation; therefore, the need to modify the files is crucial at this stage of model validation. The Elements software program provides a free and user-friendly platform to create and modify weather files for building energy simulation programs; it helps visualise and modify weather data loaded from various formats, such as the EPW or Excel, by loading the existing files into the integrated program and editing them to create a new, modified set of weather data based on measured data (Elements., 2021).

Heswall weather files included the dry bulb temperature, which is the outdoor temperature, and relative humidity. The data were extracted from the outdoor data logger and downloaded into an Excel formal sheet, and they were saved over 1 year. Later, they were manually edited in Elements. Once the data were edited, they were saved in an energy simulation program (EPW) that is compatible with DB; thus, they could be easily imported for further evaluation. These new weather condition files provided real weather condition that could be assessed in the case study model validation.



Date/Time	Dry Bulb Temperature [C]	Wet Bulb Temperature [C]	Atmospheric Pressure [kPa]	Relative Humidity %	Dew Point Temperature [C]	Global Solar [Wh/m2]	Normal Solar [Wh/m2]	Diffuse Solar [Wh/m2]	Wind Speed [m/s]
2005/01/01 @ 00:00:00	0	-1.19	100.14	78	-2.98	0	0	0	3.1
2005/01/01 @ 01:00:00	-0.1	-1.85	100.14	70	-4.35	0	0	0	2.6
2005/01/01 @ 02:00:00	-0.4	-2.25	100.14	68	-4.98	0	0	0	2.3
2005/01/01 @ 03:00:00	-0.5	-2.34	100.14	68	-5.08	0	0	0	2.6
2005/01/01 @ 04:00:00	-0.7	-2.58	100.14	67	-5.45	0	0	0	2.6
2005/01/01 @ 05:00:00	-0.8	-2.55	100.14	69	-5.2	0	0	0	2.9
2005/01/01 @ 06:00:00	-0.9	-2.7	100.14	68	-5.47	0	0	0	2.5
2005/01/01 @ 07:00:00	-1	-2.85	100.14	67	-5.74	0	0	0	3.1
2005/01/01 @ 08:00:00	-1	-2.73	100.14	69	-5.39	1	0	1	2.9
2005/01/01 @ 09:00:00	-0.3	-2.21	100.14	67	-5.06	34.97	10	34	4.2
2005/01/01 @ 10:00:00	0.5	-1.84	100.14	59	-5.83	71.26	24	67	3.8
2005/01/01 @ 11:00:00	1.3	-1.29	100.14	57	-5.56	109.69	70	94	3.7
2005/01/01 @ 12:00:00	1.9	-0.85	100.14	56	-5.27	122.32	91	101	4

Figure 4. 14: Elements software platform. (Elements)

The weather conditions of outdoor temperature were recorded and saved separately in Excel sheets. Later, the recorded weather conditions of Heswall, modified in Elements, were imported into DB for simulations. The results of the simulation were also saved in an Excel sheet and compared with the original recorded weather file. The simulation results followed the same trend as the recorded temperature on site (See Figure 4.15)

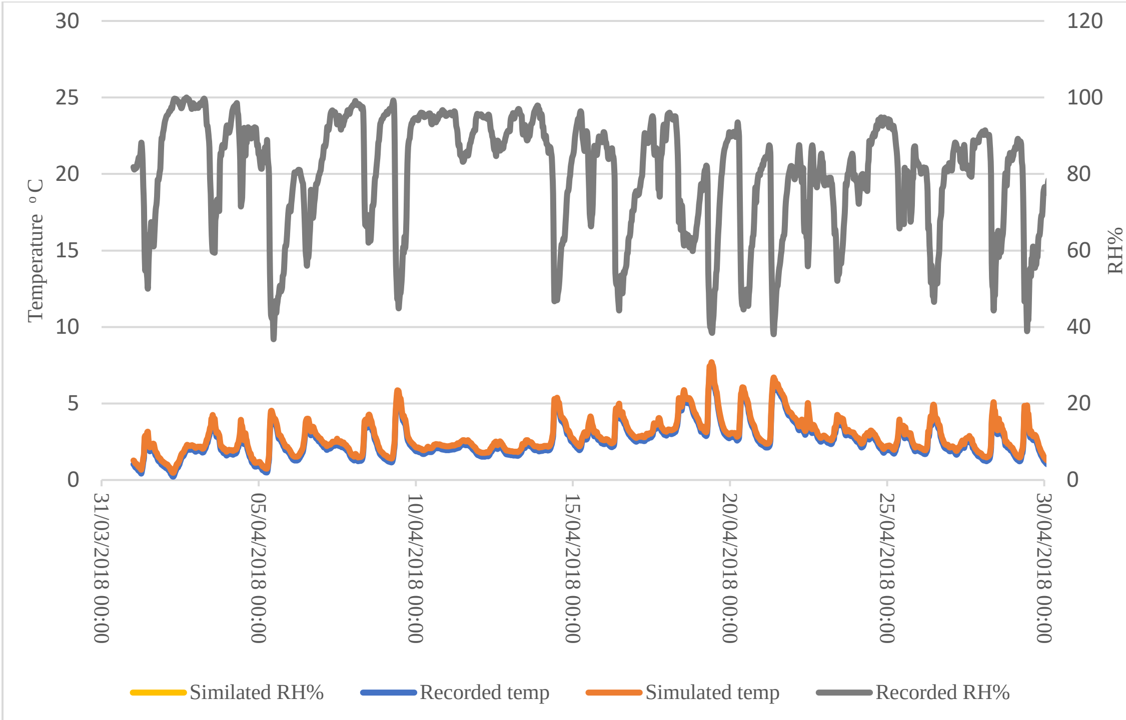


Figure 4. 15: Outdoor temperature and RH% recorded and simulated for the month of April 2018

4.3.5 Energy loggers

The SIPs House is supplied with 100% electricity and no gas. The electricity powers the mechanics and home appliances, including plug loads, appliances, lighting, thermal storage heating, an immersion heater, an ASHP and an MVHR system, external CCTV cameras and Wi-Fi. To monitor energy usage, the author of this research used Energy Efergy sensor (Energy Efergy, 2020); (refer to Appendix 1. G) for the website platform. The sensor records real-time energy in kW, the size of the sensor 80x85x25 and weights 61g. The voltage range is 110-300V AC and powered by AC/DC adopter. It also provides history usage of daily, weekly and monthly data with accuracy of 98%, and the data are recorded at 30 minutes interval. The sensors were fitted to the consumer unit of the home, and a lead from the sensor was then connected to a transmitter

The transmitter sent real-time data wirelessly to a Wi-Fi hub connected to an internet router; with transmission time every 12 seconds, coin this way, the data were transmitted to the website and could then be downloaded. The sensor only measured the total amount of energy supplied directly to the home with no separate estimation of the electricity used in each appliance.

The energy consumption of the house was recorded for a period of 12 months. The data on electricity consumption were downloaded from the Energy Efergy website and compared with the simulation outputs. The comparison between the recorded and simulated electricity used in DB indicated a similar trend; however, the results also showed a performance gab between the simulated and recorded results. Therefore, statistical methods were required to evaluate that the simulated results of DB were statistically validated in compliance with ASHRAE Standards 14-2002, the method used of calculating error with the coefficient of variation of the root mean square error (CVRMSE) was adopted in the research to statistically validate the energy simulated model. Similar approaches were used by (Abuhussain, 2020; Englund et al., 2020) to validate the hourly dry bulb temperature with indoor simulations.

Moreover, ASHRAE, (2019) has published a guideline to deal with modelling uncertainty which has been adopted in the research. One of the mathematical approaches sought from ASHRAE is the use of CVRMSE and RMSE as a method of calculating the relative error. To calculate the CVRMSE, the author used 12 months of energy hourly data for 2018, as shown in Table 4.8 and Figure 4.16.

According to ASHRAE, (2019), a rate of $\leq 30\%$ of CVRMSE based on hourly data is acceptable when comparing recorded and simulated measures, the CVRMSE values range between 7% and 24%, it can be indicated that the CVRMSE calculated values are lower than 30% as a define limit by ASHRAE.

In the case study, the CVRMSE method of calculation is presented in Equation 4.1, which consisted of two main steps following ASHRAE guideline 14:

1. Finding the root mean square error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{N}}$$

$\sum$: Summation

N : Sample size

Y_i : Predicted value

$Y\hat{}_i$: Observed value

$(Y_i - Y\hat{}_i)^2$: Difference squared

1. Normalising the RMSE by calculating the coefficient variation (CV) of the RMSE.

$$\mathrm{CV(RMSE)} = \frac{1}{\overline{\overline{Y}}}\sqrt{\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{N}}$$

Equation 4. 1: Data normalization method

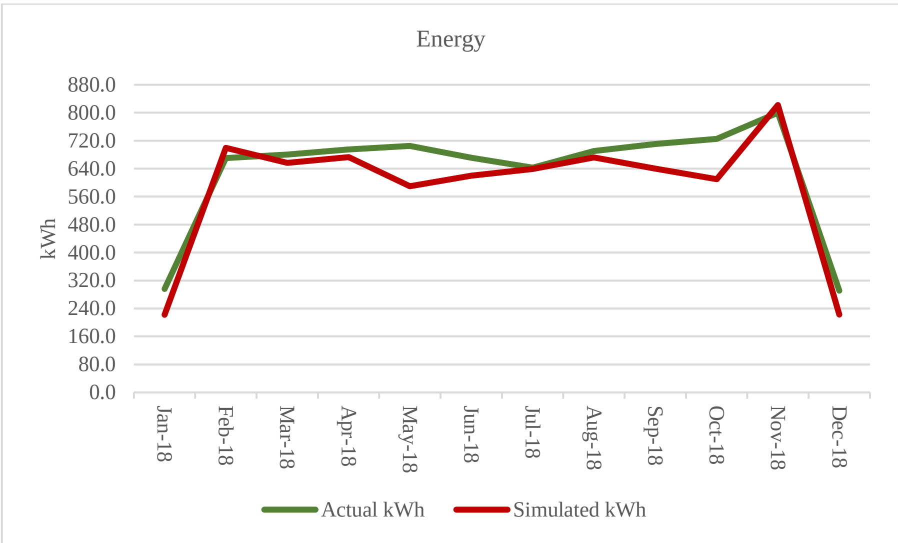


Figure 4. 16:. Monthly energy recorded data and DB energy simulations outputs.

Table 4. 8: The analysis results of CVRMSE for each month in 2018.

Month	CVRMSE
January	14%
February	7%
March	10%
April	15%
May	24%
June	7%
July	8%
August	16%
September	12%
October	21%
November	9%
December	13%

It can be indicated that the results of the CVRMSE values for each month are lower than 30% as suggested by ASHREA limits of variance, the results of validation techniques using CVRMSE indicated a relative satisfactory result between the measured data of energy used and DB outputs.

4.4.6 Heating system type and Domestic hot water

According to the survey the house is heated through a hot water thermal store that is charged up by immersion heater element with 3kWh which runs 3 hours per day to charge the thermal store (300L) and then supplies heat to the post heater and is operated 24/7. The heating system is controlled by a thermostat in the bedroom which has a setpoint of 20^{o}C and controls the MVHR and the temperature was measured in the house to be between 20^{o}C-25^{o}C during occupied hours, the same water in the thermal store is used for DHW (taps and shower) refer to Table 4.9. The system also backed up by a post heater that provides additional heating in the colder days. Also, the owner of the house has installed ASHP in the living/kitchen room for an additional heater if heating was required, but in the interview, it was mentioned that the use of it was infrequent, see Table 4.9.

Table 4. 9: The main heating and DHW in the house.

SIP House	**Systems**
Heating	Thermal store
	Post heater
	MVHR
	ASHP
Ventilation	MVHR
DHW	Thermal store
Occupancy density people/m^2	0.021

4.3.7 Home appliances and heating setpoint temperature

A home survey of the case study house was conducted to check the placement of the appliances, their number and their location. The data collection from the detailed survey was used mainly to define settings in the DB model. To calculate the energy consumption in the simulation phases, the type, number and size of the home appliances had to be determined. The lighting setting requires detailed inputs, such as the number of lights and their capacity in watts per area. In addition, DB requires the function of each room to be defined, including the required appliances. In addition to the functionality of each room, DB requires the occupancy per area—the number of people divided by the total area. In the case study, the occupancy density was 0.021 people/m^2 for a house of 92 m^2 with two people. It was observed from the house that the occupant setpoint of the heating temperature was 21°C, and the same value was recorded in the activity tab in DB. The list of appliances with their capacities and kWh per year as per site survey are shown in Table 4.10

Table 4. 10: SIPs House mechanics and appliances and energy estimation from survey.

Device	Power (Watts)	Hours per day	Number	kWh per year
LED Light	10	2	20	146
LED TV	80	1	2	58
Desktop PC	200	5	1	365
Laptop	60	1	1	22
WiFi	6	24	1	53
Phone charger	5	2	2	7
Cordless phone	2	24	1	18
Washing machine	500	1	1	183
Fridge Freezer	100	24	1	876
Oven	2000	1	1	730
Induction Hob	2000	0.5	1	365
Microwave	1200	0.01	1	4
Toaster	1200	0.2	1	88
Hairdryer	1500	0.1	1	55
Iron	100	0.25	1	9
Vacuum	1400	0.1	1	51
ASHP	5000	0.5	1	913
Immersion	3000	3	1	3258
MVHR	30	24	1	263
			Estimated kWh per year	**7,489**

4.4 Model normalisation through long term monitoring.

Normalising the model in DB can have a significant impact on the outputs; DB uses default inputs to calculate the energy demand. As mentioned above, the site survey contributed significantly to modifying the values in DB to enable the normalisation of the outputs. The occupancy density and number of occupied days, including temperature set points, can affect the results of heating demand.

4.4.1 Ground temperature

While trying to match the DB model with the case study, there were many variables that affected the calculation. For example, in the initial stage, when trying to match the recorded temperature outputs with the DB model, the results were different. Therefore, several simulations were conducted to assess whether the gap was real or related to some kind of error. One of the variables that needed modification in DB was the ground temperature for the whole year, as the ground temperature in the program was set at 14°C for the whole year as a default input in the program. Moreover, across the United Kingdom, the mean annual soil temperatures at 1 m in depth were reported as an average of 1°C higher than mean annual air temperatures based on a study conducted by (Busby, 2015). Another study by (Stífany Knop, & E. G, 2012) reported that the soil temperature was obtained from the slab temperature of the building. The average was calculated by averaging the outdoor mean temperature and internal air mean temperature, which means that for each month, the slab of the ground floor will have a different value rather than a fixed value for the whole year. Thus, the ground temperature is not a constant value, and it keeps changing based on the climate of that specific month. As a result, for this study, 1 m depth with 1°C higher than the average mean temperature was considered for each month. Therefore, the default value was changed to a more accurate figure when calculating the heat gain, although it had a minor impact on used electricity, but it was decided to modify the ground temperature from static to variable as a process to improve the model.

4.4.2 Occupants' lifestyle and behaviours

In homes, energy consumption is mainly related to the consumptions of space heating which uses around 27% of energy, and domestic hot water uses around 14%

and lighting around 12% (London 365, 2019) however, in well insulated buildings with energy efficiency standards have seen a great drop on in heating demand and domestic hot water (Hamilton et al., 2013). In recent years, the contribution of better thermal conductivity and wall insulations has significantly lowered heating energy consumption. One the other hand, several studies have suggested that the occupant's behaviour plays a major role in contributing to the actual energy use in the building; for example, about 40% of energy consumption in Northern Europe is used for space heating and hot water, which have become an important aspect of daily life needed to maintain people's standard of comfort (Branco, 2004). Consequently, delivering the same comfort at a lower energy consumption level is an important task to tackle the climate change agenda. A study by (Haas et al,. 1998) suggested that an occupant's behaviour has the power to control energy use via choosing the temperature set points, ventilation rate and thermostat; a similar study was found in (Guerra, 2011) paper, which suggested that the total amount of energy used is caused by several parameters, such as the quality of HVAC systems, the wall insulation properties and occupants' behaviour. Furthermore, (Guerra, 2011) maintained that the behaviour patterns of the occupants determine the actual energy performance of the dwelling, and these patterns are based on several parameters, such as the number of households, children and elderly people; people working from home; and lifestyle characteristics. A similar result was found by (van Raaij & Verhallen, 1983), where the family size and composition had a direct effect on energy consumption.

Occupancy behaviour is the most complex part of energy assessment in post-occupancy analysis studies. Many studies have been conducted to study post-occupancy patterns as a tool to equip building designers. Nonetheless, it has been found that this is a challenging task to achieve (Khalfan, 2017) because there are many issues with tracing the occupant's behaviour, including age, location, ethnic group and type of building. As a result, there will always be an unpredictable measure between the occupant's behaviour and energy consumption that needs to be considered in the simulation phase. In DB modelling, the occupancy profile plays a big role in the simulation program because the inputs from the occupant's lifestyle can create a full set of building energy analyses. The schedule for household equipment, such as the lighting schedule and MVHR, has the capacity to estimate the internal heat gain and energy consumption in a particular zone in the house. The heating system is on for 24 hours to ensure indoor temperature of 21C throughout the day, which is controlled by the HVAC system, which is on 24 hour a day to supply fresh air and maintain the internal temperature of 21C, and the ASHP in the Living room is used only when additional heat required. Furthermore, one of the inputs in DB modelling is the number of occupants and the occupants' daily pattern, as changing the parameter in DB will affect the space heating the default value in DB was changed to actual amount of 0.021 people/m^2 for the $92m^2$. The couple spend most of their time in the house, as there are retired couple and work from home, their daily routine is almost typical of UK household. Heating system is operated during wintertime and switched of typically from May till October, including the two months holiday in winter. A survey was conducted to understand the typical daily patter of schedule of lights, and equipment as indicated in Table 4.9. Therefore, typical daily profile was used in the simulation model DB as these parameters are vital at the modelling stage because they determine the amount of heating used per person per square metre, and the outputs are presented in the results chapter.

4.4.3 Set point temperature

The default temperature in DB is set at around 18°C-21°C; it was observed from the temperature data loggers that the average indoor temperature was 21°C-25°C during occupied hours therefore, the heating profile for each room was specified in the model based on the observation of the indoor recorded temperature. Once these inputs were modified in DB, they affected the overall energy consumption rate. The change of heating consumption and model validation is observed from changing the heating set points to bring it closer to the case study.

4.4.4 Operation schedules and holiday profile

Some home appliances, such as the Wi-Fi and refrigerator, are assumed to be running on a 24-hour basis; others, such as the computer, TV and coffee machine, run on an ON/OFF basis. From these data, a schedule profile was created for model making. Another important aspect of the occupant profile was the holiday pattern, which occurs once per year for a month (Dec-Jan); at this time, all the electrical appliances are switched off. The house is equipped with 20 LED lights with a 10-Watt capacity. In DB there are two ways to define the lighting energy use, either by Watts/ m^2 or Watts/m^2 per 100 lux. The model lighting energy was set as 4.3 W/m^2 as a default figure, but it was changed to the correct value of 2.17 W/m^2. The energy is equivalent to a total energy of 1.58 kWh/ m^2.year. Normalising the lighting parameters did not have a significant impact on the heating demand; this was mainly because of the number of LED lights in the house and their energy capacity. The MVHR in DB is set on by zone and the natural ventilation by minimum fresh air/person. These options enabled more steady temperature in the SIPs House, during summer times when the external temperature was high, the internal temperature recorded lower than the outdoor weather temperature.

Heating is provided by thermal store of 300L, places in the bedroom on the first floor and controlled a thermostat. The thermal store is charged up by an electrical immersion heater which runs 3 hours per day. The Post Heater is supplied with hot water via pipework from the thermal store and this provides heat to warm the air in the mechanical ventilation and heat recovery (MVHR) system. The heating profit is modified to operate on 24/7, excluding summer months and holiday season. The holiday period is around two months during December and January of every year, where is it was observed the total energy consumption dropped around 291 kWh and 296 kWh respectively during the cold months. To normalize the model in DB, holiday period was considered and modified in DB.

4.4.5 Energy validation of electricity consumption

In the last stage of model validation, energy simulation was conducted in DB for a whole year based on the model normalizing stated above. The results of energy simulated were used to be compared with the recorded energy from the energy loggers for 12 months in 2018. The total energy recorded in 2018 was 82.4 kWh/m^2.year and

DB energy output was 87 kWh/m^2.year, which presents a 4.6% difference between the DB energy consumption and the recorded data from onsite data recording. The results of energy simulation were compared between the recorded energy and DB simulation outputs for the month of June, July and August in 2018 are shown in Figure 4.17. The highest energy consumption was recorded during the month of November 2018 as the energy consumption was recorded 986 kWh and the least energy consumption was recorded during December/January as the house was vacant. Based on the holiday profile DB was modified to reflect the vocation period and bring the model of DB as close to the case study (see Table 4.10 for breakdown of energy). The simulated results present a breakdown of energy use including, heating, DHW, fans, pumps and lighting, were the recorded results presents the total energy used, due to the fac that submetering was not performed as explained earlier. See Table 4.11 for energy breakdown.

Table 4. 11:Breakdown of energy after DB model normalizing.

Energy use (Electricity) kWh	Simulated	Recorded
Heating	3104.0	0.0
DHW	2242.0	0.0
System Fans	1462.2	0.0
System Pumps	0.2	0.0
Interior Lighting	1203.0	0.0
Total	**8011***	**7577**

*Simulated results is rounded in the research to 8000kWh

The comparison demonstrates that overall, the energy consumption predicted from DB is reasonability close to the recorded data from the energy logger.

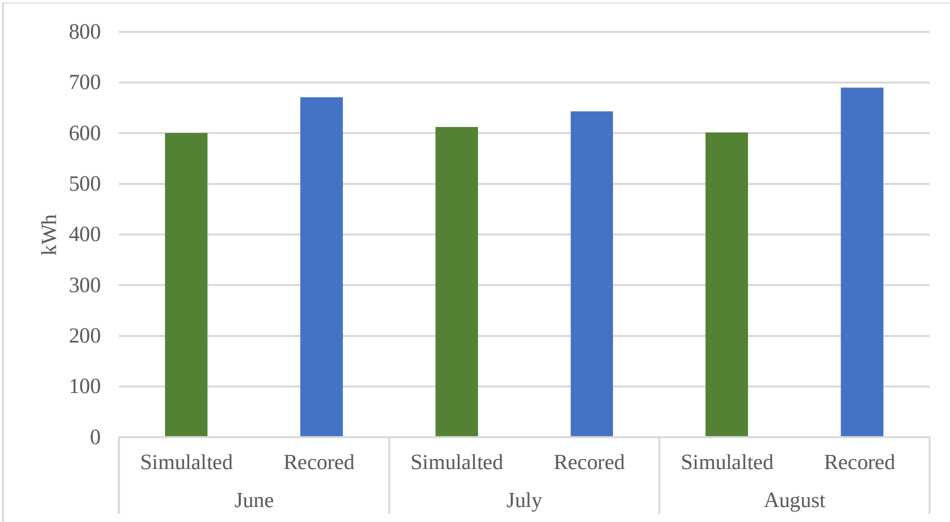


Figure 4. 17: Comparison between the energy recorded and DB energy output simulation for three months in 2018.

4.5 Summary

The data in DB have been modified to match closely the simulations outputs. The DB calibration is a process to confirm that the statistical output from the model is relatively acceptable with recorded measures. The next chapter will discuss the options of the model simulations through parametric studies. The process of creating a model in DB was divided into several stages. First, the architectural drawing, received in hand-drawn format, was developed into AutoCAD format. Second, the site was visited and surveyed to detail the drawings and the model. Finally, the model was created virtually in DB in a 3D format.

The challenge in creating the case study SIPs model was to create a new type of material in the DB library because MgO SIPs panels are a relatively new material and limited research has been done on the whole life impact. The best solution was to find a similar wall in DB that replicated the thermophysical properties of MgO and edit it to the appropriate specifications. The process also required weather files to create a model at a specific location on the map to configure the weather condition. Once the model was created, it had to go through different layers of simulation and refining in the validation phase. The method used is a form of comparison between the recorded data and DB simulation output. The model was validated in DB via two types of investigation. The first type was a comparison of what had been recorded through the data loggers of temperature and relative humidity and the DB results after simulation. The comparison of energy consumption showed that the simulated results had predicted higher energy consumption than the recorded measures during the months December and January and this is mainly due to the vocation period. But after normalizing the occupant's holiday profile in DB the results showed relative similarity between them. The results were statistically evaluated using the ASHRAE Standard 14-2002. DB model calibration had improved the overall simulation results based on the input parameters, and the final DB model presents acceptable results between the recorded and simulated results. The measured parameters, and especially the occupants' behaviour, have crucial effects on the energy requirements. Hence, modification and detailing the model in DB can result in an improvement in energy reading outputs from the model simulation. To prepare this type of construction material to fit the future energy conservation plan is vital at this stage of preparing the model and simulating future scenarios. Consequently, the next chapter will discuss methods and assessment of optimising the case study model by optimising the envelope properties and relative parameters. The objective of the research is to upgrade the energy performance of the SIPs House.

Chapter Five: Results

5.1 Chapter overview

Chapter five presents a comprehensive discussion on the results of the base case house from the current weather file scenario and future weather files by using DB simulation software. As explained in the previous chapter, the base model was compared to measurements through long-term monitoring data that assisted in making the model in the simulation program as close as possible to reality, which allowed the author to base the future scenarios on an accurate and reliable existing model. The base case model was properly created, as discussed in chapter four, and it was later simulated to optimise the current conditions using various approaches.

The first part of this chapter discusses the current performance of the base model—the SIPs House. It presents details of the current energy consumption and demand using the existing HVAC system and heating and DHW in the SIPs House. It also presents the comfort level of the house. Two comfort models were used to assess the SIPs House—Schneider's comfort chart, and Passivhaus summer design, which incorporates the use of a psychrometric chart to analyse the thermal comfort in housing using a specific weather file, in this case, that of Heswall, UK. The second part of the chapter presents the approaches for optimising the overall building fabric enhancement to potentially reduce the heating demand that can be realised when increasing/decreasing envelope insulations. The base model was developed to reduce the energy heating demand of electricity usage, which has a direct link to operation carbon production to nearly zero based on the UK carbon reduction plan of 2050 (Department for Business, Energy & Industrial Strategy, 2021c). One of the clean energy productions sought is the use of solar photovoltaic (PV) technology, which is mainly targeted to be placed on the roofs of buildings. By adding new green technology to the building, the base model could generate its own clean energy to supply the consumption demand; the same base model was simulated for 2030, 2050 and 2080 to analyse the overall performance of the SIPs House in terms of the thermal comfort level. The performance of the SIPs House is analysed in this chapter with a focus on the total energy used, thermal comfort and envelope performance. The first section consists of the energy consumption using the on-site recorded measurement validated with the virtual DB model and recorded temperature and relative humidity, followed by a discussion of the thermal comfort performance of the SIPs House and the results from parametric analysis of improving the base model for the future. Finally, the analysis and discussions of the results of the current model and the future scenarios from the simulations are presented.

5.2 The current performance of SIPs House

The current performance of the SIPs House is based on two sets of measured data that were available to use in this research. The energy data was obtained from on-site sub-meter reading in the SIPs House that presented the actual energy used during a specific time; these data were later compared with the predicted measures. The temperature and RH% data were obtained from the data loggers placed in the SIPs House, such as the living room/kitchen, office, bathroom and master bedroom. The next section gives comparative analyses between the recorded and the predicted data. The results support the claim that the DB simulation outputs present proximity between the recorded and simulated results.

5.2.1 Onsite measurement results- energy use

The SIPs House has been monitored post-occupancy for about 12 months, where the energy logger was installed directly on the meter in the house. The total energy consumption was reported rather than subdividing the data based on the total home devices because of technical boundaries in the house; to fill the resulting gap, additional fieldwork was carried out to estimate the energy consumption of each appliance, as stated in previous chapter Table 4.9; The total energy used (kWh) of the SIPs House was recorded via the placement of the Efergy Energy sensor that transmitted the data through Wi-Fi, and it is based on accurate data measured every half an hour.

The SIPs house used around 7577 kWh of energy in 2018 based on recorded data, and the figure was compared with utility bill in 2018 of 7972 kWh (appendix I.H), and simulated results of 8000 kWh. Figure 5.1 shows the recorded energy in comparison to the utility bill and simulated results, it can be observed that the recorded data had lower energy consumption than the simulated and the house utility bill and this is mainly due to the vocation period. The maximum consumption occurred in November 2018 at 800 kWh, where the minimum and maximum outdoor dry bulb temperatures were recorded as 0°C and 12°C respectively, the average indoor recorded temperature was 21°C and the relative humidity was 45%. The minimum usage was around December/January, at 296 kWh, and the reason for this reduction was the holiday pattern, which implied that the majority of energy used comes for heating and DHW as both of them were turned off during this time or presumably the heating was set on frost control setting only. During summer, the energy demand from heating is low and the majority of energy comes from DHW specially after the month of May till September and energy demand spikes up again in the cold months to supply heat.

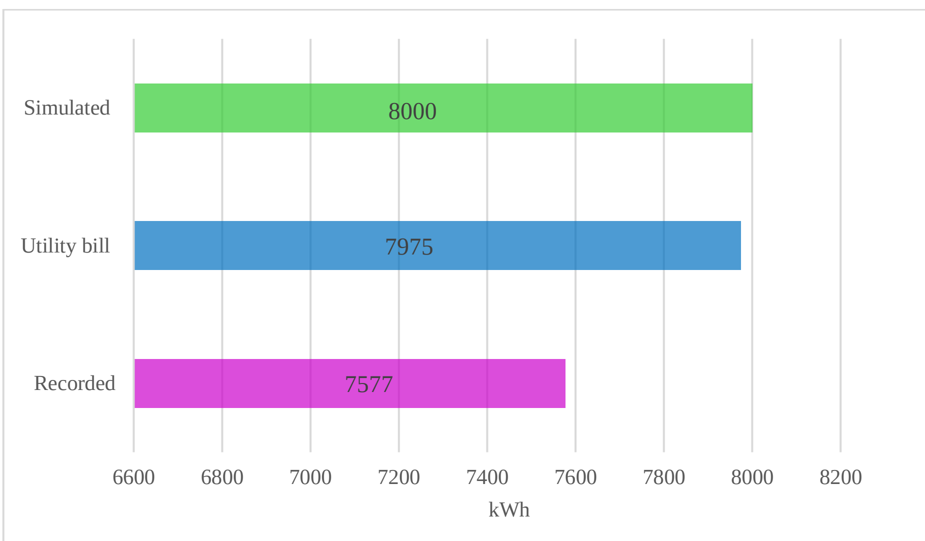


Figure 5. 1: Energy comparison between utility bill, energy recorded and simulated in 2018

The energy consumption drops to less than 300 kWh during Jan/Dec based of the occupants' lifestyle, and the house is left with the minimum energy consumption during their holiday, which indicate that major energy use come from heating and DHW. However, this is not the case in most UK homes where they vacate for a period of two months each year; as a result, normalising the energy consumption throughout a year was crucial to better understand the behaviours of the envelope throughout, an estimate of energy usage for Dec/Jan was estimated to normalise the yearly energy. Therefore, energy analysis is based on an average result based on simulation output from DB prediction and utility bill of estimation the total energy is around to 8000 kWh which is equivalent to 87 kWh/m^2.year

Based on DB energy simulation results, it was indicated that the heating system is the highest consumption of energy in the SIPs House and DHW comes second highest, the heating system almost uses 39% of total energy, DHW uses around 28%, system fans around 18% and lighting 16%. Figure 5.2 illustrates the monthly energy consumption; the rate of energy increases during the wintertime due to heating requirement and dropped in the summer with DHW consuming the most. During the holiday months the data loggers reported energy used for the month of December 296 kWh and January 261 in 2018 where the monthly recorded average is 700 kWh. After normalising DB based on the occupant's holiday profile, DB predicted energy consumption was lower than the recorded measures as presented in Table 5.1, the recorded results showed that although the two major energy consumptions are inactive, yet there is still energy used during this period because the owners do leave at the end of first week of January and retune at the end of December. DB has predicted that system fans (HVAC) used 140kWh during January and 123kWh during December, and the difference of energy is assumed to be the other appliances in the house such as freezer/fridge, WIFI, nightlights and possibly heating default setting on frost control.

Table 5. 1: DB predicted energy consumption and recorded energy during the holiday months.

	Actual KWh	Simulated kWh	Heating kWh	DHW kWh	Fans/other appliances
Jan-18	296	222	0	0	222
Dec-18	291	223	0	0	223

Moreover, as there was not sub-metering in the SIPs House, the energy segregation was not provided from the energy logger, but it was estimated from the DB (See Figure 5.3) The results indicate that around 60% of 8000 kWh is dedicated to heating and DHW.

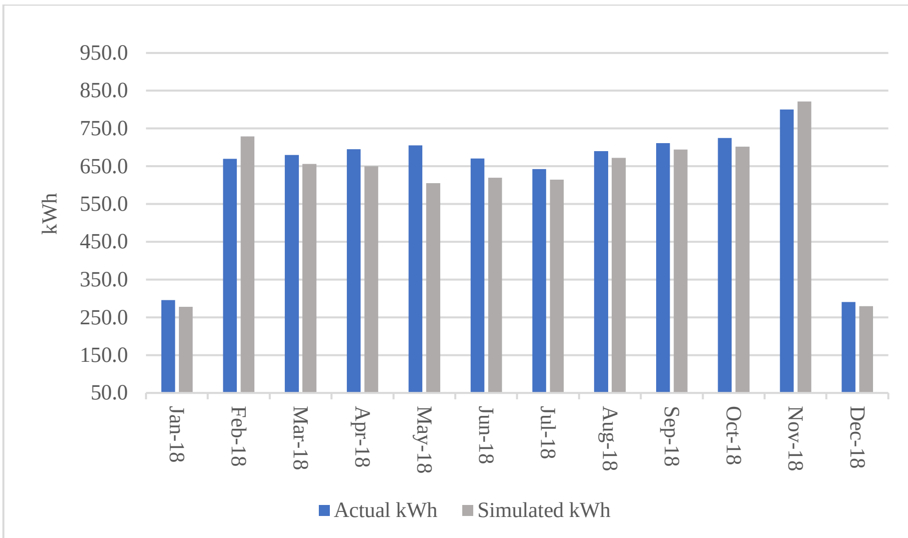


Figure 5. 2: The comparison between the recorded monthly energy and simulated results in 2018

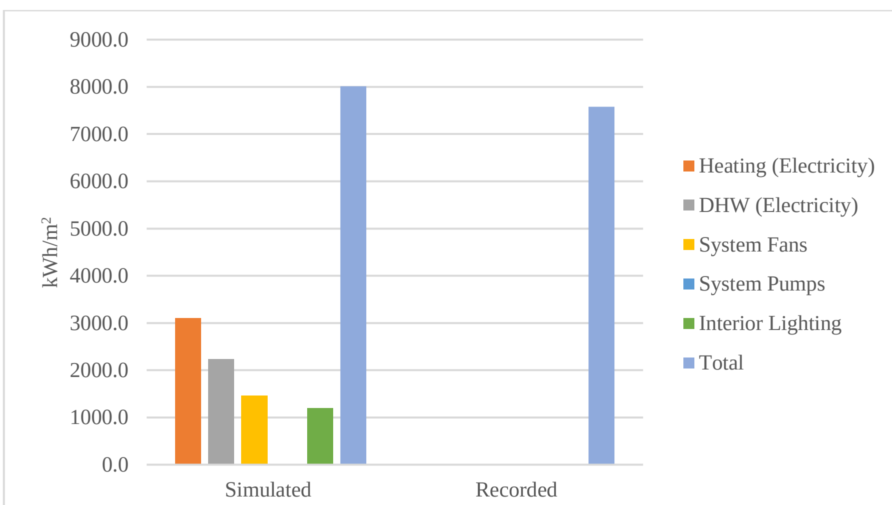


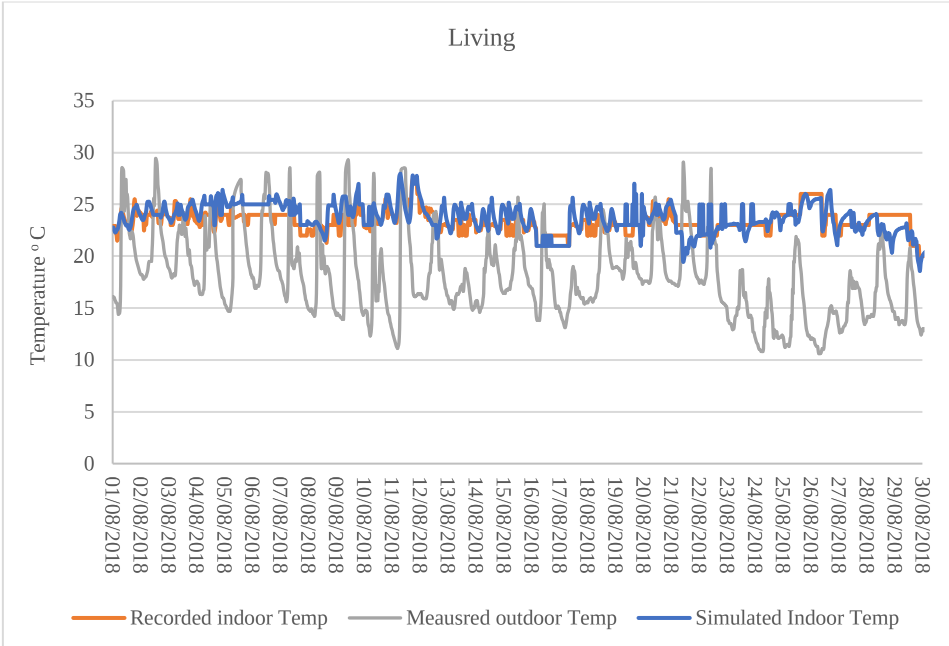
Figure 5. 3: DB simulation results based on energy breakdown and recorded total results 2018.

5.2.2 Onsite measurement results – temperature and RH%.

EL-Wi-Fi temperature and humidity sensors were used to monitor indoor temperature and relative humidity, on half-hour interval. The result indicated a fair similarity of temperature and relative humidity between the predicted and recorded measures when assuming the house was occupied for the period of 12 months; however, the occupants do vacate the house during December and January, when the house's appliances switched off. This time was eliminated from the simulation period to better understand the SIPs House performance when it was occupied and running throughout the year.

In the SIPs House, the maximum average temperature difference was recorded as 15%, and the minimum was 2%. The average difference between the recorded temperature and simulation in the living room/kitchen zone was 9%, with a maximum of 15% and minimum of 4% average difference. Similar results were found in the office zone, where the average difference in the temperature was reported at 2% with a maximum of 13% average difference. The master bedroom reported a comparable mean difference of 5%, with maximum variance of 7%. The results of compression are later statistically analysed using ASHRAE document for model validation.

The logging reported satisfactory results between the recorded indoor temperature and simulation in almost all the rooms, especially during the cold months, except when all the indoor zones' temperature dropped below 10°C during the holiday months. The results for the predicted indoor temperature and relative humidity showed satisfactory proximity to the simulated indoor temperature and RH%. Here, the house was assumed to be occupied throughout the year because most UK households do not vacate their homes for that long. The analytical study of calibrating the indoor temperature and relative humidity was conducted based on a full occupancy rate. In validation chapter five, the results of temperature and RH% were validated using the months of August and the results show fair proximity between the predicted and recorded measurements. See Figure 5.4 for comparison between DB predicted temperature and recorded.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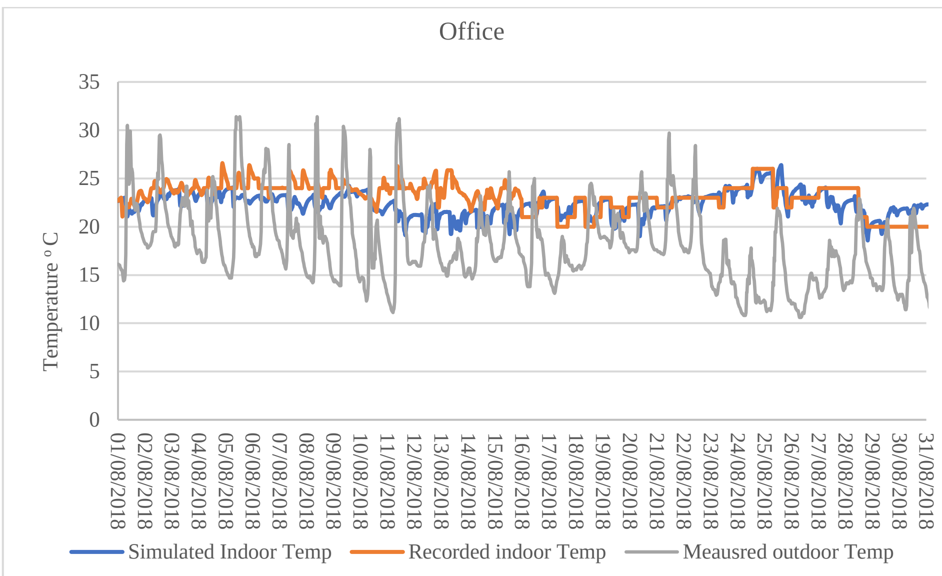
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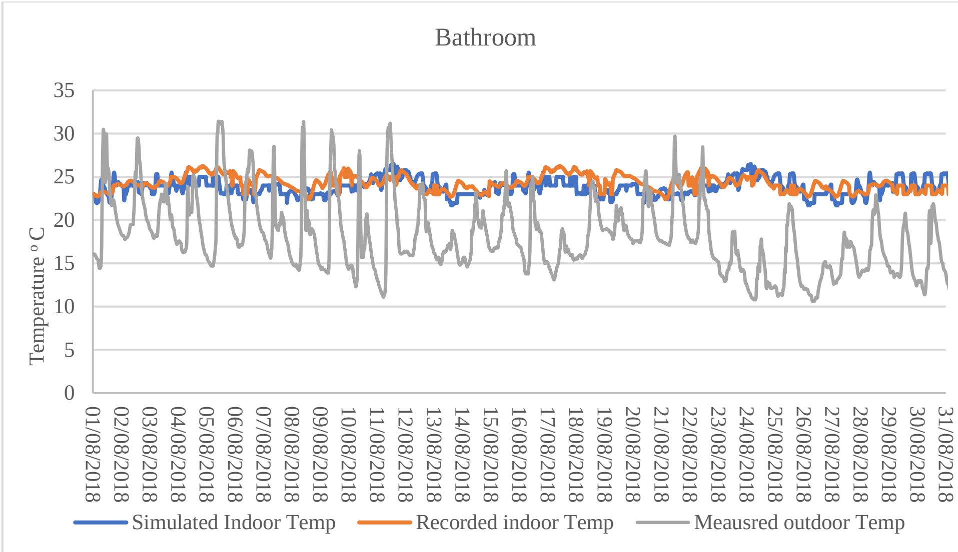


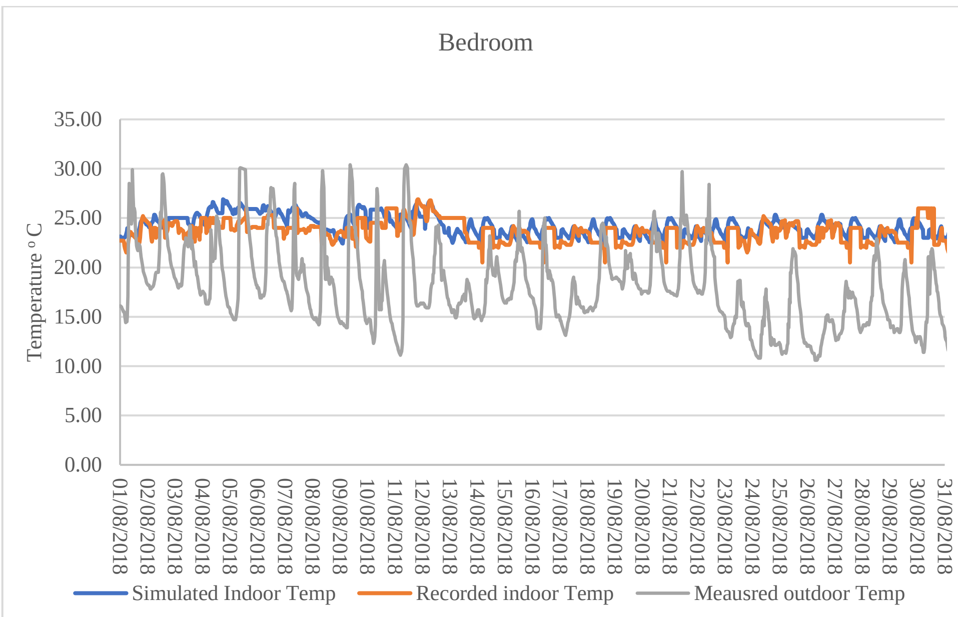


Figure 5. 4: Temperature comparison between recorded and DB predicted temperature

The average relative humidity in the SIPs House showed proximity to the predicted results. The average percentage change between the measured and predicted data indicated a closer reading than was found for the temperature data. The percentage change between the indoor average measured relative humidity and the predicted measures ranged between 2% and 10%. Overall, the average RH% recorded in the SIPs House during the occupation was high; the predicted results in the bathroom and the bedroom area showed a similarity to those for the living room/kitchen and office. The predicted average RH percentage change in the bathroom and bedroom was 2%–5% respectively. According to ASHRAE, (2017) standard for indoor air quality, the indoor humidity should be around 60% or less to maintain a comfortable air quality. On average, all recorded temperature and RH% data loggers showed a higher humidity level than the predicted level of approximately 80%. During August, the RH% in the SIPs House was higher, with a maximum average recorded RH of 80% and a minimum average recorded RH of 39% which was recorded in the office; On average the bathroom had the highest RH% than the other rooms in the SIPs House, the DB predicted results showed that the maximum RH% of 77% where the recorded showed 80%, and this is mainly due to the function of this room. See Figure 5.5 for a comparison between DB predicted RH% recorded.

Figure 5. 5: Comparison between DB predicted RH% and Recorded RH% during August 2018 in each room.

5.3 Thermal performance of the SIPs House.

Thermal comfort is defined by the indoor temperature parameter, which is the state of mind that the inhabitants feel in an enclosed area. It includes the actual room temperature and operative temperature. The term was defined by Thullner, (2010) as a good indoor climate; one way of meeting the desired level of comfort is the use of PMV as a parameter, where -3 is consider cold and +3 is hot. In contrast, thermal performance is usually expressed in the form of a temperature threshold with limited hours as a percentage of a year. The CIBSE, (2015) design guide design guide, advises maximum operative temperature of living room of 25^{o}C and 23^{o}C for bedrooms as sleep can be impaired above 24^{o}C.

Well-insulated panels perform perfectly to reduce the rate of heat loss during winter, but the major concern with super-insulated walls like in SIPs construction has to do with how they will perform without overheating during the summer in the future, when the global average temperature is projected to rise. According to the UK Passivhaus principles of summer design comfort (Passivehaus Trust, 2016), the total number of uncomfortable hours in year should not exceed 10%, which means the total number of hours greater than 25^{o}C in 1 year (total hours 8760) based on full occupancy rate, should not be more than 10% for the zone to be comfortable, as 25^{o}C is considered a limit of overheating in the UK Passivhaus summer comfort design. In this study, the average recorded indoor temperature was recorded between 21^{o}C and 25^{o}C in all the rooms, as DB generates environmental condition data in regards to comfort level including air temperature which measures the average temperature of air in particular zone, internal radiant temperature that measures the average mean radiant temperature of the zone, and internal operative temperature that calculated the mean of internal air and radiant airt temperature (DesignBuilder, 2020), based on DB simulation results the operative temperature showed slightly lower air temperature than operative temperature. The differences were measured between 0.31^{o}C and 0.56^{o}C.

To assess the thermal comfort of the SIPs House, two approaches were conducted. First, Schneider's thermal comfort was used, which defines thermal comfort based on temperature and RH%. Second, the Passivhaus summer design, which provides a detailed analysis of the summer comfort model (see Appendix 1. I) The Passivhaus measures were selected because the SIPs envelope has similar thermal properties that replicate the Passivhaus standard; both have similar airtightness, and the probability of overheating is predicted.

5.3.1 Passivhaus summer comfort design (Overheating)

Based on the PH recommendation for passive and low energy buildings, overheating should have a maximum threshold of 25^{o}C, which represents 10% of the total hours of the year (8760). In any low energy or Passivhaus home, the indoor temperature should not exceed the limit stated to be comfortable. Based on the recorded data the SIPs House indoor temperature during the summer season between June and August exhibited different temperature range based on each zone. During the summer season the occupants open the large operative windows in the living room for ventilating during the daytime.

The total hours of temperatures above 25°C in the living room/kitchen were reported around 470 hours in July and August, which presents 5.37% of the 8760 hours of the year of uncomfortable hours with the temperature reached above 25ºC. The office had a smaller number of uncomfortable hours than the living area above 25°C of 68 hours, which is less than 1%, the bathroom had 34 hours of temperature above 25°C and the maximum operative temperature in the bedroom was 24.6°C and it was during the day from 9am till 11.45am the end of July 2018. (See Table 5.2)

Table 5. 2 : The total number of Uncomfortable hours in a year in each room in the SIPs House.

	Total of hours above 25C°	**(% of uncomfortable hour)** of **8760**
Living/Kitchen	470	5.33
Office	19	0.22
Bathroom	68	0.78
Bedroom	0	0

Mechanical ventilation rate: 3 ac/h, and natural ventilation method by zone.

The data loggers reported on 26 July 2018 the highest outdoor temperature, with the most frequent higher temperature occurring during the day, the indoor climate remained within the comfort zone, the operative temperature was reported an average of 22ºC with highest recorded 24.5ºC. (See Figure 5.6)

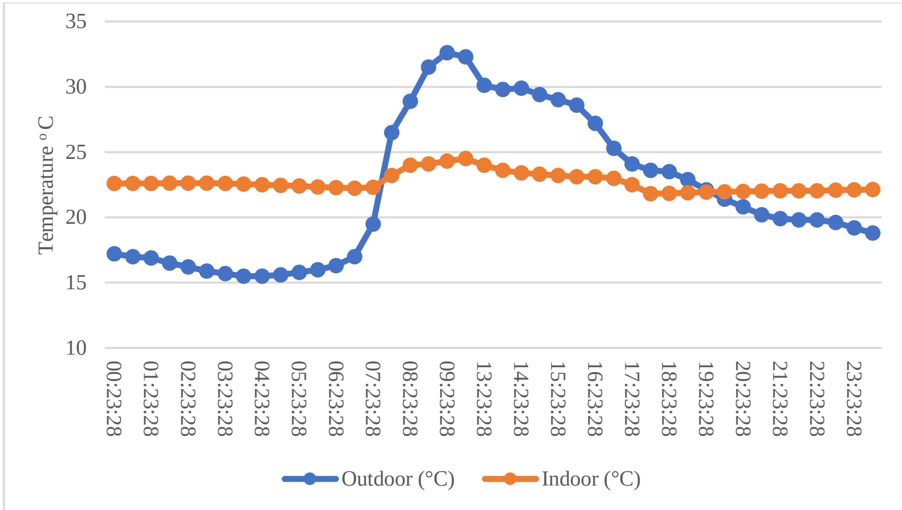


Figure 5. 6: Interior temperature in comparison with external during the hot day of 26 July 2018

As a result, based on the UK Passivhaus standard for summer comfort assessment, the percentage of uncomfortable hours in a year presented in the research are considered good.

5.3.1 Schneider's thermal model

Schneider's thermal model draws a thermal boundary around the operative temperature and relative humidity. It defines the inner boundary of the minimum of 20°C of operative temperature with a limit to humidity of 30% and a maximum of 27°C with a 70% relative humidity rate, and the outer boundary of minimum 19°C and 29°C with maximum relative humidity of 80% (see Appendix 1. J). More than 17, 000 hours of data were collected during 2018 to be analysed in the SIPs House. The data included the temperature and RH% readings from half-hour reading and are plotted in the graph, where each point presents the temperature of that hour in relation to the RH%. The results indicated that the operative temperature and relative humidity in the SIPs House would provide fair level of thermal comfort. The operative temperature of all the rooms of the SIPs house managed to sustain a temperature of almost 20°C throughout the year, disregarding the months of January–December, when the recorded temperature was reported at 10°C because the house was unoccupied. Based on Schneider's model, all the rooms maintained an operative temperature of the inner zone of the thermal comfort. In contrast, the relative humidity level has been within the inner boundary, with some exceptions when it dropped below the 30% limit during the summer when the indoor temperature was recorded as relatively high. The total hours of 30% relative humidity were recorded at 87% and 13% above 70%.

The focus of this chapter is to give the results for the total energy performance of the SIPs construction in the case study, and the thermal comfort analysis is a supplemental tool to assess the envelope performance. Therefore, investigating the level of comfort in the SIPs House was necessary to link it to the envelope performance under the current and future weather scenarios and determine how they behave differently. A detailed analysis is presented in the next chapter, the Discussion chapter. The next section presents the results of the envelope performance based on DB simulations.

5.3.3 SIPs envelope thermal performance

To measure the envelope's thermal performance, in the DB model, the heating supply was switched off for the whole year to measure the performance of the SIPs House on its own to predict the indoor temperature when the heating supply was off. The comparison was presented on the indoor temperature and the outdoor dry bulb temperature results. The indoor temperature maintained a higher temperature than the outdoor temperature during winter times, which means that the envelope has relatively good insulation system that manages to maintain indoor temperature above the outdoor temperature during the winter season; this is because the airtight panels have the ability to maintain indoor temperature by preventing heat loss through the walls, however, it does not match the Passivhaus minimum operation temperature of 20^{o}C. In summer, on average most of the rooms in the SIPs house tended to be warmer than the outdoor temperature, and the average temperature was above the outdoor mean temperature. See Figure 5.7 for indoor temperature per room. The next section provides more information about the future performance of the SIPs House under the three timelines of 2030, 2050 and 2080.

Figure 5. 7: SIPs House envelope thermal performance 2018.

5.4 Future SIPs House performance: 2030, 2050, and 2080

Future weather files for three timelines have been selected—namely, those for 2030, 2050 and 2080. These energy plus (EPW) were generated from the *Meteonorm* weather generator tool in the (Refer to Section 3.3.2); the current performance of the SIPs House was based on the base model for the future weather scenarios for comparison purposes, leaving the building components, occupancy rate, mechanical elements and heating of the SIPs House constant and running the base model without modification for the years 2030, 2050 and 2080, the weather file results indicated that the outdoor temperature will have a slight increase in temperature throughout the three timelines with small change of outdoor temperature increase in the year 2080 . This does not quite capture real-world case scenarios, where the house and the equipment fall under regular maintenance as they age. Nevertheless, the main objective of running today's case in the future is to test the current SIPs House condition in a hotter climate. One of the main factors in energy reduction is the total reduction of burning fossil fuel for energy in the residential sector; this can be accomplished through greater dependency on renewable energy on-site, as stated in the nZEB/NZC building regulations. The next section presents the results for energy production from solar panels in current and future weather files and their direct effect on energy reduction.

5.4.1 Energy from Solar panels

The SIPs House requires around 8000 kWh of energy to maintain its current level of consumption. As explained above, the current consumption rate is lower than that of most UK households, and the 1-2 bedroom in the UK uses around 8000kWh of gas per year and 2000kWh of electricity (EDF, 2022). Although the SIPs House uses less than most UK households the current pressure of reducing energy consumption to nearly zero is on the agenda of meeting net-zero, this will not be possible without the intervention of renewable technologies. The urge to reduce the electricity grid connection that powers the SIPs House for heating, ventilating, lighting, and cooking will require an alternative solution from a greener source, such as solar panels on the roof; to conduct this type of simulation, the occupancy rate, profile schedule and energy used were left as is without any modification to capture the same behaviour of the occupants and prevent any abnormalities in the energy calculation.

Solar panels were simulated in DB with four different solar PV constant efficiency rates. The DB sets a default efficiency rate value of 0.16 for solar panels, and this was used as a base model in the simulation. From a cross-check with the DB team regarding the incremental increase of the PV efficiency rate in the simulation phase, it was confirmed by the team that to obtain more realistic results, the efficiency rate should not exceed 30%. By using the base model of the PV constant efficiency rate of 0.16, the total electricity generated from PV yielded over 12 months was 6733 kWh. The entire rooftop of the SIPs House was covered with PV solar panels to meet the current consumption rate, see Figure 5.8 for energy generated from PV and Figure 5.9 for DB model with PV on the roof.

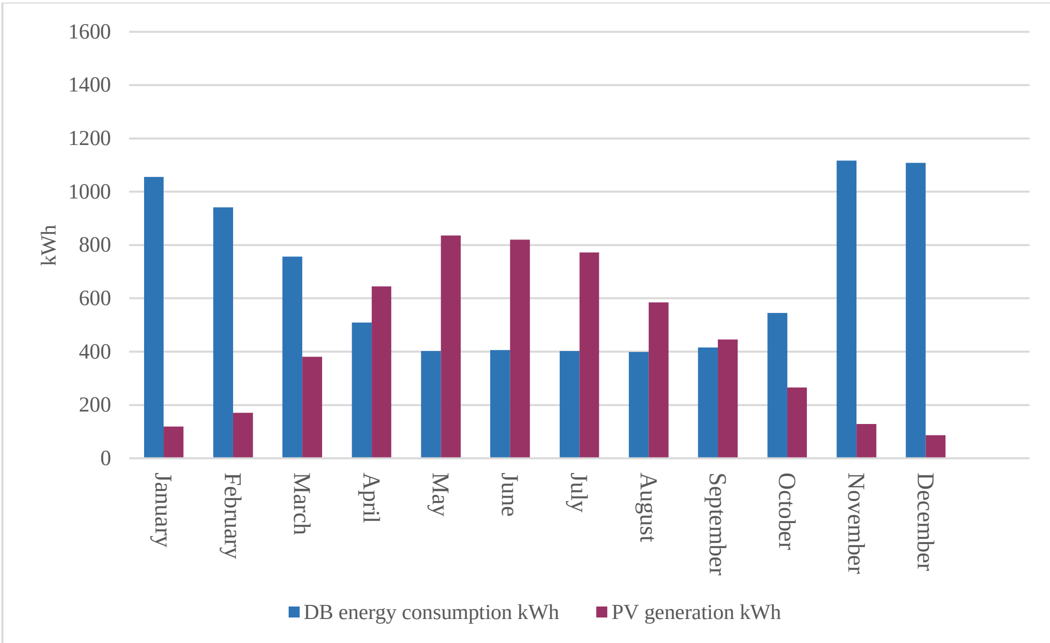


Figure 5. 8: Monthly electricity generation from solar PV in comparison with monthly consumption in kWh.

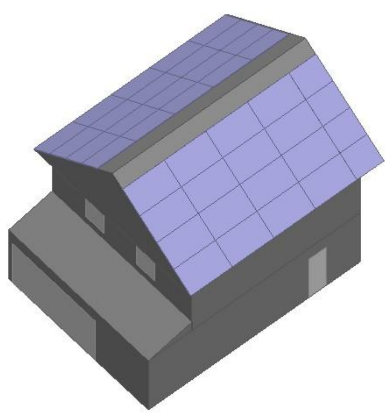


Figure 5. 9: DB model of the PV on the roof.

Four PV constant rates were tested for electricity generation; the average commercial convertor rate is between 15% and 20%, which means that the convertor's capacity to transform solar energy into usable electricity is limited to a maximum rate of 20%. DB model has estimated the energy consumption for three different constant rates 16%,18%, and 20% to simulate electricity generated from the solar panels. At the constant rate of 0.16, the total solar energy produced electricity representing 65% of the current consumption of around 8000 kWh, with a 0.18 constant rate the electricity generation covered 78% of the current electricity consumption and at the rate of 0.20 the electricity consumption covered 87% of the SIPs house energy consumption. Even with higher constant rate of 0.20, the SIPs House still needs extra 1008kWh to cover the current energy consumption.

Based on the current energy generation of the SIPs House from solar PV technologies at the constant rate of 0.18 which presents an average commercial convertor rate, the house was not able to fully generate its needed energy using solar panels on the roof. Therefore, based on the current electricity generation from solar panels, the SIPs House could not meet the nZEB/NZC requirement of energy needed.

5.4.2 Energy used.

DB simulation predicted an increase in PV electricity generation over time in the SIPs House. The PV generation was predicted in 2020 failed to meet the energy requirement of the house. Using future weather files, the DB model was simulated in the three timelines of 2030, 2050 and 2080 to predict the PV electricity generation. The outcome in 2030 presented a slight increase of the HVAC system and a slight decrease in the heating demand, the model was simulated in three converter rates and an average of 0.18 based on commercial average was considered in the research, and the results show that at 0.16 the total energy generated was 6334kWh which presents 79% of the electricity used in the SIPs House, 7123kWh at 0.18 and 7836kWh at 0.20 which almost 97% of the energy consumption. In 2050 a similar trend of HVAC presented in the timeline of 2030 was observed in 2050 where there was an 4% of the HVAC and 8% decrease in heating, the results of PV generation at 0.16 were 6873kWh covering 92% of the energy prediction of 7420kWh, nonetheless at 0.20 converter rate the PV electricity generated almost 107%. Furthermore, in 2080 the results predicted an 8% increase in HVAC and 9% reduction in the heating system, and at the convertor rate of 0.18 the PV managed to generate 103% of the energy predicted of 7386kWh in the SIP House. Refer to Figure 5.10 for comparison between energy consumption and energy generated from the solar panels.

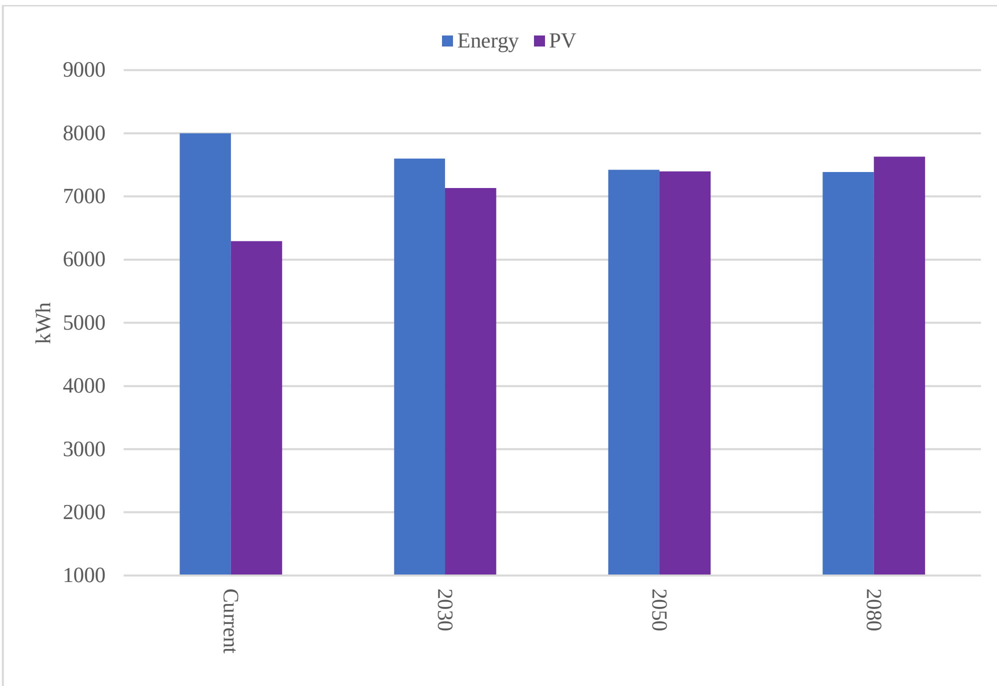


Figure 5. 10: Energy consumption and PV generation of the SIPs House for the three timelines of 2030, 2050 and 2080

Most energy consumption represented int the current weather files comes from heating and DHW in the SIPs House, and in the future weather files there has been a noticeable increase in the HVAC energy consumption and a small decrease in heating, in addition the predicted results show that there is a trivial change in DHW in the three time lines .The total energy consumption was estimated to be 87 kWh/m^2/year, which is considerably higher than the UK 2021 nZEB/NZC requirement of 44 kWh/m^2/year and even higher than the current London Energy Transformation Initiative (LETI) of limiting operational energy to 35 kWh/m^2/year to meet the ZC plan published in the

Climate Emergency Design Guide in 2020. Based on predicted results from the PV, the SIPs House cannot meet the current energy requirement of nZEB/NZC. In the base year, the house was able to generate 6291 kWh, which requires another 21% to meets its current consumption rate, similar predicted results were found the two timelines of 2030 and 2050. However, in 2080 at 0.18 converter rate the amount of electricity produce from the PV were higher than the predicted energy use of the SIP house, coving more than 100% of electricity require.

5.4.3 Thermal comfort

The indoor thermal comfort criteria of air temperature below 25°C and more than 20°C are almost still valid in all rooms for the current year. However, the operative temperature in some spaces of the house seemed to fall below the threshold in the three timelines. In the 2030 scenario, DB indicated that the indoor temperature, on average was between 22°C and 24°C throughout the year with 13.2% of uncomfortable hours >25°C; and 2050 scenario the results indicated that the indoor temperature was above the comfortable benchmark by 13.8%. In the 2080 scenario, on the other hand, the results showed that the SIPs House rooms on average maintained a thermal comfort in all the rooms except the living room, where the indoor temperature was >25°C by 24%.

5.4.3.1 Climate Consultant

Climate Consultant estimated the percentage of each design strategy to maintain the same level of comfort required in the three timelines of 2030, 2050 and 2080. Although the most dominant energy supply was heating, the results indicated that the heating demand would significantly decrease by the year 2080 (see Appendix 1. K for the psychrometric charts of the 2030, 2050 and 2080 weather files). The heating strategy in *Climate Consultant* dropped from 61% in the present-day file of 2020 to 51% in the 2030 weather file, 48% in the 2050 weather file and 45% in the 2080 file. To maintain thermal comfort in the three timelines, heating demand is the most dominant issue; however, there are other strategies to maintain a 100% comfort level inside the envelope. The *Climate Consultant* results indicated that dehumidification would be required as a design strategy to maintain comfort. In the present year, such dehumidification is not necessary, but in 2050, the program predicted 104 hours of discomfort if dehumidification was not implemented in the house design. Similar results were also presented in 2080; the total number of discomfort hours reached 301 per year. Therefore, the *Climate Consultant* thermal comfort design strategy suggested that 60 years from now, the heating demand will reduce to 45% of the total design strategies when compared with the current year requirement of 61%. The heating reduction will be accompanied by the use of dehumidification to maintain the occupants' thermal comfort. The heating reduction is mainly based on the future weather forecast that predicted ongoing climate change and the increase of the global air temperature. Furthermore, there has been a noticeable outdoor temperature increase and a decrease in RH% in the three timelines specially in year 2080 as presented in the Figures 5.11 and 5.12

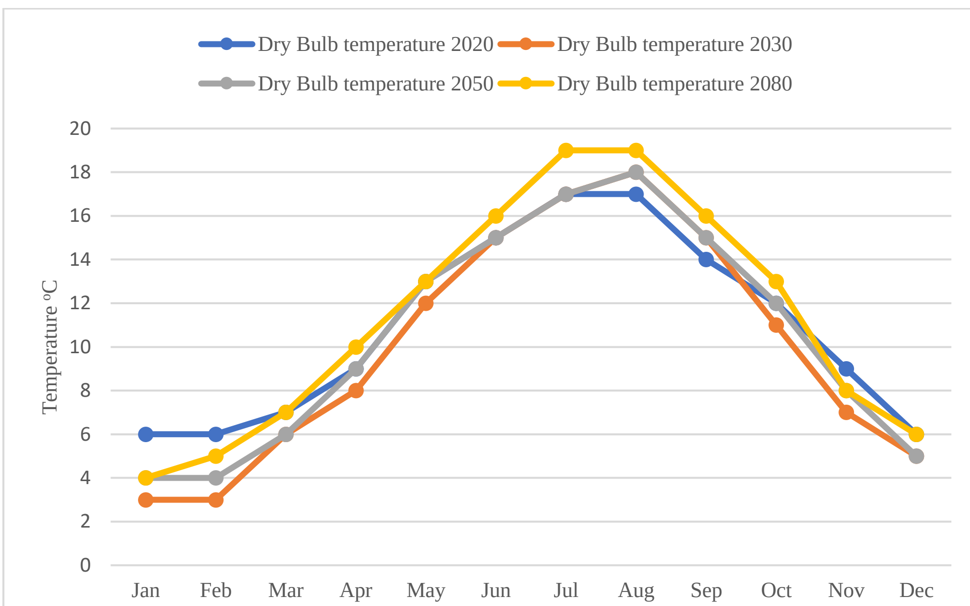


Figure 5. 11: Outdoor temperature on the three timelines.

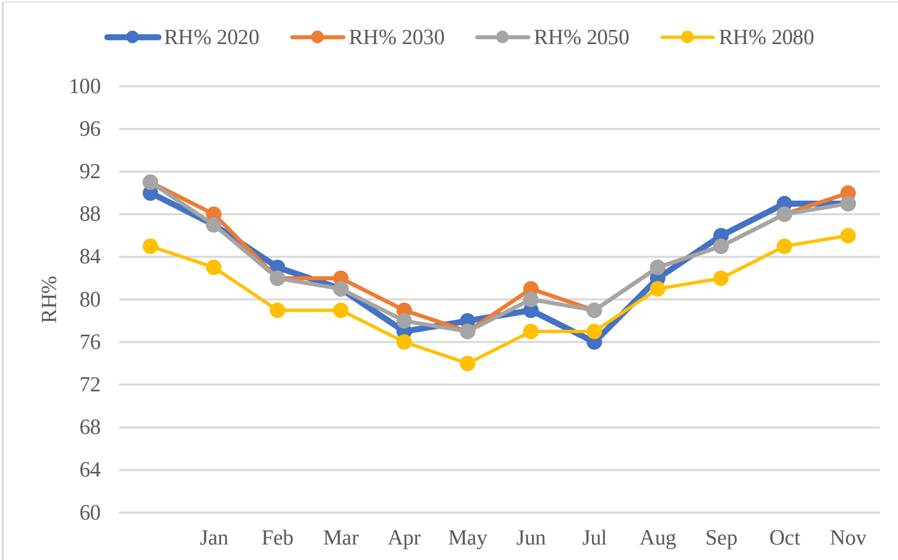
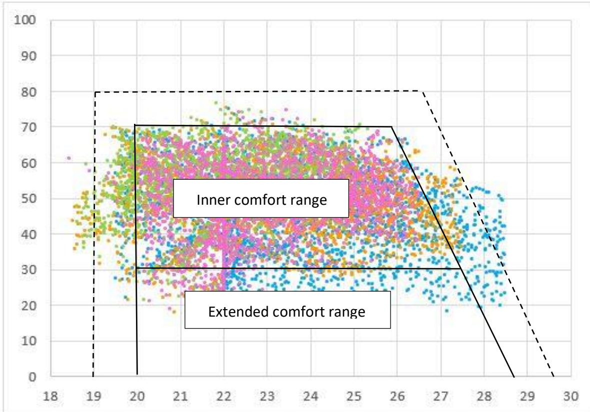
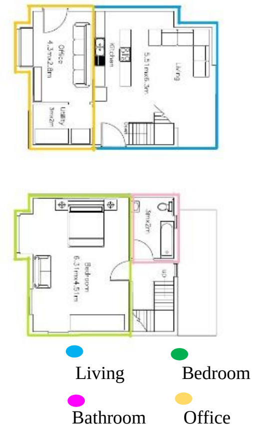


Figure 5. 12: RH% in the current and three timelines.

5.4.3.2 Schneider's thermal comfort

Based on Schneider's thermal model, the SIPs House maintained thermal comfort in the inner comfort zone with some hours beyond the extended comfort zone, especially in the living room/kitchen area and the bathroom, where the average temperature was higher than the rest of the house. In 2030, most indoor hours were maintained within the thermal comfort boundary, with some hours outside the thermal comfort zone. Similar results were found in the 2050 scenario, where the total number of comfortable hours was maintained in the comfort zone, but the living room/kitchen area reported some uncomfortable hours that were above 25°C. In addition, in the 2080 weather files, the thermal comfort model reported a clear shift towards warmer hours, although most comfortable hours were confined to the inner comfort zone, and the shift towards warmer hours was more defined in the living room/kitchen area (See Figure 5.13 A–C).





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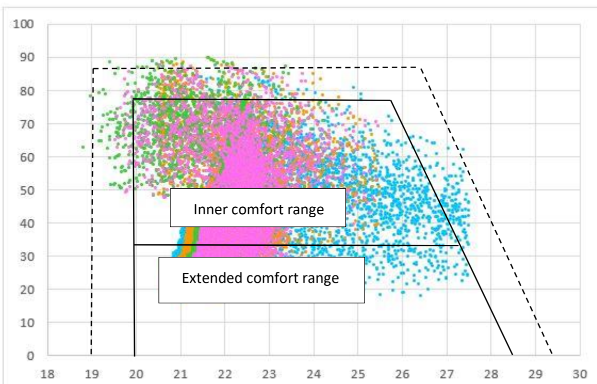
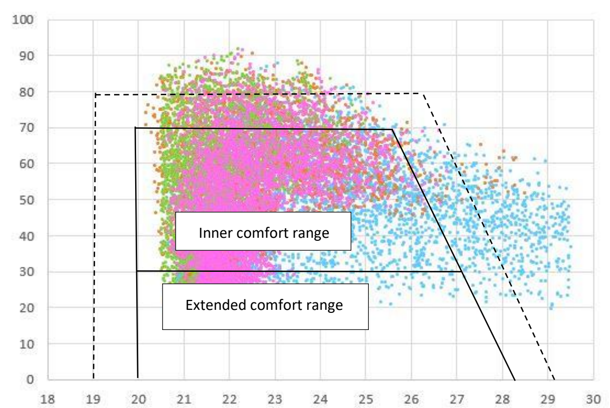


B: 2050



C: 2080

Figure 5. 13 A,B,C: Schneider's comfort model of the SIPs House for the three timelines of 2030-2050 and 2080.

5.4.3.4 Future Envelope performance

The thermal envelope performance was considered for the three timelines using future weather files. The procedure for each timeline was performed in DB by running the base model in the future and switching off the heating supply to assess the overall performance of the SIP walls and assess the ability to withstand the extreme cold weather. Based on findings, the SIPs walls can maintain a higher temperature than the outdoor temperature, this study indicates that the SIPs walls can withstand harsher weather and can benefit from the use of passive solar strategies as a method to reduce energy consumption.

The overheating analysis was conducted using the future weather file and three timelines of 2030,2050 and 2080.The indoor temperature and outdoor temperature were presented and compared in the context of energy and heating demand. The simulated results indicate that heating demand will reduce in all the three timelines, and ventilation system and cooling have been observed in the three timelines, yet no cooling was required in the current years. (See Tabel 5.3). Furthermore, although the ventilation rate remained constant at 3 ac/h in DB throughout the three timelines, there has been a noticeable increase of system fans, which indicates an increasing demand for air ventilation, especially during the summer with a noticeable heating reduction from the base year. Based on LETI, (2020), space heating demand need to reduce to 15kWh/m^2.year when compared with SIPs House heating demand the figures need to cut back by almost half of the current and future weather scenarios without the PV calculation. Further details of PV in the future weather files are provided section 5.7.

Table 5. 3: Energy breakdown in the current and further weather files.

	System Fan (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)
Base year	15	0	33.7
2030	20.1	5.2	32.6
2050	20.2	6.6	32
2080	20.4	7.7	31.7

Moreover, the Kitchen zone was assessed during the summer from May to September in the three timelines because it had the most frequent higher temperature during the summer across the three timelines. The results presented uncomfortable hours where the temperature reached and exceeded >25°C and most of them occurred in the mid-day of the summer. During the summer of 2030, the results indicated that the kitchen area experienced overheating when temperature rose above >25°C where the indoor temperature reached 25.12°C on the 30th of July, and majority of the summer the temperature was maintained around 25°C, this reflect the need for cooling which was reported at 479 kWh for 2030. In 2050 the kitchen presented frequent occurrence of temperatures above 25°C, where the results presented indoor temperature rise from 25.4°C to a maximum 25.9°C. The indoor temperature rise reflected a similar pattern to the outdoor temperature when the outdoor temperature reported 22.9°C, which were the highest during the month of July and August, also, the frequent increase of temperature resulted in a rise in ventilation system consumption. The result indicated an increase of around 28% from the base year with a reduction in heating demand of almost 5%. Lastly, during the year 2080, there have been frequent recordings of indoor temperature increase above >25°C. The outputs reported overheating hours during, June, July, August and September, and the majority of them reported not more than an hour each day during those peak days. The maximum outdoor temperature was reported to be higher than the previous year, with 24°C during July. The 2080 weather file reported a cooling demand of 710 kWh compared to zero in the base model. Please see Figure 14,15 and 16

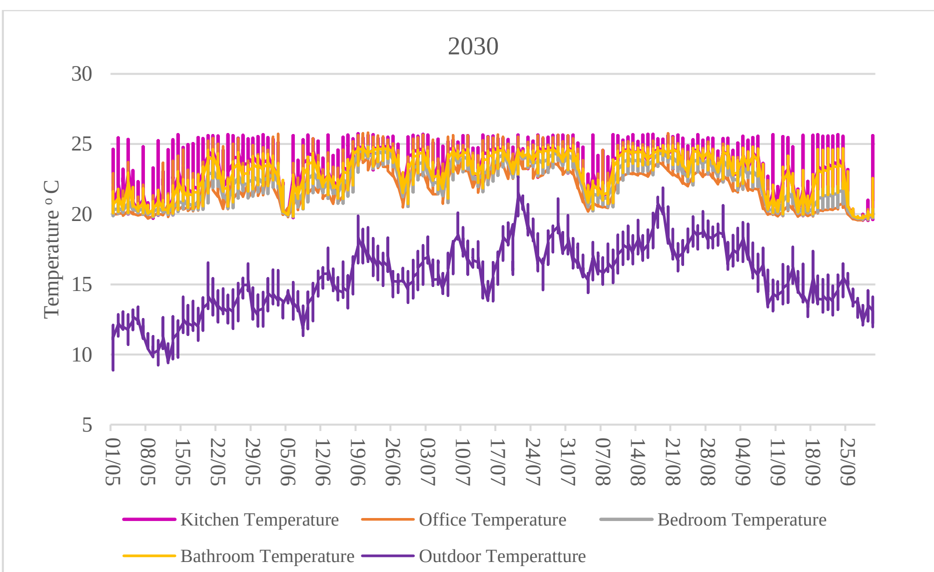


Figure 5. 14: Indoor and outdoor hourly temperature on all the rooms during 2030.

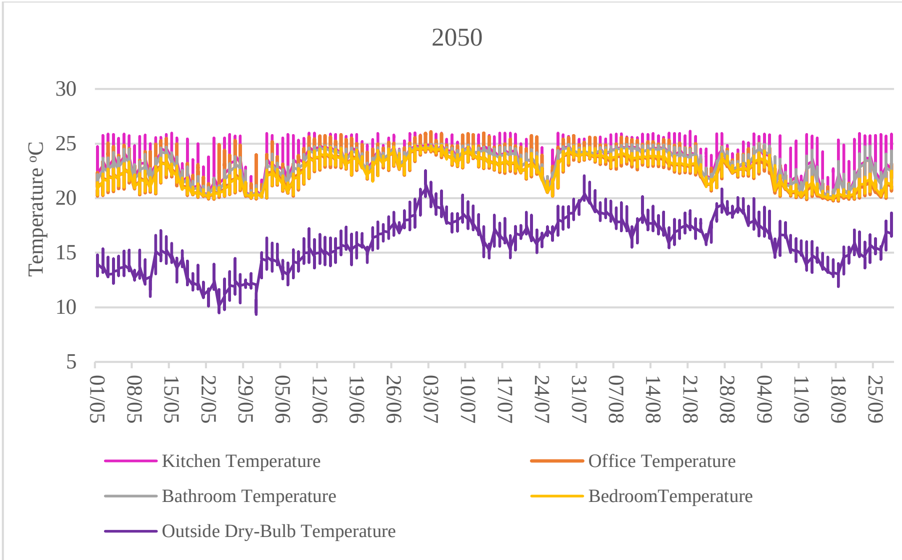


Figure 5. 15:Indoor and outdoor hourly temperature on all the rooms during 2050

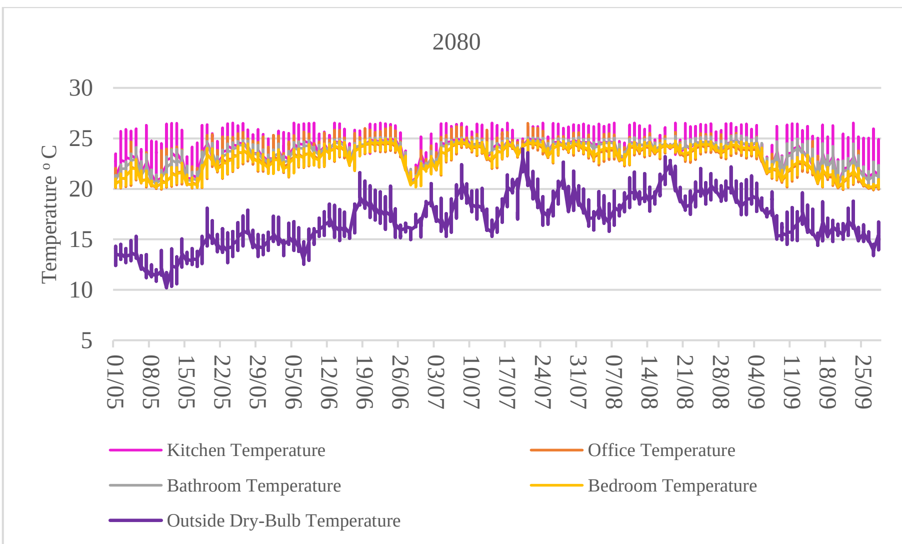
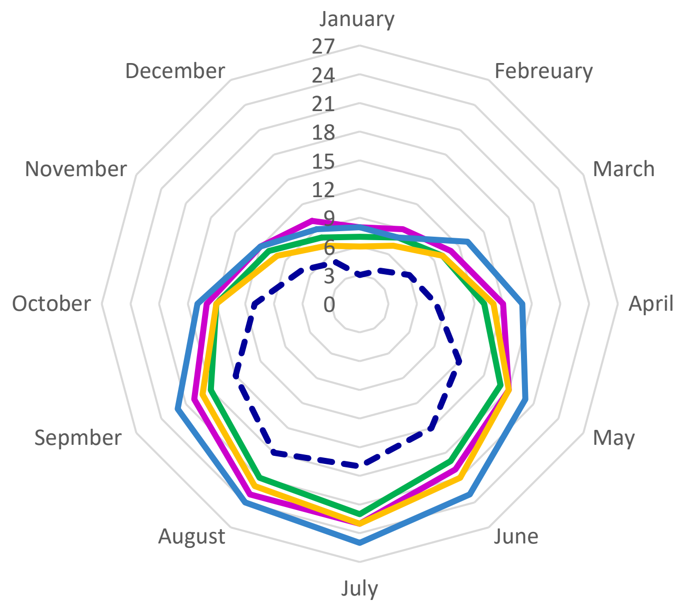


Figure 5. 16: Indoor and outdoor hourly temperature on all the rooms during 2080

In the 2030 and 2050 scenarios, each room maintained a separate indoor temperature with gaps between the data, with each room exhibiting a separate indoor temperature; however, in the 2080 scenario, the gap was diminished, and most rooms had similar indoor temperatures. Each room reported a separate average indoor temperature, which can be clearly seen in the graphs presented in Figure 5.13 A,B,C as shown in the figure, some rooms were colder or hotter than others based on the location and functionality of the space, but in 2080, most of the rooms showed similar results.

As presented in Table 5.3 the heating consumption results will decline over the next century, it demonstrated the effect of climate change on reducing the amount of heating needed and predicted a rising trend in cooling. The house performance based on the fabric and HVAC in the three timelines presented the need for cooling from the year 2030 as the cooling rate was calculated to be 20.1 kWh/m^2 reflecting the overheating assessment during the summer, especially in the month of July. Similar results were predicted in the 2050 and 2080 where heating demand has a falling trend and cooling energy demand were rising, where the highest cooling demand was calculated in 2080, which reflect the overheating trend during the summer where the indoor operative temperature was reported frequently above 25^{o}C.

Moreover, the SIPs wall can retain indoor temperature above the outdoor temperature in the three timelines in colder months but does not match the Passivehaus specification for free running house, as the indoor operative temperature should be 20 ^{o}C and the SIPs House indoor operative temperature in the three timelines were below 12^{o}C . The SIPs fabric when combined with passive solar gain strategies can be useful as a method to reduce energy consumption in the future. Specially that the house is equipped with large windows facing south, the heat gain through glazed windows can absorb and collect heat during the day and release it at night. The findings can be used in the future analysis to investigate passive strategies with SIPs construction material.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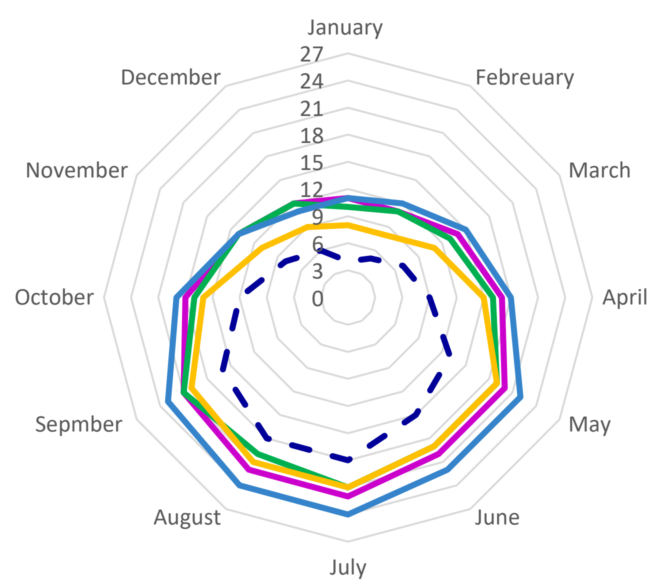
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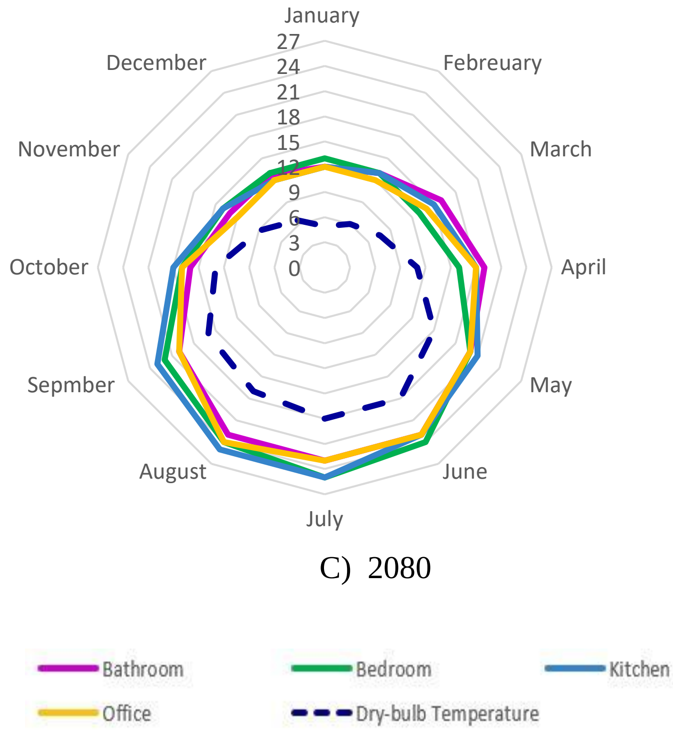


C) 2080

Figure 5. 17: SIPs House future envelope thermal performance in the three timelines of 2030, 2050 and 2080.

5.5 Improving the SIPs House to minimise operational carbon.

To address the carbon reduction objectives, there are eight passive and active design strategies that need to be addressed (Attia et al, 2013), the research presented energy saving strategies that included weather files, orientation, dimensions, north and south windows, wall type, wall insulation and wall thickness. Based on the results presented in the previous section, there were six areas of energy design that covered the overall performance of the SIPs House in terms of durability and energy efficiency. The SIPs House skin proved to be robust, maintaining the thermal comfort level throughout the year, by using the existing mechanical system and occupants' schedules, the indoor thermal comfort was achieved in all the rooms. In addition to the thermal comfort results, the energy consumption results were optimal. With the aid of solar panels on the roof, the house could generate energy and meet most of the energy efficiency requirements. Correspondingly, one of the main aims of the research was to identify whether this type of MMC SIP system is compatible with the net zero carbon target. Currently, based on the results presented above, the SIPs House is almost able to generate its own energy to meet the energy supply.

With the gap presented in energy requirements, another set of studies were conducted to analyse the modification of the parameters of the building by identifying the environmental impact from varying parameters of the study. A number of researchers have used a similar approach to measure the energy impact in a building by modifying aspects of the environment, such as the envelope, mechanical system, OC and opening (Abuhussain, 2020; Al-Graiti, 2021; Khalfan, 2017). The SIPs House was constructed by Dragonboards using the latest MgO panel technology. Since the focus of the study was on the durability of the MgO SIPs skin and whether it can sustain the same level of thermal comfort with minimum energy supply, the energy simulation program DB was used for its powerful parametric analysis feature, which processes multiple simulations when defining two design variables to find the optimum case (see Appendix 1. L).

In this study, the total energy was the main point of analysis when changing the type or thermal conductivity of the variables. The parameter study was conducted to study the total energy saving by modifying the design variables. The study was performed on the base case model over the three timelines using the building envelope, which included the exterior walls, ground floor, roof, windows, glazing type and orientation.

5.5.1 Exterior walls

As discussed above, the exterior walls of the SIPs House are made of MgO SIPs, which consist of two layers of MgO (12 mm) cement-texture outer layer boards and an EPS core (127 mm) with a U-value of 0.15 W/m^{2}K; this currently meets the net zero homes requirements (See Figure 5.2), a typical MgO SIPs exterior wall section. The approach was to optimise the thermal transmittance level of the MgO panels (currently with a U-value of 0.15 W/m^{2}K) via an incremental increase in wall insulation and compare the results with heating demand in the SIPs House. Thermal insulations in walls reduce the heat transfer between outdoors and indoors and contribute significantly to the thermal comfort, therefore, analysing the impact of the thickness was vital for this research.

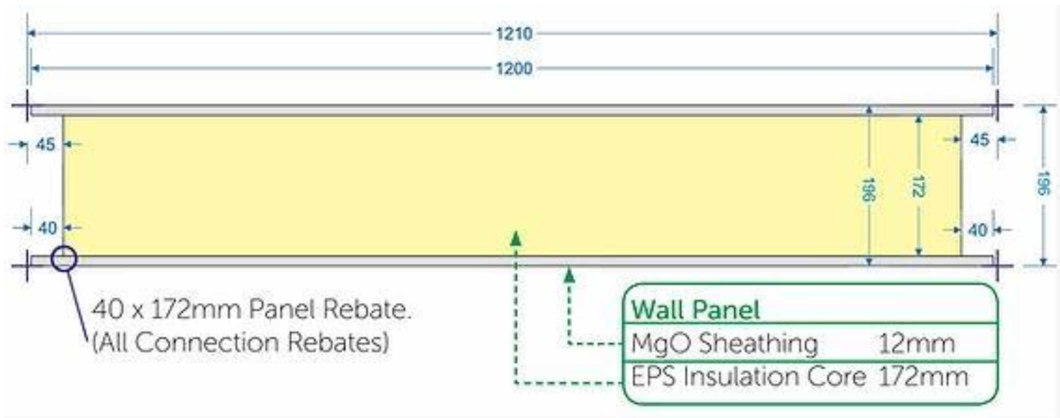


Figure 5. 18: MgO SIPs wall, ground, and roof section.

However, with a 50%-60% increase in wall insulations, the reduction of total energy and heating was evident; the total energy reduced by 6% and 8% respectively, with a U-Value of 0.10 W/m^{2}K .

Heating was reported in the base model to be 3104 kWh and with an incremental insulation increase there has been a noticeable decrease in the heating, where 10% of the insulation layer on the exterior wall yield a decrease of 14% in heating where 60% of insulation thickness increase produced 18%. Refer to Table 5.4

Table 5. 4: The Thermal transmittance with SIP wall modification

Exterior wall Insulation thickness	Energy kWh	Heating kWh	U-Value (W/m^{2}K)
Base model (SIP)	8000	3104	0.149
+10%	7601	2668	0.153
+20%	7573	2640	0.142
+30%	7521	2611	0.133
+40%	7543	2602	0.125
+50%	7490	2568	0.120
+60%	7390	2545	0.118

5.5.2 Roof insulation

The SIPs House was designed with a pitched roof consisting of the three following layers: roof tiles, roofing felt and the MgO SIPs with a 0.195 W/m^2K. The thermal transmittance level of the MgO roof panels was evaluated in this study, the insulation thickness was modified to reach the optimum heating requirements. Similar results to the exterior wall thickness increase, the roof has similar reduction pattern. The results indicated a reduction of 14% in heating demand and 4% of total energy with roof insulation thickness increase which reduced the fabric U-value from 0.195 W/m^2K to 0.178 W/m^2K and according to LETI, (2020) fabric U-values of the roof should measure between 0.10 -0.12 W/m^2-K which was achieved when the roof insulation was increased by 60%. (See Table 5.5).

Table 5. 5: Thermal transmittance with SIP roof insulation modification

Roof Insulation thickness	Energy kWh	Heating kWh	U-Value (W/m^2-K)
Base model (SIP)	8000	3104	0.195
+10%	7620	2687	0.178
+20%	7591	2658	0.164
+30%	7571	2639	0.152
+40%	7554	2622	0.141
+50%	7540	2608	0.132
+60%	7530	2589	0.110

*The roof U-value (W/m^2.k) must be between 0.10-0.12 to meet net zero requirements. (LETI, 2020)

5.5.3 Ground floor insulation

The ground floor exerted a robust structural system. The ground floor has five layers consisting of plywood in the outermost layer, followed by underlay rubber, SIPs, sand and gravel, and concrete in the innermost layer with a U-value of 0.12 W/m^2-K. The ground floor alteration method of increasing the insulation thickness presented almost no major impact on energy saving. Currently, the house consumes around 8000 kWh per year; with heating of 3104 kWh per year, with 10% increase in the ground floor layer a total heating demand was reduce by 13%. The remaining incremental increase from 20% did not have huge impact on heating reduction, as there was accumulative decrease as the thickness of the wall increased to 60%.

Furthermore, the 30% increase of the ground floor insulation matches the LETI,(2020) fabric U-value requirement, given the fact that the ground floor is already highly insulated with the use of cement and increase of 30% yield lower U-value. (See Table 5.6).

Table 5. 6: The Thermal transmittance with SIP ground insulation modification

Ground Insulation thickness	Energy kWh	Heating kWh	U-Value (W/m^{2}k)
Base model (SIP)	8000	3104	0.126
+10%	7639	2705	0.118
+20%	7637	2703	0.112
+30%	7636	2700	0.106
+40%	7635	2699	0.100
+50%	7633	2697	0.096
+60%	7629	2692	0.091

5.5.5 SIPs House site orientation

The building orientation with glazing ratio is the key to minimising energy consumption; The SIPs House is located at 32° NE, with most glazing areas facing SW at 210° (refer to Appendix 1.M) for DB representation of the sun orientation) and surrounded by three walls from east, west and south as shown in Figure 5.20, the modification of several orientation variables was analysed in this research, and the site was rotated at each angle and parametric analysis was simulated. The results from the analysis revealed the best and worst site orientations for energy saving. As illustrated in Figure 5.19, the SIPs House rooftop was illustrated on the compass to present the best- and worst-case scenarios for the site orientation. According to the parametric results' outputs, the least energy consumption was found between 195° and 240° (S and SW), where the energy consumptions reported were between 7928 kWh and 7945 kWh, the simulation result did not reveal any remarkable enhancement in the energy consumption. These results confirmed that the current site orientation of the SIPs House was within the optimum window. The results also indicated that the glazing orientation at 90° has a significant effect on the energy and heating consumption rate. The total energy was reported at 8770 kWh, which is 7% higher than the current annual energy and heating consumption.

Best Location – facing South and SW Worst Location – Facing East

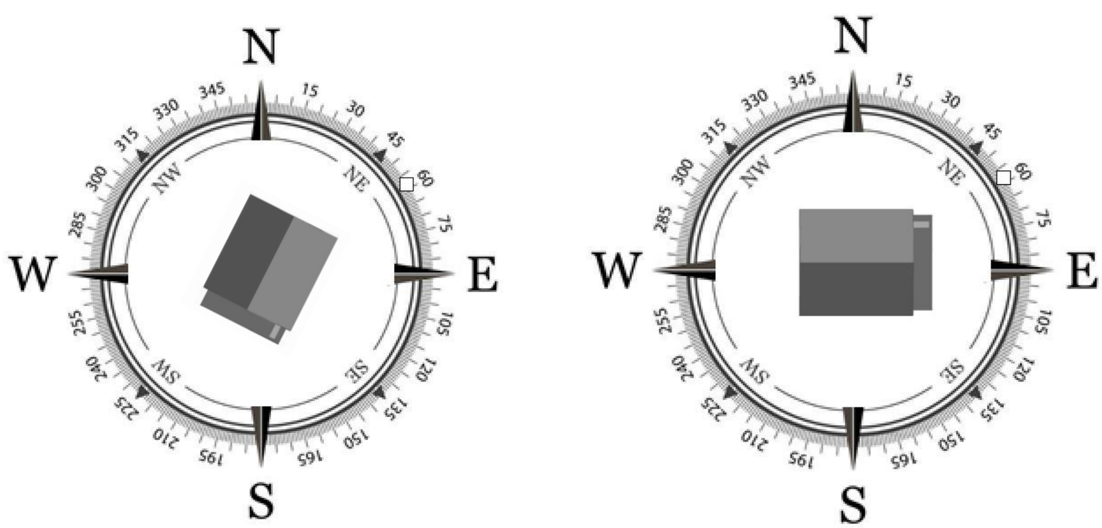


Figure 5. 19: SIPs House Roof top location on the compass for Best and worse site orientation.

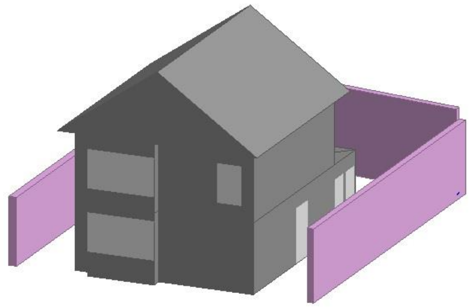


Figure 5. 20: SIPs House representation with boundaries.

5.5.4 Window glazing type

Window type is often considered in many literature reviews as one of the energy saving characteristics. L.De Boeck, et al. (2015) evaluated the use of double- and triple-glazed windows in accordance with site orientation and size and compared them with energy consumption. A similar approach was adopted in the parametric study. The SIPs House uses the most recommended window type by many energy efficiency policymakers—the triple-glazed window—filled with air in between, and this is the case for all the windows in the house. Based on the parametric variables' modification, some of the variables resulted in a higher consumption rate than the existing energy consumption. In the DB library, there are more than 100 types of window glazing; the sections below were either based on feasibility or energy saving. Seven glazing options were selected to study their ability to save energy when compared to the existing glazing type of the SIPs House, with triple glazing and air filling in the gap. The house needs nearly around 8000 kWh of electricity, similar to the existing base model energy requirement. A similar result can be reduced to 7460 kWh is the same type glazing but filled with argon gas instead of air, resulting in a total energy reduction of almost 7%. In addition, the use of triple-glazed windows with a low emissivity (Low-E) metallic coating, which is a technology that uses invisible layers of metallic coating that allows natural light to inter the house and blocking UV light, this method reduces heat gain and creates energy efficient widows —a type of window glazing mentioned as one of the EnergyPlus recommendations for high-efficiency window types (Energy Plus, 2014)—this type of glazing also had similar results to triple-glazed windows with argon gas. In addition to the previous type, Sage glass was also considered in this study. Sage glass uses a similar technology to triple-glazed filled with Argon gas, but this type has the ability to darken the window colour when needed. This technology also did not have a major effect on energy saving, and the total heat load was reported as 7941 kWh.

Another type of window used in this parameter was thermochromic glazing, which is a technology of drastically reducing the heat load entering inside the building by using sun heat during the day to tint the window accordingly and saving on the use of blinds or curtains; however this type yield total reduction of energy to 3% from the base case.

Moreover, an increase in energy consumption of 8298 kWh was found when using triple-glazed Low-E bronze-tinted 6 mm/13 mm windows filled with air were incorporated in the parametric study. Furthermore, in the book of *Designing Zero Carbon* by Jankovic, (2012), the author recommended the use of quadruple Low-E filled with krypton gas; however, the use of argon gas presented similar results at a lower cost than krypton gas, and the results showed that they are almost the same when it comes to energy saving, with a total energy of 7420 kWh (See Figure 5.21).

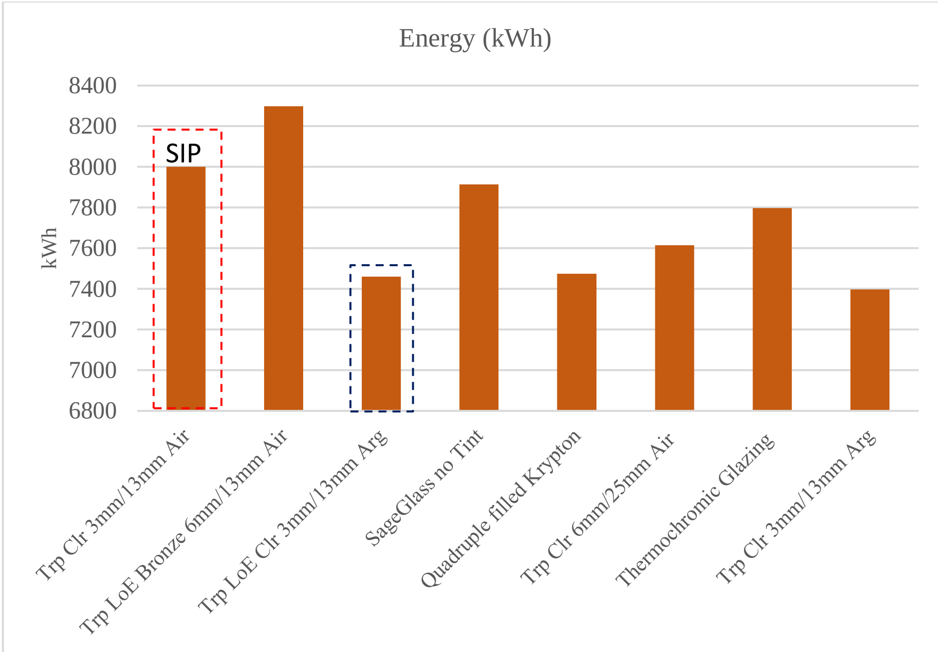


Figure 5. 21: Parametric study of window glazing types.

5.6 Findings and analysis of the parametric study.

Numerous upgrade methods were considered in this research with the aim of saving energy. The focus of this parametric study was on measuring the effectiveness of thermal modification on energy consumption and potentially finding the optimum solution. As stated by Athienitis, et al., (2010) the most important part of parametric analysis is the identification of strategies in early design by methods of reaching optimum design solutions. The parametric study was divided into three main areas: The first stage was to enhance the thermal insulation of the SIP envelope, where the exterior walls, ground floor and windows were configured; the second stage was the site orientation of the SIPs House; and the last stage was window glazing type (See Figure 5.22) for graphic demonstration of the five parametric studies). Several thermal configurations were examined in the exterior walls, where the insulation layers were incrementally enhanced in size from 10% to 60%, and the results were compared with the total energy requirement. The results showed minor changes of almost 2% in energy from 10%-20%, and 1% -12% reduction between 30% and 50%, and the most significant energy reduction was reported at 60% insulation enhancement, at almost

13%. This means that the size of the exterior walls will increase from 127 mm to 166.1 mm.

This massive size change seems to be unrealistic; however, with this type of MMC, the MgO SIPs sizes can be modified based on the construction and energy requirements. The other area of configuration was the SIPs roof; the findings showed that by an increase of thermal insulation of 10%, the thermal transmittance U-value improved from 0.195 W/m^2K to 0.178 W/m^2K, but with 60% increase the U-value was 0.110W/m^2K that meets the LETI fabric requirement, with a direct reflection on the energy saving, where the total energy was reduced by almost 5%. Nonetheless, a notable increase between 30% and 50% yielded a decrease in energy of about 14% and 15%, respectively. However, the most significant energy reduction was presented in the roof was presented when the thermal insulation panels were increased by 60%; this yielded a reduction of 19% in the U-value, at 0.12 W/m^2k, which meets the net carbon zero roof fabric U-value requirement.

The output predicted that the ground floor was more resilient than the roof, mainly because of the complexity of the layers of which the ground floor is made. It was found that increasing the insulation layer of the ground floor had minor changes to the energy saving. In addition, the window glazing exhibited a similar output to the ground floor configuration. The SIPs House uses an efficient window glazing type. In terms of the SIPs House site orientation, the parametric study indicated that the house could perform best in terms of energy saving if it is oriented between 31° and 65° north facing, with reported energy consumption between 8156 kWh and 8023 kWh, respectively. This configuration resulted in no impact on the energy saving because the main orientation on the SIPs House with main glazing area is facing SE, which meets the passive solar design, enhancing energy and environmental performance.

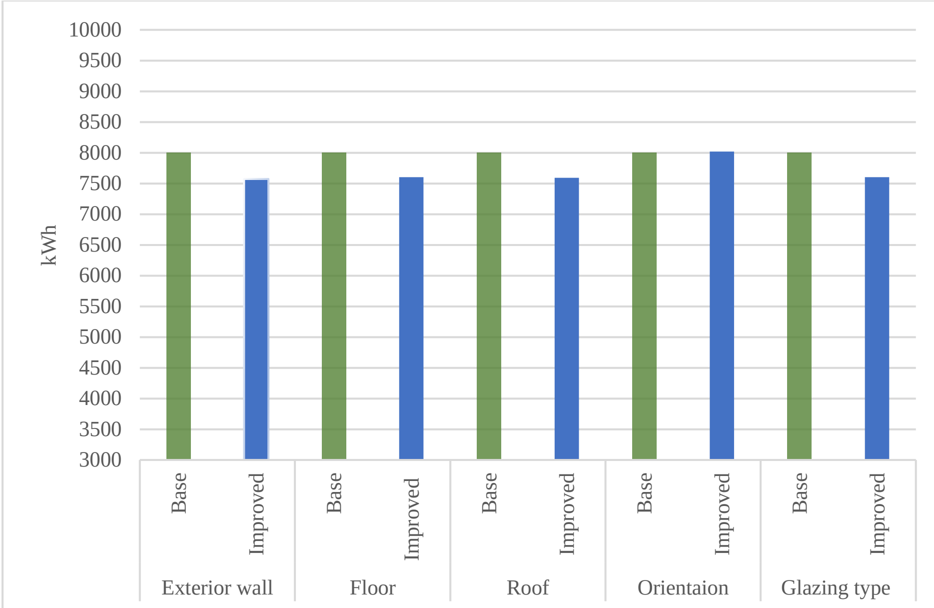


Figure 5. 22: Single effect of the parametric variations on the energy consumption in the SIPs House.

Whereas the main area of focus in this analysis is the modification of the house's fabric, orientation and glazing type, other aspects could be examined, such as lighting, HVAC and home appliances, to enhance the overall energy performance of the house. The results indicated that the most effective areas of energy saving relate to the following main parametric variables: roof insulation enhancement of 60%, making the thickness of the SIP roof 277 mm, can reduce total energy consumption by 8%; exterior wall thermal enhancement can contribute a 6% of energy reduction; and window glazing type changes can contribute to the total energy reduction by 10%; Implementing these parametric variables' configuration strategies can contribute to total energy saving; however, economic feasibility was not included in the design process.

The parametric analysis highlighted a couple of possible outcomes that could contribute to electricity reduction in the MMC of SIPs houses:

1. Improving the thermal properties of the SIP roof by increasing the thickness of thermal insulation.
2. Enhancing the thermal properties of the exterior wall to improve insulation.

3. Modify the window glazing type using argon gas instead of air in between the gaps in windowpanes.

5.7 Current and future energy performance of the SIPs House.

The study carried out in the parametric analysis was intended to reinforce the building's fabric system by fortifying the thermal envelope. In the parametric study, three main areas were identified that need fortifying, which are as follows: the thermal enhancement of the SIP exterior wall, SIP roof and window glazing type. These types of modifications might be additional areas of study focus that require economic feasibility analysis, which is outside the scope of the current research. he outcomes of the research clearly emphasise energy consumption and how these MMCs (MgO SIPs) can be used for the current ZC movement in the United Kingdom.

To achieve NZC or nZEB, the use of renewable energy is required. This type of development (SIPs House) could not achieve the minimum energy requirement for residential buildings on its own because it was not designed to be passive, and there are multiple options in the form of renewable energy to reduce the total electricity consumption. As already described in the previous chapter, the SIPs House uses around 8000 kWh, which is equivalent to 87 kWh/m^2.year and heating of 33.79 kWh/m^2.year , this amount of energy is considered low with similar houses in the UK. According to LETI, (2020) the energy consumption should be 35 kWh/m^2/year without the use of renewables which is lower than the current SIPs house energy rate also the heating requirements is stated to be 15 kWh/m^2/year and the SIPs House currently have almost double this amount. Similar heating requirement by the Passivehaus recommends heating demand to be <15 kWh/m^2/year which is similar to LETI. When the SIPs House compared with the energy standards in term of heating requirement the current heating rate of the house is double the minimum requirement.

Considering the three timelines of 2030, 2050 and 2080, the amount of energy generation from the solar panels was discussed in section 5.4.1, where the results indicated that according to future weather files, the SIPs House is able to generate enough electricity using PV panels to supply the current demand for energy consumption for the current year and produce a surplus in the following years. The next section discusses the parametric analysis implications for energy savings in the three timelines.

5.7.1.1 Energy performance for 2030

Figure 5.17 illustrates the impact of the four following variables: A) triple glazing filled with argon gas, B) 60% increase of roof thermal insulation, C) 60% increase of wall thermal insulation (See Table 5.7 for details). These three variables have an impact on energy savings according to the parametric analysis done on the base case model in DB. The study was carried out by analysing each variable A, B, and C individually to identify the possible energy savings variables that could reduce electricity consumption by modifying the existing variable in the base model. In the 2030 timeline, the total energy consumption was estimated to be 7600 kWh in the simulation program prior to the configuration steps. To identify the variable associated with the most energy savings, energy simulations were conducted in DB. The first step was the modification of variable A, where the existing window glazing type of triple glazing with air filled in the gaps was replaced with triple glazing with argon gas in between window layers.

The results show that by applying variable A, the total energy reduction was around 11%, and variable B had 17% energy reduction, and variables C had the more significant impact on energy saving; the modification carried out in the parametric analysis yield a total energy reduction was around 20%. As a result, the most significant configuration comes from variable C, which is the enhancement of thermal insulation in the roof in the 2030 future slice.

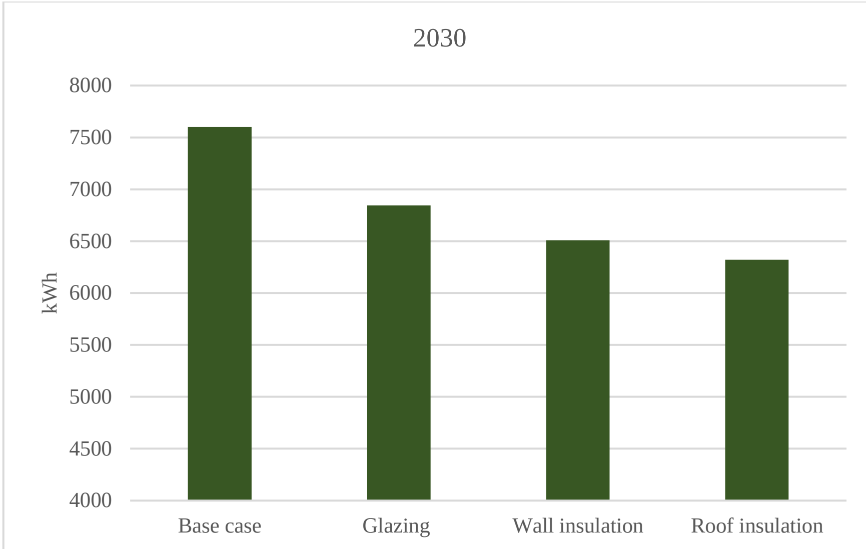


Figure 5. 23: The impact of four types of variation on the energy consumption in future file 2030.

Table 5. 7: Representation of the main parametric variables.

Base Case	Improved A	Improved B	Improved C
SIPs House	Argon gas	Wall insulation	Roof insulation

5.7.1.2 Energy performance for 2050

In the 2050 timeline, the energy consumption was estimated to be 7420 kWh. Figure 5.24 illustrates the total electricity consumption in the base model with different variables. The base model in the 2050 timeline didn't have a higher energy reduction than 2030. Nonetheless, to study the effect of the three main energy reduction variables, the base model of 2050 was modified to estimate the possible energy savings that could be achieved from improving the building fabric. Variable A, which is the change of glazing type, was analysed individually to figure out the total impact of that change on the energy savings; a single change in A managed to reduce the electricity consumption by 9%. Another decrease of electricity consumption was observed in variable B (improving wall thermal thickness by 60%), where the total electricity was reduced by 12%. The most energy saving variable was C (thermal roof insulation enhancement by 60%), where the total electricity saving was around 23%. It was observed that the more thermal insulation was applied, the more energy saving was calculated, and this study found that increasing the roof thermal insulation was the most energy efficient design for 2050.

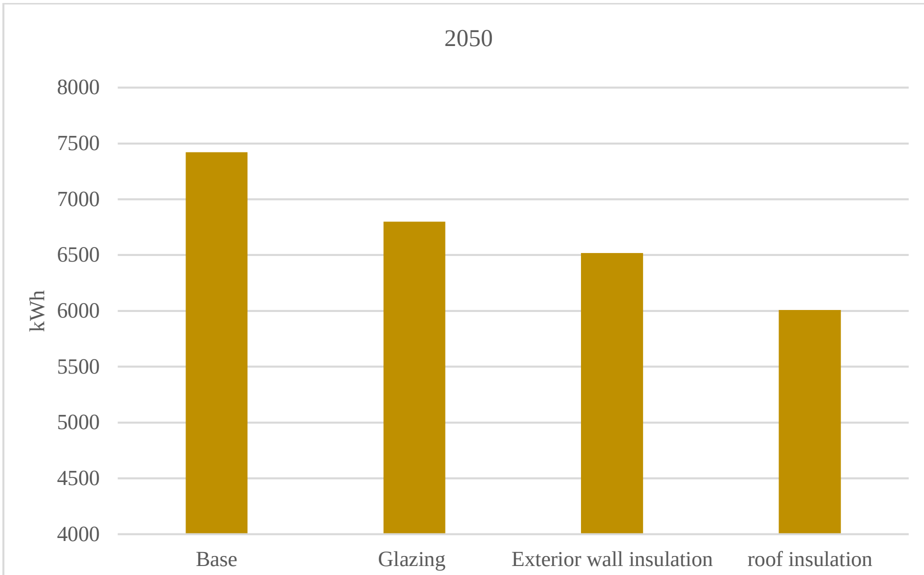


Figure 5. 24: Impact of four types of variation on energy consumption in the future file for 2050

5.7.1.3 Energy performance for 2080

Figure 5.25 presents the individual impact of the parametric study analysis on energy consumption. DB predicted a total energy consumption for the timeline of 2080 to be around 7386kWh. The results indicated that using variable A had minimum impact on energy consumption in the year of 2080 which was 3%, variable B which presents the insulation increase of exterior wall by 60% yielded a similar result to option A of total energy saving 5%. However, variable C had noticeable energy reduction where the total energy was reduced by 18% Therefore, the results suggest that an increase of the roof insulation in the timeline of 2080 has a major change in the energy reduction.

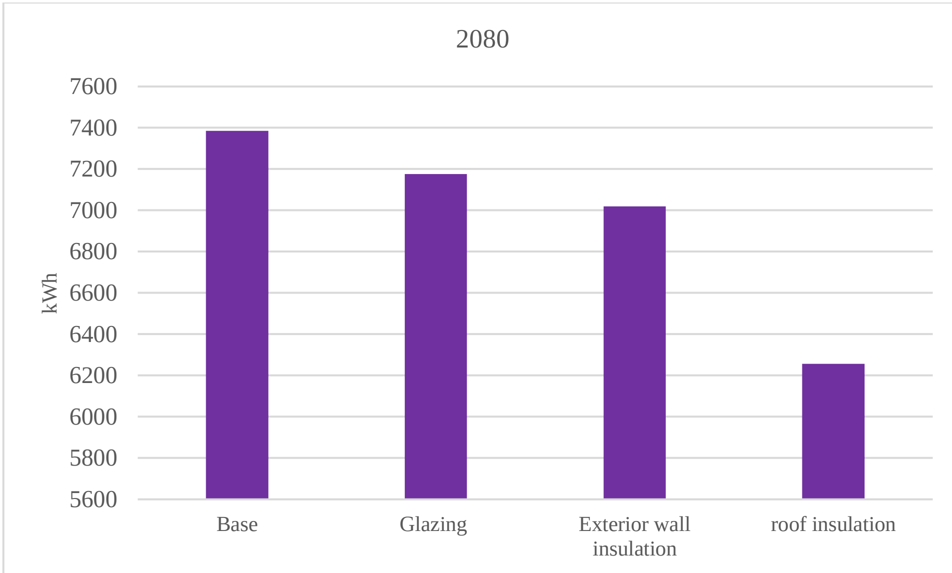


Figure 5. 25: Impact of four types of variation on the energy consumption in future.

5.7.1.4 Optimum model

This section is dedicated to the optimum model case in the three timelines based on the recommendation observed in the study above. The parametric study analysis in DB was conducted to test the model capability of energy saving by configuring the existing building's fabric in the three future timelines of 2030, 2050 and 2080. Three types of parametric variables were tested in the simulation program to identify the energy saving impact of the variables' modification. Based on the energy saving parameters, these three variables proved to have the ability to contribute to energy saving in the base model; therefore, further studies were conducted to test these implications by using the same variables in future weather scenarios. It was reported in the 2030 timeline that the total simulated energy was around 20% from modification of the enhancement of roof insulation layer, and 17% from the exterior wall, however the window glazing variable yield 11% energy reduction. Similar results were predicted in the 2050 timeline where the most effective energy saving reported in the thermal wall enhancement reducing total energy by 23%, but variable A didn't have a large impact on energy saving as reported around 9%. Furthermore, 2080 time lines showed that the most energy saving was variable C with total energy reduction of 18%. Finally, by further optimising the thermal insulation and envelope configuration, energy saving is achievable through these main configurations (See Figure 5.26).

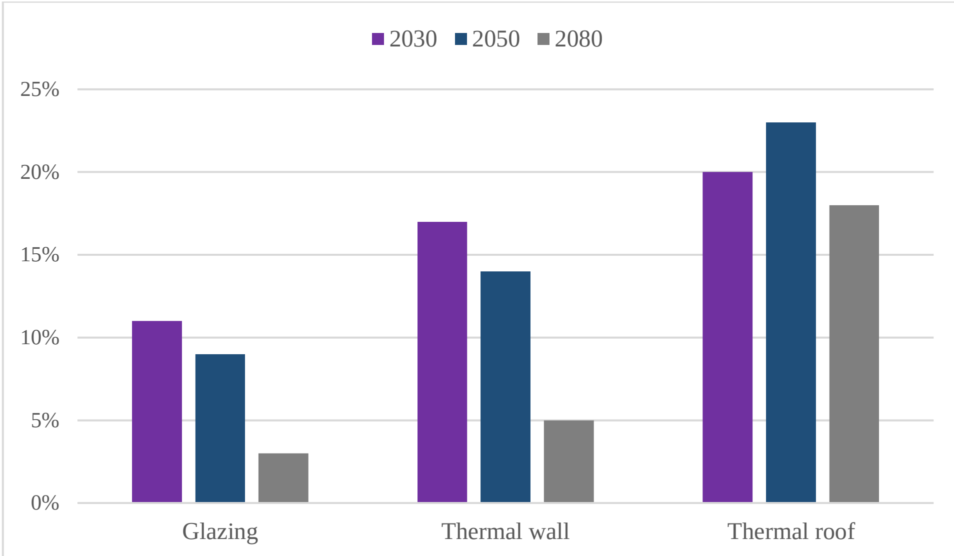


Figure 5. 26: Energy saving using variables A, B and C in the three timelines.

Achieving net zero carbon in the residential sector would require a substantial reduction of energy consumption; nonetheless, decarbonising the energy source is crucial. and the only way of reaching this target is by increasing renewable energy usages. In this study, the first stage of the model was tested for energy saving on its own, sourcing the energy for the national grid, and the second stage was sourcing the energy from the renewable energy offered by solar PV roof panels. In the base model of the current year, the house was able to generate clean sources from the PV on the roof. In the base case the total amount of energy used was 8000kWh in and the total energy generated from the PV of was 6291kWh which covers 78% of the current energy requirement and the remaining of 1709kWh would be sourced from the grid, bringing the net energy requirement to 18 kWh/m^{2}year. In the future weather file of 2030, the amount of electricity generated from the PV technology was estimated to be around 7123 kWh, which covers almost 93% of the 2030 energy requirements, with this amount of electricity generated from the solar panels, the will only requires 7% from the grid to be Net Zero, which means that the SIPs House will not be able to sustain its energy requirement by 2030 based on the predicted results.

Similar results were found in the 2050 timeline when forecasting the energy used and energy generated. The SIPs House was able to generate 7389 kWh with PV technology, covering the energy requirement by 96% which means the house is almost net zero accoutring as it only requires 4% of extra energy to sustains its power. On the other hand, in the 2080 timelines, it was reported that PV can produce 103% of the SIPs House energy requirement as the predicted net energy was reduced 2kWh/m^2.year, which means that the house can sustain its energy consumption using solar panels in the future.

Moreover, a trend was observed where the PV electricity generation was on the rise throughout the base year, 2030,2050, and 2080 timelines. In 2050 the electricity generation from the PV at the constant rate of 0.18 was 7061kWh which covers 95% of year energy requirement, and in 2080 the total electricity generated from the PV was reported 7631kWh which is 103% of the year energy consumption and creates surplus 245kWh. . Excluding the PV energy contribution, in the 2030 weather file, it was indicated that the energy consumption declined by 17%, making the energy consumption 73kWh/m^2.year. This is still higher than the minimum requirement of most energy efficiency standards.

5.8 Summary

The construction industry is responsible for almost 50% of carbon emissions in the United Kingdom. This is mainly caused by OC, which is sourced from burning fossil fuel; operational energy is an energy used in a building to heat, ventilate, cool, light and operate appliances. Climate change is an inevitable crisis, and many local and international initiatives have been tackling the issue by setting decarbonising targets for existing and new builds. It has been suggested by many energies' efficiency institutes that the most effective way to tackle the rise of energy consumption is to source energy from renewables. Renewable energies are clean and sourced naturally without burning fossil fuel; the most common one is solar PV energy, sourced from the sun, where PV panels can easily be installed on the roof of a house or mounted nearby. In addition, the type of construction materials has a huge impact on energy savings. For example, using well-insulated materials can have an enormous effect on energy consumption, as such materials can sustain thermal comfort within the walls without the need for more energy to be consumed. The combination of the right insulation materials and clean energy can contribute significantly to energy efficiency policy. Around the world and in the United Kingdom, the energy efficiency typology is the focal point, and each country has developed specific energy requirements for each building type.

In the United Kingdom, LETI has specified net zero carbon energy efficiency targets for each archetype. For instance, small-scale housing must reduce its energy consumption to 35kWh/m^2.year, commercial buildings to 55 kWh/m^2.year and schools to 65kWh/m^2.year. The requirements are not limited to the energy consumption but also have implications for the building fabric characteristics, such as the U-value, efficiency rate of the mechanics and building orientation window area calculations. In Europe, nZEB/NZC based on Giordano, et al., (2015) have also developed energy performance based on different climatic zones; for example, a Mediterranean and Continental zone's new single house should limit the energy use to 50–65 kWh/m^2.year and generate 50 kWh/m^2.year from on-site renewable sources. Another well-known energy efficacy standard with a tougher energy requirement is Passivhaus.

In the United Kingdom, Passivhaus has a specific energy requirement that is the lowest among all standards of energy efficiency, at 15kWh/m^2.year similar requirement presented by LETI. As discussed above, the SIPs House has the ability to outperform all the standards by adopting solar PV technology as a measure of energy generation.

The MgO SIPs House in the United Kingdom was selected and investigated in this research to assess its capability to address climate change through its performance. The research also assessed other energy efficiency standards, such as net zero carbon, nZEB/NZC and UK Passivhaus. Three main indicators were used to assess the SIPs House performance, which were as follows: 1) energy consumption, 2) thermal comfort and 3) envelope performance. The results indicated that the current usage of electricity of 87 kWh/m^2.year is lower than the usage of similar type dwellings in the United Kingdom. Furthermore, PV panels are able to generate 78% of the current energy requirement, bringing energy requirement to 1709kWh which is equivalent to 18 kWh/m^2.year, which is lower than all the energy efficiency standards but yet not zero. In addition, the house had an acceptable level of thermal comfort throughout the year, and it was tested in the current year's weather file and for future weather scenarios. The results indicated that almost all the rooms maintained thermal comfort despite some hours being beyond the comfort zone. Moreover, according to the standard, the bedroom average temperature was unacceptable during the summer, where the temperature recorded was beyond the maximum thermal comfort of 25°C; this issue can be resolved through natural ventilation during the summer.

The heating system and hot water are provided by hot water storage tank fitted with electric immersion heater, Hot water from the thermal store is pumped via pipework to a post-heater, which creates hot air that is circulated to each room of the house. The energy consumption was divided into two phases because the first one related to the occupancy rate with vacation; when the base model energy consumption was compared to measurements through the use of the energy monitors in 2018 and cross-referenced with the utility bill, the total energy used was recorded as 7577 kWh. The second phase was the full occupancy rate, where the energy was calculated based on 12 months' occupancy, and the energy consumption was estimated to be 8000 kWh.

Finally, a parametric study was carried out to study the effectiveness of the thermal envelope in the current and future weather files for the timelines of 2030, 2050 and 2080. Based on the parametric studies, several configurations were assessed, and the results indicated that an energy saving of 10% could be achieved in the current year by changing the window glazing type. Nevertheless, the window glazing had the minimum effect on energy savings in the three timelines; instead, enhancing the outer fabric of the SIPs House was the most effective configuration in the parametric studies, with energy savings of 20% in 2050 and 18%. in 2080. This discussion is further expanded in the next chapter, which provides a detailed analysis of the results and recommendations.

Chapter Six: Discussion

6.1 Overview

This chapter discusses and reviews the results provided in the chapter six regarding the carbon reduction plan based on the UK government target. This research aims to provide enough evidence from the results to answer the main question of this research can the SIPs meet the nZEB/NZC roadmap of 2050? Moreover, the chapter underlines the performance of MMC the SIP to combat climate change in the future by extensively explaining and evaluating the findings.

6.2 Heswall SIPs House performance before and after the application of the NZC recommendation.

The simulation results demonstrate that the SIPs House has low energy consumption when compared to similar dwelling in the UK. The total amount of energy was around 8000 kWh which is almost half of the current energy consumption in most of the UK housing. The simulations demonstrate that the majority of energy consumption comes from heating and DHW. The current energy rate was estimated 87 kWh/m^2/year before applying the renewable energy system, the solar panels (PV), The simulated results predicted the total net energy consumption of 18 kWh/m^2/year after the PV system application.

6.2.1 Energy Used

The current energy used was estimated at 87 kWh/m^2/year without the use of renewable energy. Nonetheless, the SIPs House is equipped with photovoltaic solar energy on the roof that generates energy on-site. The use of renewable energy on-site facilitates a significant reduction of OC, thereby reducing a net total energy 1709 kWh. At the present time, energy generated from the renewables could not cover the whole load, to meet the national agenda of nearly zero carbon. Nonetheless, in the future weather scenarios, the energy in the three timelines of 2030, 2050, and 2080 predicted continues energy reduction, with total reduction of energy after the PV application of 89%, 95%, and more than 103%, respectively. Concurrently, there have been noticeable heating reduction in the three timelines and slight increase in the HVAC system, the simulation predicted a slight increase in the fans system throughout the three timelines in proportion to the total energy predicted, this pattern is mainly due to the increase of temperature in the three timelines.

Energy consumption in the SIPs House was measured during full occupancy. The data provided a true energy measurement that gave actual data of every appliance in the case study house. The results indicated that 43% of total energy consumed in the SIPs House came from heating/DHW system, making it the most contributor to energy, and the small power and medium power accounted for 23% and 34%, respectively. In the UK, the nZEB requirement for housing is 44 kWh/m^2/year where some countries have set tighter energy standards than others and each can decide upon how they achieve nZEB through any construction method of their choosing (please refer to Appendix 1. N). In 2018, the house total electricity consumption was recorded at 7,577 kWh/year, and the simulation predicted results at 8000 kWh/year before the PV. (Table 6-3).

Table 6. 1: SIPs House energy and nZEB/NZC requirements.

SIPs House actual	**SIPs House normalised (*DB*)**	**nZEB/NZC requirement**
7,577* kWh/year	8,000** kWh/year	4,048 kWh/year

*Average calculated

**Estimated and simulated, not actual

This research mainly focuses on energy reduction strategy in residential sector to meeting nZEB/NZC goals. As stated in the previous chapter, the heating/DHW system in the case study the SIPs House is the main contributor to electricity usage, as most of the SIPs Houses other appliances are considered low energy. Thus, a reliance on renewables is the direction to generate low carbon energy.

The SIPs House is equipped with solar panels on the roof and demonstrated in the simulations. Simulation results indicated a projection of annual energy reduction and an increase in electricity production from the solar panels of the three timelines. The annual energy generation from the PV was estimated for the base year (2020) to be 6291 kWh/year; now at the current rate of energy consumption, the house could generate almost 78% of electricity to supply the yearly demand, the base year consumption was around 8000 kWh/year, which leaves an energy requirement of 1709kWh which is needed to be supplied for the grid. The outcomes confirm the expected results, as the SIPs House consumes almost half of similar UK dwelling before the PV application, it was expected to meet the energy standards with the help of renewable energy incorporated on the roof.

To incorporate the SIPs House analysis into the pragmatism of achieving nZEB/ZC by 2050, the simulation results were predicted and estimated in the DB for the three timelines of 2030, 2050, and 2050. Based on the simulated result of the future weather scenarios of 2030, two main factors played major roles in energy reduction 1) Roof insulation and 2) Window glazing type, the results shows that energy consumption would reduce by 20% from increasing the roof insulation layer and 17% from changing window glazing. Also the simulation predicts a small reduction in the heating load based on climate change trajectory of 2030; in the timelines of 2050 and 2080, the climatic projection indicates a shift in the heating demand HVAC system, the results presented in 2050 show that are the two major contributors to energy reduction, which are the increase of insulation layer in the roof and exterior wall, also there has been noticeable decrease in heating demand and increase in HCAV system. The noticeable increase in the HVAC system was evident during the summer times with 7% increase. In 2050, the total energy generated from the PV was predicted to cover 95% almost 3kWh/year, this finding confirms that the SIPs House can meet the nearly zero by 2050 requirements. Similar results were also evident during the 2080 timeline, the total energy was predicted 7386kWh which is equivalent to

80kWh/m^2.year before the PV application, the results presented a total reduction of 8% from the previous timeline of 2050, nonetheless in the year of 2080 the energy generated from the PV were predicted higher energy generation as the simulation predicted 7386kWh the energy consumption of and the PV were predicted at 7631kWh, producing more than 100% of 2080 energy rate in the SIPs House. Furthermore, the results of fabric modification presented 18% of energy reduction in the roof insulation, which was the highest in the year 2080, where previous timeframes window glazing, and wall insulation were prominent. Based on the outcomes from the future energy analysis the SIPs House could meet the road to nZEB/NZ by 2050 in the current and in the timeline of 2030 and 2050 but in the year 2080 the total energy predicted from the solar panels can outperform the energy consumption in the SIPs house. The results confirm the literature review of emphasising the need and the importance of incorporating PV as a source of clean energy to reduce the carbon emission in the most carbon producers in the economy which is the housing sector.

6.2.2 Thermal comfort

This section discusses the thermal comfort in the SIPs House by assessing the ability of the walls to maintain a certain indoor temperature and RH% during the hottest months in a year based on the thermal energy models. The thermal comfort of the SIPs House was measured by data loggers on-site to measure the indoor temperature and RH%. and the result were plotted in the Schnieders' thermal comfort chart.

The indoor temperature and RH% were recorded on half an hour interval, and it was performed during the cold winter days and hot summer days. As stated in the previous chapter, the comfort level was measured as temperature range stated for the period of summer and winter time. For occupants to feel comfortable, different operative temperatures must be followed, the indoor temperature range should fall between 20^{o}C and 24^{o}C, and in summertime 20^{o}C to 26^{o}C. Now, the range of indoor temperature can be easily achieved in well-insulated envelopes like the SIPs House, preventing any heat loss during wintertime. The average indoor temperature in wintertime was recorded around 21^{o}C in all the rooms which exception to the living/kitchen area were higher temperature were recorded, and in during the summertime the indoor temperature was averaged 24^oC

During the summer season June, July, and August, the records indicated that the average maximum indoor temperature was recorded at 30^oC, and the minimum average was 19^oC, where the hottest day in the summer was recorded on 26th July 2018. When the maximum temperature reached 33^oC, the minimum indoor temperature was recorded in the month of August, where the indoor temperature dropped till 19^oC. The RH% levels were reported between 30% and 65% during the summer times, and the rates were consistent throughout the hotter months. The measured and predicted data of temperature and RH% were compared for June, July, and August (refer to Appendix 1. O) for average monthly temperature of Wirral). During the hottest months of July, the average indoor temperature was recorded an average of 24^oC with the maximum temperature degree of 30^oC recorded in the late afternoon of July 26th. Furthermore, similar results were found in the month of July with one-degree difference, with the hottest day reported on 24th July 2018. The predicted data results showed lower temperature level than measured ones in July, and the results indicated difference of ±1% degrees higher than the measured data. Conversely, August, which is the end of the summer season, presented a lower maximum and minimum temperature than the previous two months, where the maximum and minimum indoor temperatures were recorded at 28^oC and 18^oC, respectively. Now, the variance between the recorded and the predicted data could be attributed to many factors, it could be environmental or physical; however, the proximity between the predicted and the measured data indicates that energy simulation programme is reliable. Detailed explanation of dynamic simulation and validation is presented in the model-making chapter.

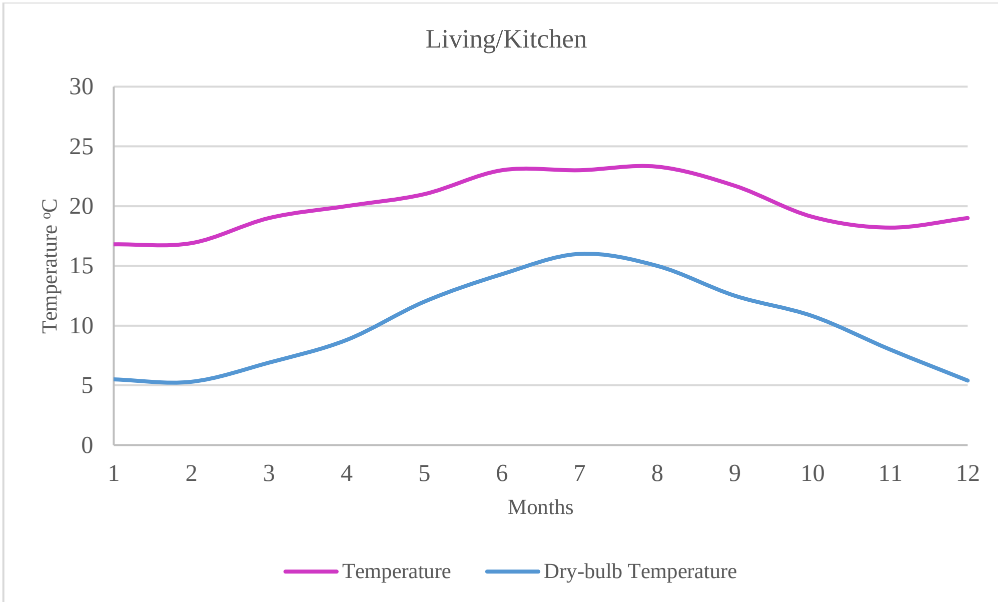
Based on the results of summer indoor temperature recording, the high temperature was not persistence throughout the day; they usually peak during the mid-day when the outdoor temperature rose; however, the results were not persistence in all zones. The ground floor zones comprising living/kitchen and office tend to have similar temperature with Max average of 26^oC reported and are due to proximity.

Based on the results, the Living room reported 477 hours of temperature above 25°C however, based on Passivehaus overheating model the total number of uncomfortable hours recorded were within the threshold. Furthermore, although the bedroom did not record any hour above 25°C there has been few hours recorded beyond CIBSE comfortable threshold of 23°C but they were minimal and not consistence. The first floor tends to be more warmer during the day with max indoor temperature reported at 30°C at one point in the Bathroom. Furthermore, the living/kitchen area benefit from the large operable curtain walls, which supply fresh air from natural ventilation during the daytime—one of the building features to regulate the air temperature. However, this feature is unavailable on the first floor, and further analysis would offer a deeper understanding of the reason behind why the upper floor tends to get warmer than ground floor.

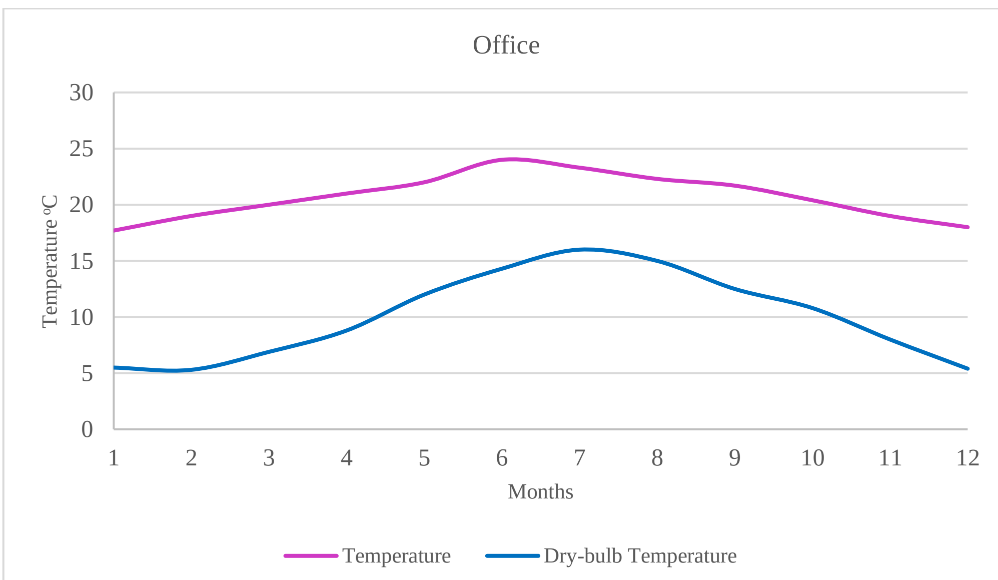
According to Schnieders' model of thermal comfort and the energy consumption, the SIPs House could regulate its average indoor temperature between 20°C and 25 °C in all the zones, with fewer hours beyond the extended outer comfort zone. Moreover, the outcome indicated that, on average, the SIPs House maintained the thermal comfort within its boundary during the summer months, proving that the SIP envelop is a capable system for energy-efficiency building. In addition, the indoor temperature during the summertime was averaged at 24°C in almost all the zones in the house, except the living room where the temperature was reported above 25°C for 477 hours during the year. The Passivhaus indoor thermal comfort limited the threshold of uncomfortable house to maximum 10% of uncomfortable hours during a whole year; now, 5.33% of uncomfortable hours in the SIPs House presents an acceptable percentage according to Passivehaus and CIBSE. Notwithstanding, based on the Passivhaus standards for summer comfort assessment, the results are considered good based on the assessment scale for low-energy homes. The future weather scenarios will impact the performance of the building. In the book of (CIBSE, 2005), the impact of climate change on building was discussed by shifting from heating to cooling demand and providing efficient air-conditioning systems if needed. Also, based on the climate consultant results for the current and future weather scenarios, it was shown that, in the current weather scenario, there were 60% of dependency of heating system for an enclosed environment to be thermally comfortable; however, such a percentage of heating dependency is expected to diminish over three timelines in the future (2030, 2050, and 2080). As the climate change is expected to heat the globe, less heating and more passive or mechanical cooling would be required in the design to maintain the required thermal comfort. For instance, in 2030 future weather files, psychrometric chart showed 17% drop of heating systems, and further reduction in heating system was presented for 2050 and 2080. Adjustment of building design for future weather condition is suggested in the model studied—vulnerable buildings will suffer the most; therefore, a holistic approach of building design should be implemented in the codes of design to realise the nZEB/NZC criteria in the UK. Based on the results presented in the research, the SIPs method of construction has the ability to maintain its thermal comfort and with solar passive design in the future the SIPs will be able to heat the building without the need to extra heating, and therefore a suggestion of implementing SIPs homes in the UK to battle the climate change is recommended.

6.2.3 Envelop performance

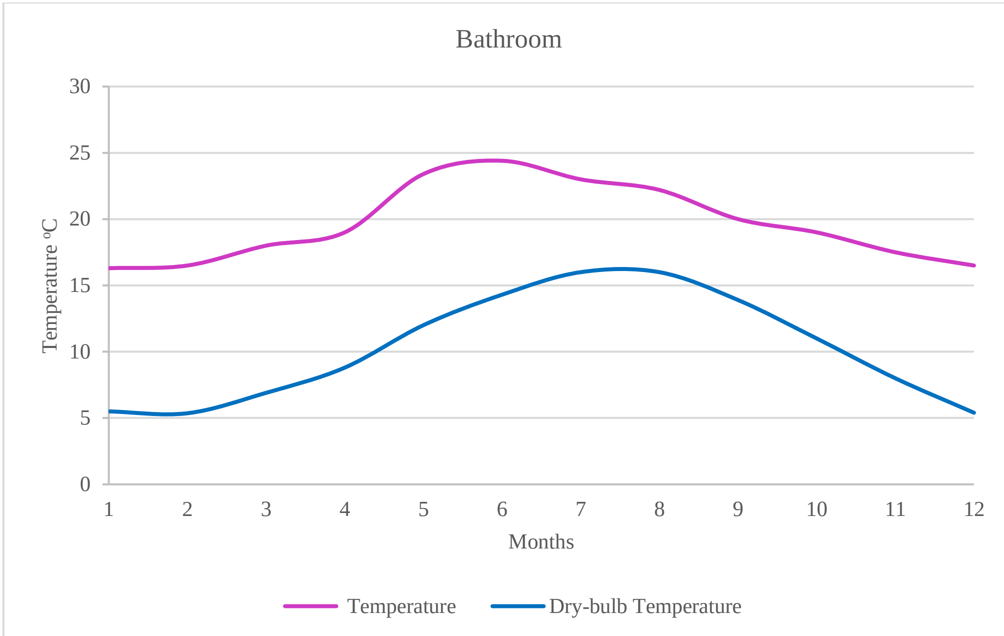
In the last section of fabric assessment, this section discusses the indoor climate based on the current occupancy rate and behaviour and presents the actual data of the temperature recorded throughout the year. The SIPs House thermal performance was assessed using the thermal comfort measurement and parametric analysis of the thermal properties of the walls and openings in DB. Based on the thermal comfort, the house could regulate its temperature against the outdoor dry bulb temperature; during the wintertime from November till January, the heating system is on for three hours per day, and the house could maintain an average indoor temperature of 21^{o}C without the use of extra heating from the air source heat pump placed in the living room/kitchen for extra heating requirement. The results indicated that the indoor average temperature during the wintertime was maintained progressively above the outdoor extreme cold weather—for example, in December, the outdoor temperature dropped below zero for consecutive two days, and the indoor temperature was recorded at 15^{o}C, simultaneously; similar results were found in the month of January. Moreover, winter recording period was especially valuable period of measuring the data since the house's appliances switched off. As stated in the previous chapters, during wintertime, the occupants travel for two months each year for vocations. All the rooms in the SIPs House show that indoor temperature was mentioned above the outdoor dry bulb temperature, proving that the SIPs wall can perform under the extreme weather condition of cold winters of the UK (See Figure 6.1 A-D); however, the summer thermal performance can be unreliable at this stage. The overheating status of the house was assessed using the Passivhaus model of comfort that regulates the maximum overheating hours, and the house was measured during summer period and all the room results were below the maximum threshold. Nonetheless, there were few hours that fall beyond the framed comfort level where the temperature reached beyond 25°C in one day, and the change in ranking order between the simulated and recorded data was found to be more erratic; now, these hours of overheating could be due to too many factors—for example, the ventilation system was not working, or the passive cooling or even internal heat gain measures. Overheating is a complex measure and requires more than maximum indoor temperature to be assessed, as stated in (Zero carbon hub, 2012b); thus, further investigation is required in the summer time to better assess the overheating causes in the SIPs House, and passive intervention could have a potential element to reduce overheating during summer times. These models of intervention could enable the UK housing to tackle climate change in the future without the need for redesign or remodel.


Living/Kitchen
30
25
20
15
10
5
0
Temperature ºC
1
2
3
4
5
6
7
8
9
10
11
12
Months
Temperature
Dry-bulb Temperature

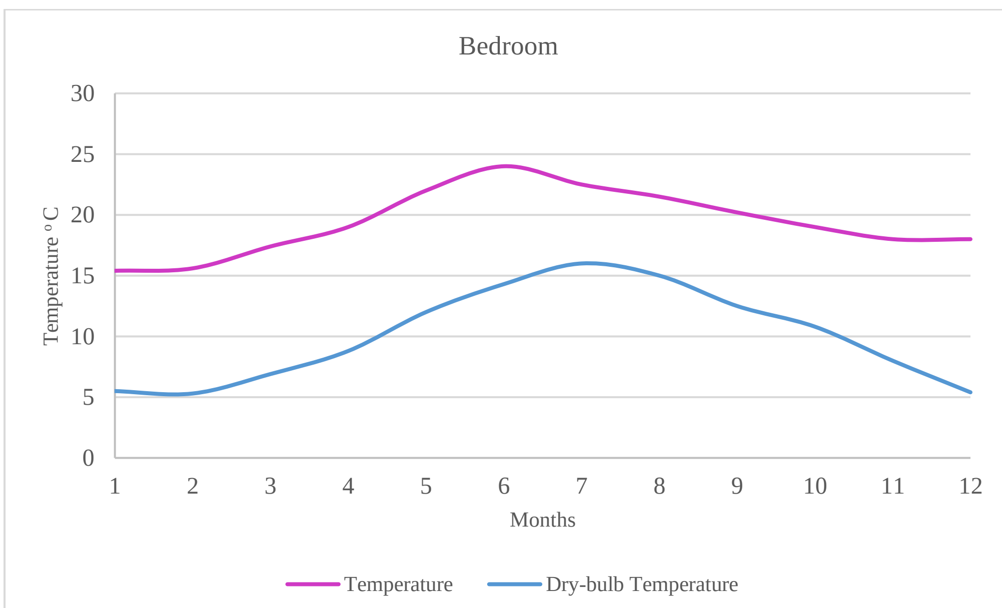
(A)


Office
30
25
20
15
10
5
0
Temperature ºC
1
2
3
4
5
6
7
8
9
10
11
12
Months
Temperature
Dry-bulb Temperature

(B)



(C)



(D)

Figure 6. 1(A-D): Measured indoor and outdoor dry bulb temperature (2018)

The measurement to assess the performance of the thermal walls were conducted in the current weather scenario and further weather scenario of the three timelines. The current assessment indicated that the system could adapt to the weather condition by keeping a warmer indoor climate above the outdoor temperature throughout the day. As simulated during the coldest day on 27 December the outdoor temperature was recorded at -5^{o}C, during this time the house reported an average indoor temperature of 10^{o}C, where the house's appliances switched off which means the house was 15^{o}C warmer than outside. The DB results during the unoccupied period demonstrated the ability of the envelope to maintain thermal comfort in all the zones in the winter, where the indoor temperature in all the zones were reported above the outdoor dry bulb temperature.

6.2.4 Parametric study

Furthermore, the thermal model in DB was investigated in the parametric analysis. Envelope reinforcement is the key element in energy reduction, and six areas within the envelope were investigated to evaluate the most energy reduction factor in the SIPs House. The results showed that the most parametric impact was related to window glazing in the current weather scenarios, and it contributed to more than 10% of total energy consumed in the SIPs House. System efficiency improvement is the most important aspect in energy reduction, the current market offers multiple options of efficient system; nonetheless, investing in energy efficiency systems and consumption reduction is the most cost-effective way to achieve zero carbon rather than changing the whole system when the time will come to enforce all the UK dwellings to be zero carbon. Budget is the key factor in the selecting process. The second important parametric configuration was the MgO panel insulation thickness. In the analysis, an incremental insulation thickness increase was established, where the MgO sheathing layer of 12 mm and the EPS inner foam of the panel were increased from 10% to 60% to identify which thickness has the maximum energy saving factor.

The results showed that from 20% of wall thickness increase a noticeable energy reduction was observed however, at 60% insulation thickness increase there were significant energy reduction in the walls and roofs; moreover, the ground floor had the minimum effect on the energy reduction this is mainly due the robust concrete system. Notably, the six incremental percentage change were back by the fact that the MgO SIPs were prefabricated and designed based on the requirement as stated by the manufactures. However, these special configurations come at a cost and might not be feasible to many users. Energy reduction in the SIPs House can be easily obtained from changing the current heating system. The results indicated that a similar energy reduction is obtainable without the need to increase the wall thickness.

Based on the Zero carbon home criteria of energy efficiency, the SIPs House performance in the current weather scenario indicated that SIPs House performed according to standards. The house could meet some of the energy standards and building regulations. In terms of envelope specification, the house could not match the Passivhaus standards for assessing the thermal properties of the entire envelope through the total calculation of the overall U-values. The analysis of the future performance of the SIPs House was based on energy efficiency measures, and as indicated in the previous chapter, the future performance of the house based on energy measures was subdivided into two main characteristics: the insulation of the roofs and the exterior walls.

6.3 Summary

This chapter presented a detailed analysis of the results' chapter in the Zero carbon homes context. The main goal of reducing energy in the housing sector is to gradually eliminate the use of burning fossil fuel for energy. Given the large scale of energy savings in the residential sector more than non-residential, energy reduction can substantially contribute to the national energy reduction plan. Therefore, the collective effort of energy-efficient initiatives will soon be evident in the carbon emission calculation. The design guidelines and building regulations define the overall approach to energy reduction in the built environment, especially in the housing sector.

In this research, a specific type of MMC was investigated for the first time in the UK, where the carbon impact was assessed in various aspects of the material and design. According to the main current measures of energy reduction, the SIPs House was examined to calculate the total operational in the current and future weather scenarios, and the results suggested that according to energy standards, the SIPs House can meet most building regulations and energy standards. furthermore, the house was assessed in terms of operational energy to estimate the total energy used and compare the results with the Zero carbon and nZEB/NZC energy requirement and building standards. The results indicated that, using renewable energy, the photovoltage on the roof of the SIPs House could generate enough electricity to feed the energy consumption in the SIPs House in the current and future weather scenarios, meeting the nZEB/NZC and Zero carbon criteria. Further assessment was carried out to measure the thermal properties of the envelope systems, as they have a direct correlation with the energy performance. Based on the literature review, there is evidence in the knowledge that it is vital to optimise the building fabric to maximise thermal comfort with less energy.

The level of airtightness in a building is normally associated with energy efficiency; the thermal property of the envelope system, particularly measured by the U-value, according to LETI, (2020) to meet Zero carbon by 2050 they have fabric specification values to be classified as energy efficient for example wall's U-value must be between 0.13-0.15 $W/m^2.K$ and windows for example need to be 0.80 $W/m^2.K$. The outcomes of calculating the overall U-value presented in this chapter indicated that the SIPs House envelope matches almost the Passivhaus U-values, ensuring the durability of the efficiency of the structure system.

The results revealed that to meet energy efficiency building standards, two main areas and three subareas should be considered, the main areas specify the reduction of operational carbon, and the supplement to these main criteria is the use of innovative engineered low carbon method of construction and facilitating the house with energy efficiency equipment that run on the carbon free energy created by the renewables.

Finally, based on the research on energy reduction plans by the government to reduce carbon footprints in the building environment, especially in the residential building sector, with building regulations in place, here are some suggestions and recommendations that could be implemented to further fortify the Zero carbon policy:

1. Based on the current demand and population trajectory of 66.80 by 2050, the UK is obliged to construct about 250,000 new homes on a yearly basis to address the current shortage according to (McLeod, Hopfe, and Rezgui, 2012), the main challenge to address this demand is to meet the carbon reduction by 2050 and, concurrently build to energy efficiency standards. However, by 2050, there will be around 23%, according to Boardman et al., (2007), extra homes in the UK; this number of new stocks in the market would require construction material carbon specifications that contribute to the total energy emissions.
2. The UK government could develop a manifesto in the construction industry that defines the design and material boundaries rather than just the thermal specifications of the walls.
3. The UK government must support MMC (SIPs) manufacturing to boost the prefabricated economy since MgO SIPs have the largest potential for saving energy.
4. The government should support research and development (R&D) in the SIP industry to encourage the construction industry to invest in innovative and intelligent home designs.

To conclude, the next chapter will discuss the main findings of the research by answering the main research questions and supplement questions. The chapter will also discuss the significance of the findings to address the knowledge gap identified in the literature review, limitations of the studies, and possible further research in the field of modern method of construction and final remark.

Chapter Seven: Conclusion and final remarks

7.1 Overview

This research aimed to identify whether the SIPs House was capable of meeting nZEB/NZC building standards by 2050 in the context of the UK residential sector. The research was successfully able to address the aim by evaluating the overall performance of the SIPs House. The research also addressed the research hypothesis, aims and objectives based on the quantitative analysis of the thermal and energy performance under current and future climate change scenarios. The aims were designed to address the current need to develop energy efficient housing in line with government initiatives to combat the rise of global warming and simultaneously address the current housing shortage. The research was also able to calculate the total carbon impact of the SIPs House to identify the carbon parameter of the particulate construction material in the MMC and compare the results with the current carbon reduction plan. This research presented an effective mechanism that could be an added value measure in the climate change and current housing demand context, and by meeting the identified goals, the results could define the holistic approach needed to meet the nearly zero carbon building plan in the United Kingdom. The next section discusses the findings in relation to the thesis questions.

7.2 Responses to the research questions

This section recaps and highlights the research questions provided in the introduction chapter and answers each in detail.

7.2.1 What is the SIPs House energy consumption rate compared with other houses using similar methods of construction?

To answer this question, two research approaches were used—data collection using an on-site energy monitoring energy logger and simulation using an energy simulation program. Measuring the energy consumption for the SIPs House was necessary to investigate the current energy usage to be able to compare the results with similar dwellings in the United Kingdom with similar types of building typologies. However, there is currently limited literature on the energy consumption of SIPs homes in England, particularly MgO SIPs. The only literature currently available is the prototype MgO house in Vancouver, Canada. The house is an experimental project, and it is unoccupied; therefore, the energy consumption reported is mainly simulated. Hence, drawing a realistic comparison of energy from the SIPs house in Vancouver and the UK SIPs House will be based on estimates and not measurements.

Another challenging factor was finding a similar type of construction material in the United Kingdom; therefore, a similar category of energy efficient buildings was used in this context. The building characteristics of the SIPs House, including building materials, the heating system and the occupants' profile, were simulated in DB along with data monitoring on site. Energy results were compared to measurements using two types of validation methods. First, the total energy used mainly from electricity was validated with the simulation results from DB to ensure the validity of the results. Second, the energy consumption was compared to measurements during the winter break, when the house's appliances switched off for two months, and the energy loggers were validated against the simulated results.

The measured energy results indicated that 87kWh/m^2/year of energy was used in 2018, The total energy consumption was reduced because of solar panel installation on the roof, bringing the net energy consumption to around 18kWh/m^2/year with the use of the renewables, and heating was reported 3104kWh. The results were compared with similar types of MMC in the Vancouver prototype house, the electricity consumption was simulated in the prototype due to the fact that nobody lives in it, and the annual space heating simulated was estimated to be 735kWh (Li et al., 2018b), which is significantly lower than the SIPs House current heating energy.

Other examples of energy efficiency homes were selected for this research to draw a comparison of energy using MgO MMC and the traditional method of construction. The first example, called the Caplin home in the United Kingdom, was constructed using solar walls and roofs, and it is one of the low carbon homes recognised by ZC Hub. The total energy consumption was measured as 44.1 kWh/m^2/year. The second home was built with masonry and a highly efficient structure to meet the nZEB/NZC building requirement (Homes et al., 2014). The house energy consumption was measured as 46 kWh/m^2/year. With its very low energy consumption, the SIPs House has the ability to match most of the energy efficient codes and standards, the SIPs House can meet most energy standards, including UK Passivhaus, which is the most stringent energy standard (Boughton, 2012), limiting the energy of residential buildings to 120kWh/m^2/year and heating to 15 kWh/m^2/year. In addition, the SIPs house method of construction is an underutilised construction technique in the housing sector in the UK despite all the environmental and economic benefit that it offers. From a scope perspective, the SIPs House is a resourceful method of construction that meets all the energy efficiency standards and is capable of meeting the nZEB/NZC standard by 2050.

7.2.2 Is the SIPs House really capable of meeting nZEB/NZC standards for the 2050 plan?

As stated in the answers to the previous questions, not all the criteria have been met. The research assessment was divided into two aspects—the fabric performance, where it failed in one area which is the roof U-Value rate, and the energy performance of the building, where it passed. The research findings are as follows:

1. Energy performance

nZEB/NZC are highly efficient buildings that are usually connected to a national grid and rely on on-site renewables' energy to balance their energy demand. The current energy standards require all residential buildings in the United Kingdom to limit the primary energy rate to 44 kWh/m^2/year; however, this rate could be around 0 kWh/m^2/year when conditions are suitable, typically because of renewables used on-site or fed in from nearby green stations (Kurnitski et al., 2011). Based on the research energy analysis, the primary energy demand for the SIPs House was estimated to be around 8000 kWh in 2018 after normalising the energy rate, which is equivalent to 87 kWh/m^2/year before the implementation of the PV technology and around 18 kWh/m^2/year with PV. Furthermore, the results from simulations indicated that the amount of energy generated from the solar panels was not able to cover the current consumption rate in the base model, which brings the net energy of the SIPs House to around 18 kWh/m^2/year, which means that the majority of the energy demand was not met by the solar panels. However, in 2050 the total energy generated from the PV was estimated 7398 kWh and energy demand was 7420 kWh which brings down the total net energy to almost 0 kWh/m^2/year. As a result, the SIPs House is capable of meeting nZEB/NZC standards by 2050.

2. Fabric performance

The building fabric was assessed using the building's four elements, which are the exterior wall, roof, floor and window glazing. The building air permeability was reported in DB to be 0.60 $m^3/(h.m^2)$ at 50Pa based on the SIPs House SAP report. Over all the results showed that SIPs House fabric performed very close to the Passivhaus standards, where the walls U-Value was 0.15 W/m^2K, the floor had more rigid system with U-value of 0.12 W/m^2K however, the roof had higher U-value reported at 0.19 W/m^2K and the energy efficiency state the U-value to be between 0.08-0.10 W/m^2K according to (LETI, 2020).

The nZEB/NZC set minimum standards for energy efficiency through two main criteria—the highest standards of envelope efficiency and a low-carbon heating system. However, the latest report published on future homes (Ernst & Young, LLP, 2021) emphasised the need to shift the current focus towards fortifying the envelope to save energy rather than changing the heating system. Furthermore, although the fabric performance did not exactly meet the energy efficiency standards in the UK, which are the highest energy standards in the United Kingdom—mainly due to the roof U-value rates not meeting the current specification—the SIPs House energy performance did meet the current nZEB/NZC standards.

To conclude, by referring to the research hypothesis and questions to identify whether the SIPs House is capable of meeting the nZEB/NZC for 2050 in the United Kingdom, the results show that through multiple assessments, the SIPs House has the capability to meet the nZEB/NZC standard for 2050. This mainly in terms of the energy performance: Although the SIPs House has a building fabric efficiency rate that is close to the Passivhaus design standards, the results show a slight difference, disqualifying it from the Passivhaus standards. Building fabric specifications play a major role in energy efficiency standards as the building elements dictate the amount of energy used. It was evident in the parametric analysis that with lower U-values of the elements, less energy was required to maintain the thermal comfort indoors.

7.2.3 How well does the envelope of the SIPs House perform under the current and future UK climate?

To evaluate the current and future energy performance of the SIPs House, it was necessary to use current and future weather files in EPW format to be readable in the DB simulation program. Data were obtained for the three future timelines of 2030, 2050 and 2080. Meteonorm (a weather generator tool) produces monthly, daily and hourly weather data from all over the world, the program also includes IPCC emission scenarios for four storylines (A1, A2, B1 and B2) and projections to the year 2100 (2000 - Emissions Scenarios Summary for Policymakers, 2021; Meteonorn, 2020). These data were used in the simulation program, which demonstrated the changing pattern of temperature over the years as a result of global warming, which predominated in the usage of the heating supply. As the temperature is predicted to be on the rise, the heating consumption presented a slight reduction in heating and 2030, 2050 and a sharp decline over timelines of 2080.

On the other hand, SIPs House has the highest stake of energy consumption of 43% of total energy used. The current heating system is powered by a 300 L Daikin EKHWP300B hot water storage tank that also provides hot water for the house, Furthermore, in the parametric modification process, which included four main modification criteria's— walls, floor, roofs, window and orientation —the results showed that the window glazing type had the largest stake in energy consumption in the current weather files. Also, by identifying other parameters in the parametric study, it was evident that fabric contributes significantly to the energy reduction in the SIPs House, for example the in the current weather scenarios the roof's U-value of 0.195 $W/m^2.K$ was higher than the recommended values provided by LETI,(2020) of limiting the roof to 0.10-0.12 $W/m^2.K$ a and the study recommended an amendment of the current roof U-Value to match the current ZC standards.

Nonetheless, the results indicate that heating demand will decline over the years based on future weather scenarios, heating requirements will slowly become less significant and cooling demand will be an essential system that future homes need to adopt to be comfortable.

7.2.4 How does the SIPs House compare with other energy efficiency standards like Passivhaus?

A full assessment of the SIPs House was conducted in the research against other energy efficiency standards, including Passivhaus, in the Results chapter. Passivhaus in the United Kingdom has stringent building standards when compared with other energy efficiency building regulations; however, based on the Passivhaus energy standard, the findings indicated that the SIPs House energy, which takes account of the energy for space heating, DHW, fixed lighting, and HVAC, the results indicated that the SIPs is closer to double the maximum permitted annual primary energy of the Passivhaus standard, without the use of renewable energy. This is because Passivhaus does not consider the use of renewables in the design, and the main goal of passive design is saving energy rather than producing it (Mitchell & Natarajan, 2020); therefore, the total energy generated from solar energy in this research will not be included in answering this question. As a result of eliminating PV energy from the calculation, the current energy requirements of the SIPs House presented in the research does not meet the Passivehaus standard. The true comparison lies in the essence of the fabric and its technicality to prevent heat loss from the building. The building fabric was assessed in terms of the four following elements: the exterior walls, the floor, the window glazing and the roof. The results indicated that most of the SIPs House building fabrics meet maximum requirement, with the exception of the roof.

Thermal comfort is another parameter in the building standard of passive design to assess fabric performance throughout the year, and it is measured in a total percentage of uncomfortable hours in a year. To conduct thermal comfort analysis, the UK Passivhaus standards (Passivehaus Trust, 2019), was implemented in the study, and acceptable thermal comfort was recorded in all the zones of the house despite a few uncomfortable hours being recorded in the master bedroom. The total number of uncomfortable hours per year is represented in a percentage not exceeding 10% over the course of a year, which has been discussed in the thermal analysis of the SIPs House in (Section 6.2.3). The results indicated that the total percentage of uncomfortable hours in the SIPs House did not exceed the threshold which results a matching to the Passivhaus overheating standards; this suggests that the robust building envelope is able to adjust its indoor temperature to the outdoor temperature during summer to prevent overheating, which is one major disadvantage in super airtight buildings like the Passivhaus. This leads to the conclusion that although the SIPs House does not technically meet all the fabric standards of Passivhaus, which are a requirement to create very airtight envelopes, it was successful at meeting energy standards without the use of PV panels in the calculation. As a result, the SIPs House has been proven to achieve energy efficiency standards and is consistently comfortable throughout the year.

7.2.5 Can the MgO SIPs House be classified as an energy-efficient design for the future?

MgO SIPs were created based on the energy efficiency principle to minimise construction waste and time and subsequently reduce energy in the manufacturing and installing process. At the same time, they were made to maximise design and environmental benefits by providing flexible design strategies with less EC to tackle the environmental crisis and adherence with the nZEB/NZC building standard, which states that the best method of constructing highly energy efficient housing is through implementing the best performing measures. Therefore, there are multiple criteria approaches in the housing industry to classify a given house as highly energy efficient, including nZEB/NZC, UK Passivhaus, smart houses, eco-homes and future homes. The most recent one with a tougher standard is the ZCH. ZCH is a recent policy by the UK government that focusses on making homes ZC, which is currently the focus of carbon reduction. According to the Royal Institute of British Architects (RIBA), the ZCH consists of a whole life carbon approach, where an eight-stage plan of work can be applied to any construction project.

The main target of achieving very low carbon in the operational segment is the use of 100% electricity powered by renewables and the use of low energy materials from re-use. The SIPs House is built from low energy materials and the panels must be re-usable in the end-of-life disposal. Furthermore, the house is powered by solar panels on the roof and generates almost the same amount of energy consumption. The simulation results showed that the total annual energy consumption for the SIPs House was 7577kWh in 2018; this was later normalised to 8000 kWh to match the 12-month occupancy rate. The results from renewable energy were 6291kWh of electricity generated from PV technology. Although the current energy reduction trend follows the reduction of operational energy rather than the embodied energy, this matter has been discussed in an article by (Hopkirk, 2021) in terms of future home standards, where architects criticised the government for not emphasising the need to incorporate the embodied energy as a requirement in the standard.

The base case was simulated in the future climate change scenarios in three timelines of 2030, 2050 and 2080, and the results indicated that with a temperature rising pattern, there will be a reduction in the energy consumption in the three timelines. The parametric analysis was conducted using the base mode in the three timelines, with all other variables remaining the same, and different results were presented based on the year. The results showed that in the 2030 timeline, the total energy reduction was insubstantial; however, for the following timelines of 2050 and 2080, the total energy reduction was significant, and when compared to the total energy generated from PV panels, the house could generate enough electricity that were similar to its energy usages. For this reason, the SIPs house is capable of being energy efficient in the future.

7.3 Research limitations

The research scope of this study was limited to assessing the capability of the SIPs House to meet the nZEB/NZC requirement for 2050 in the United Kingdom. The assessment was mainly focussed on building energy performance in line with the government's roadmap of reaching nearly zero carbon by 2050. The following section provides a detailed discussion of the limitations faced by the author throughout the research:

- The research's main objective was to investigate the capability of the innovative MgO SIPs to meet the nZEB/NZC energy reduction roadmap by 2050 in the United Kingdom. The scope of the research was limited to analysing one case study available in the United Kingdom, the SIPs House which made it challenging for the author to compare the results and evaluate them with similar methods of construction in the United Kingdom. Therefore, the results presented in this research are limited to the case study and cannot be generalised to the UK construction industry. The rationale of this research was to evaluate the energy performance of this type of construction in current and future climate change scenarios, which required an assessment of the fabric specification, energy consumption and thermal comfort. The limited resources for accessing similar building typologies in the United Kingdom made it challenging to comprehend the total potential of this particular method of construction. Therefore, the author relied on the estimated results from the simulation program and compared them with other energy efficiency models in the United Kingdom and in the world.

- In the model making and calibration process, the research was challenged by some limitations—namely, uncertainties related to the simulation results. The results were based on the rational assumption of the occupant's behaviours throughout the day, and they were kept constant for 12 months. However, the occupants evacuate the house for 2 months every winter, which is the most energy-consuming time of year; therefore, it was difficult for the author to identify the occupants' heating profit, home appliances and lighting usages. As a result, the author had to depend on the verbal communication from the homeowner about their average daily heating profiles and estimate the results with the average heating demand from the other months.

- In addition to uncertainty about the simulation results, there were further limitations with the validation process. Some have been discussed in the model making and validation chapter in this research. The total energy used was validated using the meter reading and compared with the simulation results; however, the energy logger was connected directly to the house electrical supply unit and transmitted the whole energy demand on an hourly basis. It would have been ideal for the author to collect energy demand individually rather than as a whole kWh measurement for the entire house. This was mainly because of technical limitations and the positioning of the home appliances, which made it difficult to connect the energy loggers directly to the electrical devices. Another limitation was the uncertainty of the energy simulation results based on the future weather scenarios. These future weather files built on an assumption created through probabilities to predict the future weather and related emission scenarios; the results are uncertain mainly because the future weather files primarily depend on future anthropogenic behaviour, and the predictions are based on the current environmental variability (Collins et al., 2018).

- Finally, although a single case study can provide more detailed analysis than a generic study can, its results are often limited to the specific case and cannot be generalised to all, since the data collection is very specific, pertaining to a certain location, climate zone and occupant profits. As a result, a singular case study might not be sufficient evidence to change a building standard or amend a policy.

7.4 Future research

MgO SIPs materials are consider quite new method of construction in the UK housing sector. This creates many opportunities in the field for work that could be carried out in the future. Based on the limitations stated in this research, the following list provides some prospects for further investigation:

- Further investigation could evaluate the energy consumption of MgO SIPs as a method of construction in different archetypes, such as semi-detached homes, apartment buildings, or even hotels.
- This research was conducted in a suburban area in the Northwest England, and further investigation could take place in a rural area in the south of the UK with a high-density rate, for example, the city of London. The study could analyse the SIPs house fabric and energy performance under the Urban Heat Island Effect in the city of London.
- Further study could investigate the energy performance of the SIPs House in detail by monitoring each home appliance separately.
- Further parametric studies could be carried out by moving the SIPs House model to different climate zones anywhere in the world and testing the fabric performance based on the geographical location.
- Another investigation could be carried out on the actual electricity generated from the PV panels and comparing the results to the simulation outputs for better evaluation of the electricity consumption and demand.

- To study the financial feasibility of building MgO SIPs homes in the United Kingdom.
- Additional monitoring loggers and measuring tools could aid in understanding and evaluating the use of MgO SIPs.
- Further study could focus on the window/wall ration (WWR) in detail.
- Further investigation could remove the whole heating system from the SIPs House and replace it with Passivhaus techniques of heating through MVHR or other low-carbon heating technologies, such as hydrogen.

7.5 Recommendation

The results of this research could benefit different parties in the UK economy, such as the SIPs manufacturing industries, policymakers, designers and homeowners. The research outcomes provide some recommendations for these parties as illustrated in the lists of recommendations below.

7.5.1 Recommendations for the SIPs manufacturing industry

- Continue investing in research and development in SIPs.

- Work closely with climate change initiatives and understand the impact of CO_2e on the built environment.

- Conduct ongoing training for the community to understand the benefit of using SIPs as a method of construction to promote public awareness.

- Work closely with the government on social and affordable housing to keep up with the current housing demand and simultaneously deliver homes that are built to ZC standards per the UK carbon reduction roadmap.

7.5.2 Recommendations for UK policymakers

- Promote the use of SIPs as a method to combat climate change.

- Support local SIP manufacturers by compensating them for some of their carbon emissions to support their continuous investment in creating innovative ZC structural panels.

- Enforce a building policy that necessitates presenting the carbon emission from the embodied and operational energy prior to project delivery.

7.5.3 Recommendations for designers

- Implement building performance simulation software, such as DB, in projects as an environmental indicator to assess the carbon impact in the preliminary design stages.

- Work with different types of building materials in the design that comply with the UK building standards and without the need to compromise on aesthetics.

- Discuss the impact of climate change with the clients, present operational and EC reports during the early stage of design and discuss methods technologies to bring the project emissions to zero.

7.5.4 Recommendations for homeowners

- Understand the economic and environmental benefits of implementing low energy methods of construction.

- Take advantage of promoting solar panels on roofs and work with local authorities to compensate for the access to electricity generated from PV technology.

- Maintain social awareness of the need to buy or build ZCHs.

- Take advantage of smart home appliances and save energy.

7.6 Conclusion

As the United Kingdom continues to commit to carbon emissions reduction, more new policies and standards will be developed and the economy needs to be prepared and adaptable. Decarbonising homes and businesses in developed countries like the UK might be easier than it is in less developed countries, mainly because of having access to all the innovative materials and methods to tackle the rise of CO_2e. The first step in the carbon reduction map was when the government committed to reaching nearly zero carbon levels by 2050; all the EU countries, including the United Kingdom, signed a legally binding agreement and the main target was a total reduction of 80% of the 1990 carbon emission levels. Later, this commitment evolved to an even more ambitious route, which is to further reduce energy to zero by 2050. Thus, many initiatives in the country have begun to draw a road map of how the economy is going to reach ZC. The plan consists of smart short objectives and long objectives to tackle the energy consumption in the most energy consuming sector in the economy, which is the housing sector. This study examined a particular type of construction material in the MMC that has environmental and economic benefits and sought to identify whether this material can meet the energy standard by 2050.

The study concluded that the SIPs House was able to meet the nZEB/NZC energy requirement for the 2050 roadmap, and in some technical areas, the SIPs House reached nZEB/NZC compliance. However, the outcomes when compared with Passivhaus standards didn't meet the energy requirements, which is one of the most energy efficient standards recognised globally. With further research and development, the SIPs House could achieve the Passivhaus standard in the United Kingdom.

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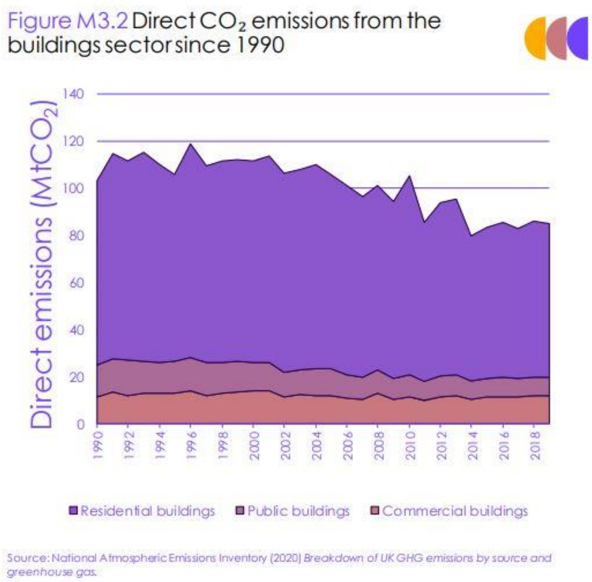
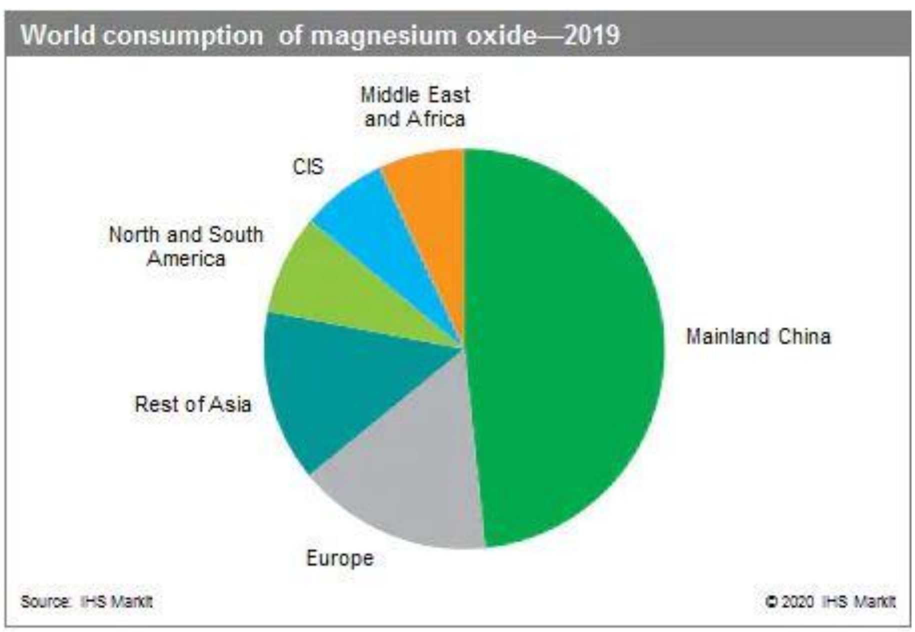
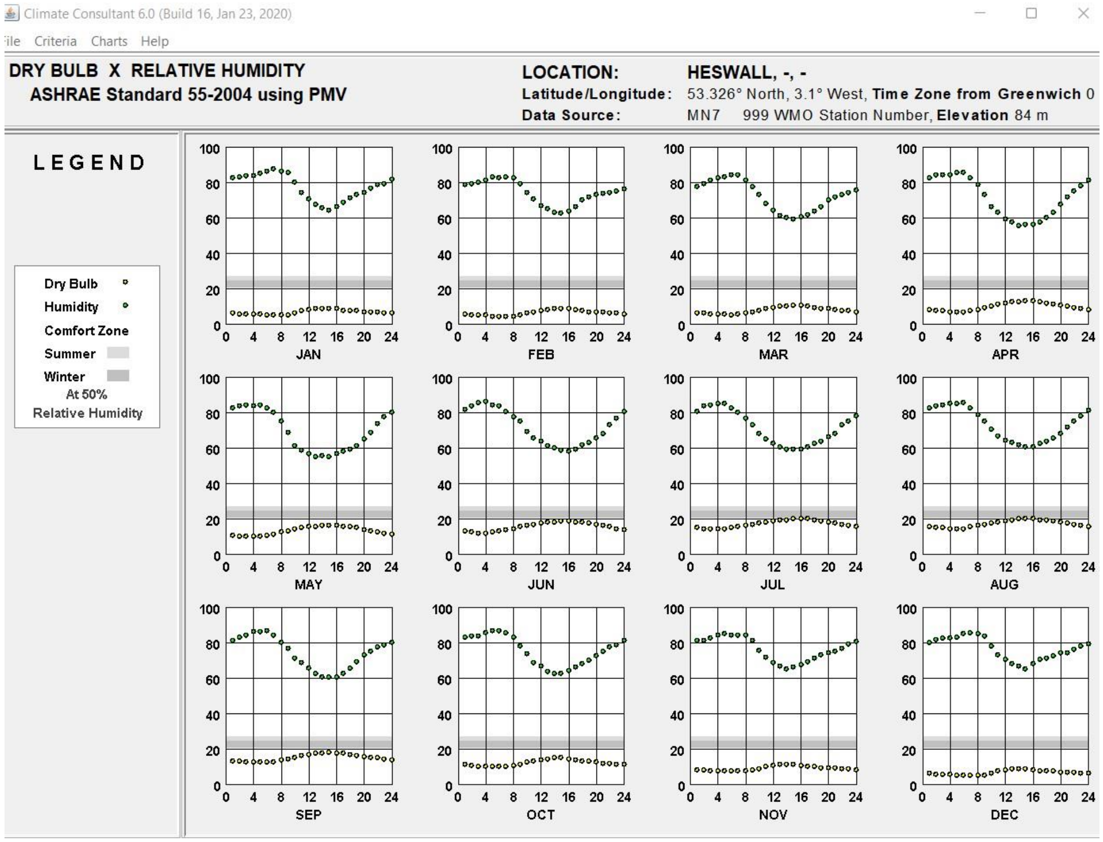
Appendix



Appendix 1. A: Direct CO_2 emission from the building sector in the UK. Source (CCC, 2019c).



Appendix 1. B: The production of magnesium oxide per county


Climate Consultant 6.0 (Build 16, Jan 23, 2020)
File Criteria Charts Help
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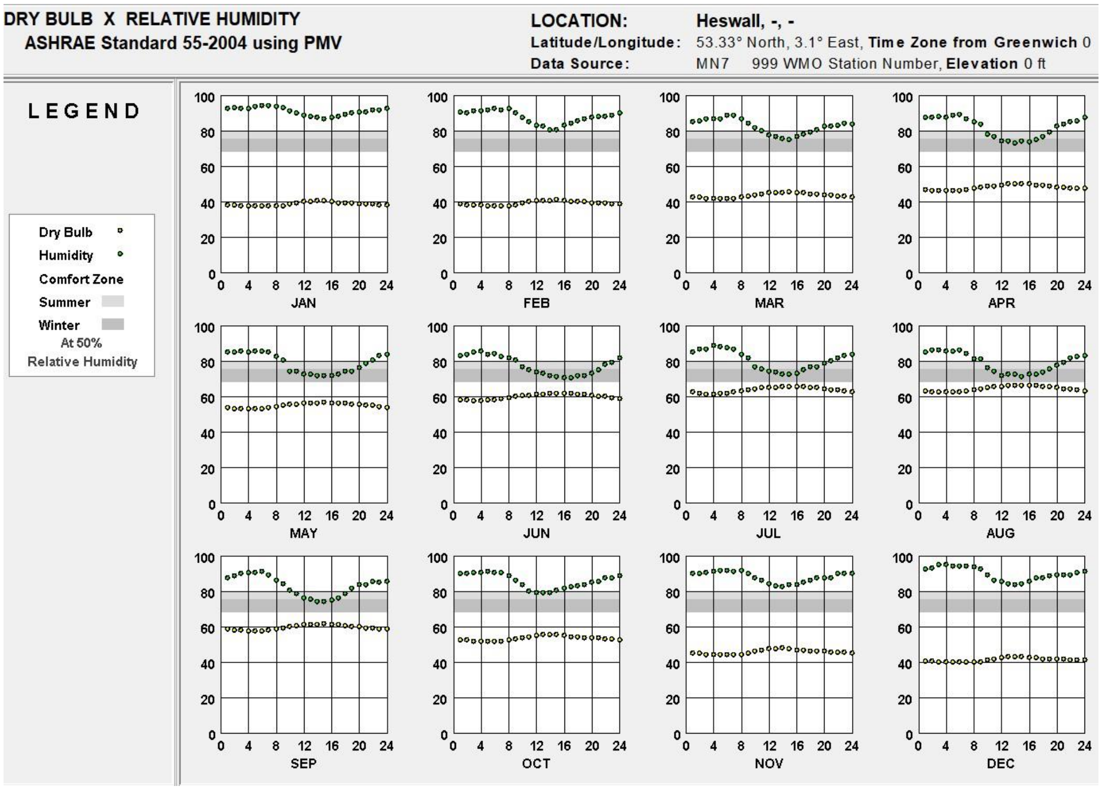
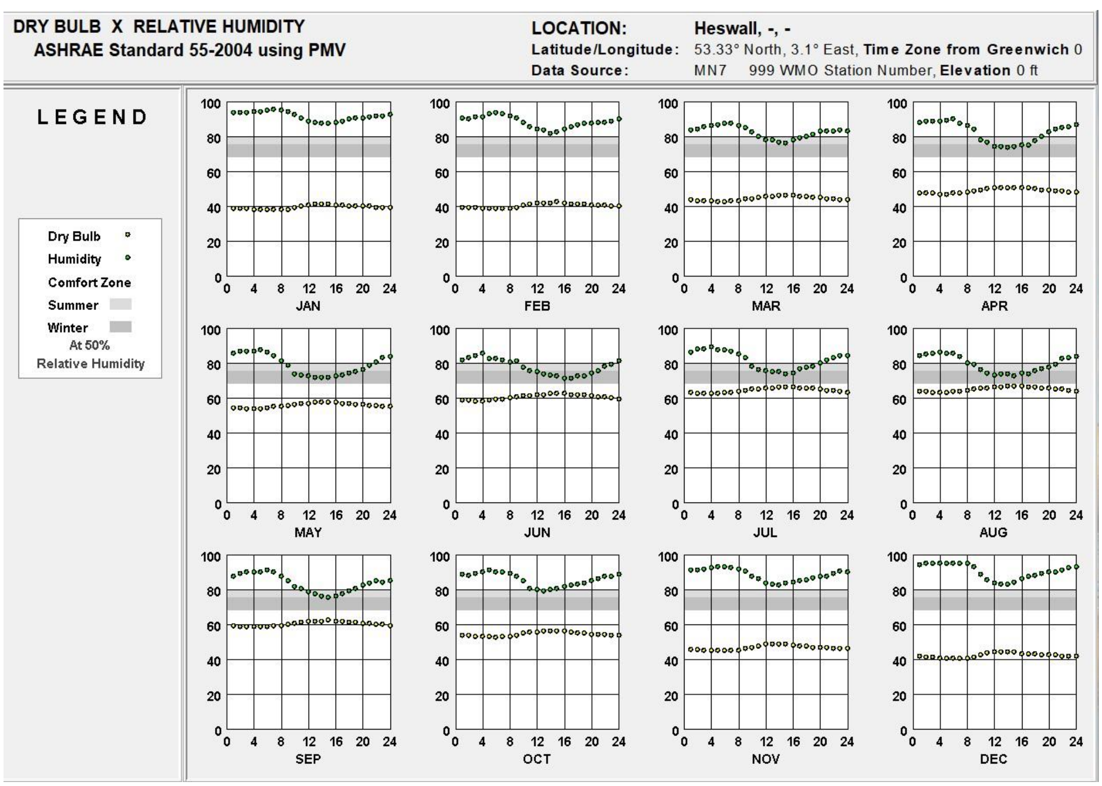
ASHRAE Standard 55-2004 using PMV
LOCATION: HESWALL, -, -
Latitude/Longitude: 53.326° North, 3.1° West, Time Zone from Greenwich 0
Data Source: MN7 999 WMO Station Number, Elevation 84 m
LEGEND
Dry Bulb
Humidity
Comfort Zone
Summer
Winter
At 50%
Relative Humidity
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

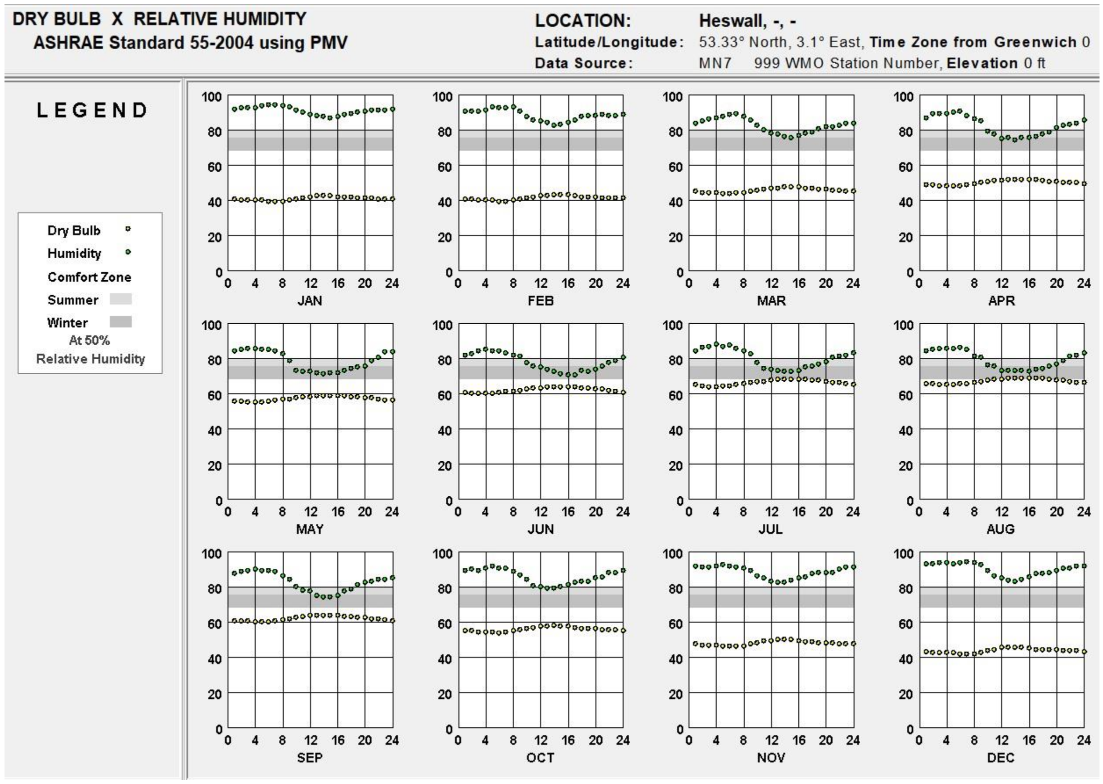
Current


DRY BULB X RELATIVE HUMIDITY
ASHRAE Standard 55-2004 using PMV
LOCATION: Heswall, -, -
Latitude/Longitude: 53.33° North, 3.1° East, Time Zone from Greenwich 0
Data Source: MN7 999 WMO Station Number, Elevation 0 ft
LEGEND
Dry Bulb
Humidity
Comfort Zone
Summer
Winter
At 50%
Relative Humidity
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

2030

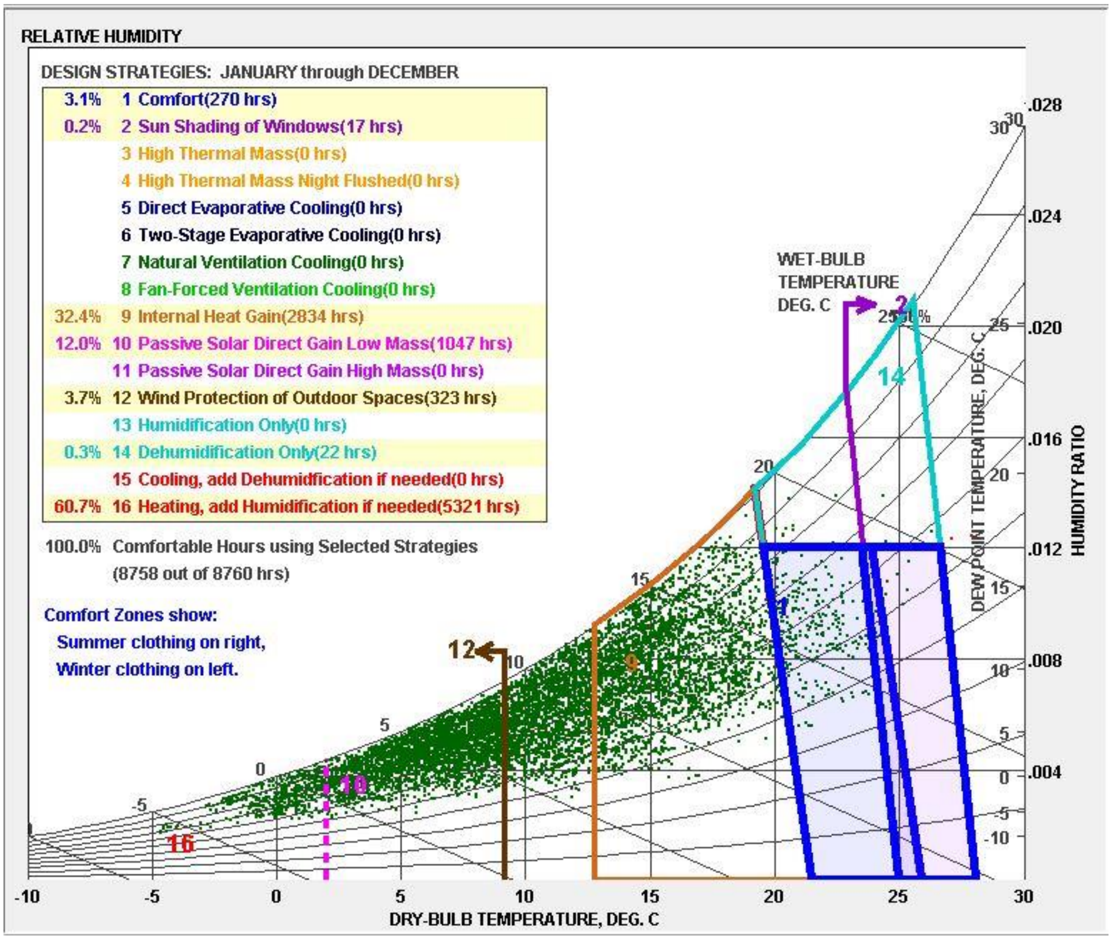

DRY BULB X RELATIVE HUMIDITY
ASHRAE Standard 55-2004 using PMV
LOCATION: Heswall, -, -
Latitude/Longitude: 53.33° North, 3.1° East, Time Zone from Greenwich 0
Data Source: MN7 999 WMO Station Number, Elevation 0 ft
LEGEND
Dry Bulb
Humidity
Comfort Zone
Summer
Winter
At 50%
Relative Humidity
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

2050



2080

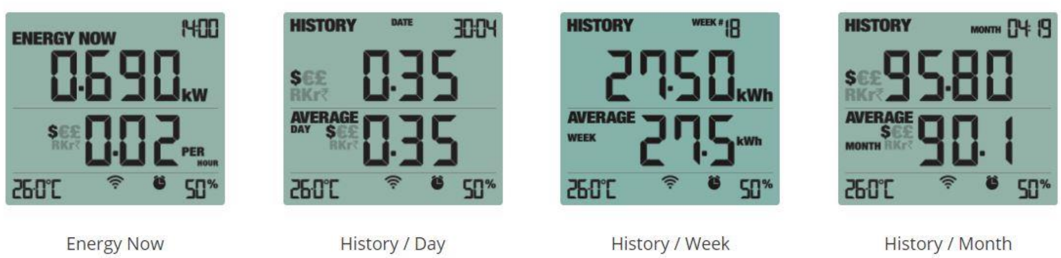
Appendix 1. C: Heswall current weather current,2030, 2050 and 2080 (Climate Consultant)



Appendix 1. D: Psychometric chart of Heswall UK – Source Climate Consultant 6.0

Appendix 1. E: Photography of the SIPs House during construction phase

Appendix 1. F: HVAC system of the SIPs House



Appendix 1. G: Energy efergy present and historical display options.

Contact Us
www.greennetworkenergy.co.uk

0800 520 02 02
Monday to Friday 08:00 – 18:30 and Saturday 09:00 – 13:00

Statement Reference: GNE400612443 (20 Nov 2018) **page 2 of 3**

Your Charges In Detail

Electricity

Supply number

S	01	801		101
	13	0006	0651	323

[redacted]

GNE Family Green 18 Month Fixed V6 (17 Oct 2018 - 16 Nov 2018)		
Energy Charges for Meter A06M03453		
17 Oct 2018	41061.2 Estimate	
17 Nov 2018	41800.9 Estimate	
Energy Used	739.7 kWh @ 12.86 p/kWh	£95.13
Standing Charge (31 days @ 20.04 p/day)		£6.21
Total Electricity Charges		**£101.34**
Subtotal of charges before VAT		£101.34
VAT @ 5% on £101.34		£5.07
Total Charges for this bill		**£106.41**

About Your Tariff

Prices do not include VAT unless otherwise noted.

Electricity

Tariff GNE Family Green 18 Month Fixed V6

Product Type . . . . Fixed Rate

Payment Method . . . . . Monthly Direct Debit

Unit Rate 12.86p/kWh

Standing Charge . 20.04p/day (£73.15/year)

Online Discount . . . . £0.00/year per fuel

Tariff End Date . . . . 16 Apr 2019

Price Guaranteed Until . . . . 16 Apr 2019

Early Exit Fee . . . . £30.00 per fuel (inc VAT)

Estimated Annual Usage 7972kWh

Your annual consumption is based on estimates.

Emergency Numbers

If you have problems with your electricity supply, call **0800 001 5400**

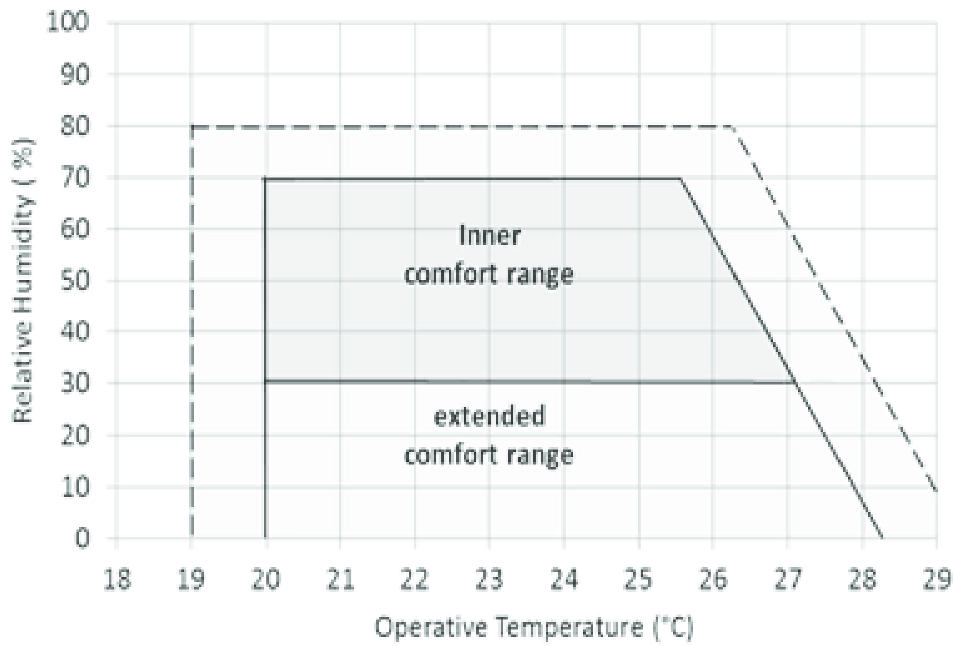
Your Electricity Distributor is: Scottish Power Energy Networks (0845 273 4444)

Appendix 1. H :Utility Bill of SIPs house (electricity)

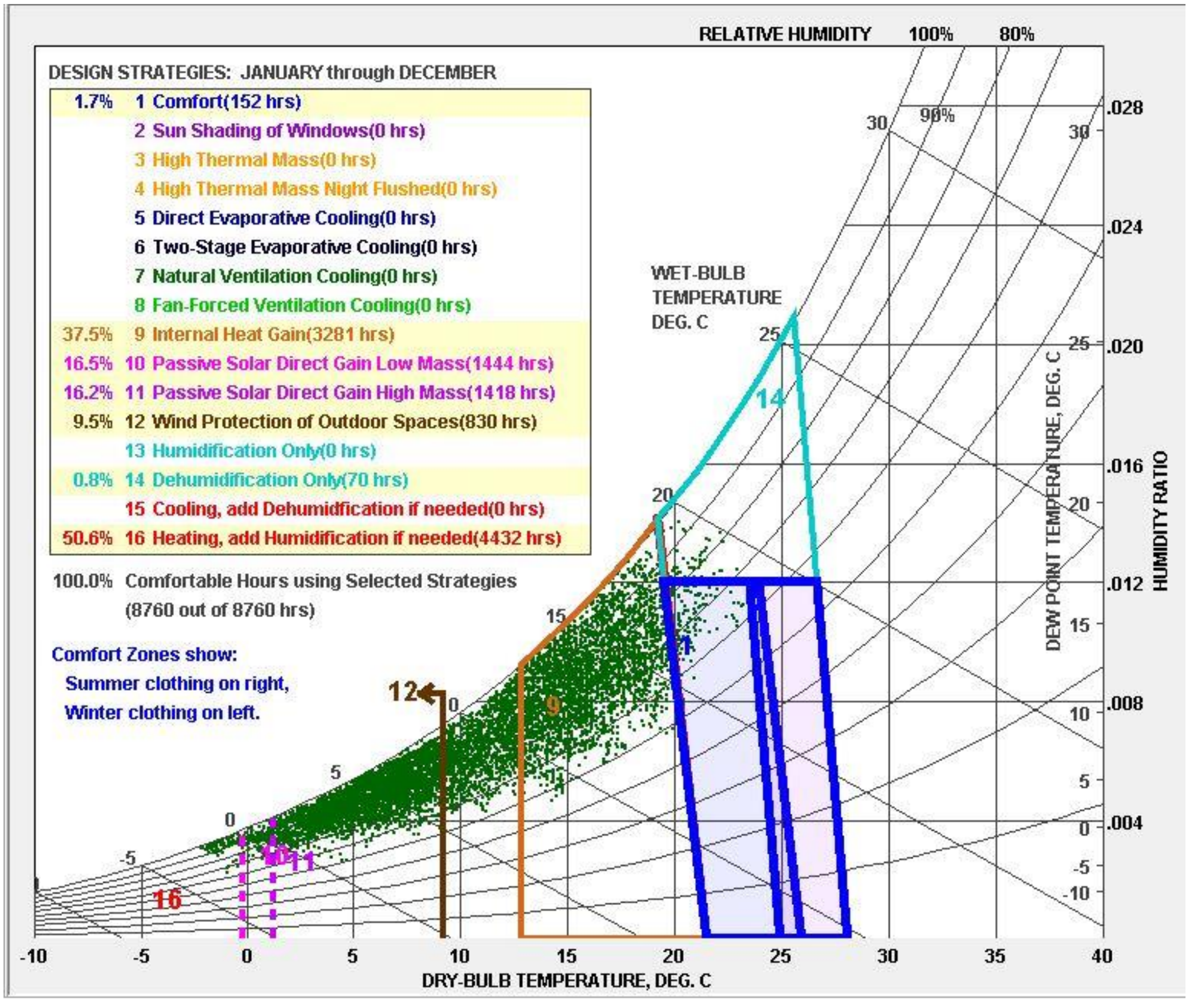
Hours >25°C	Hours/year	Assessment
> 15%	**>1314**	**Catastrophic**
10-15%	876-1314	Poor
5 – 10%	438-876	Acceptable
2 – 5%	175-438	Good
0 – 2%	0-175	Excellent
Maximum daily temperature swing according to PHPP 3K (to ensure reliable modelling)		

Table 2: summer comfort scale for Passivhaus buildings.

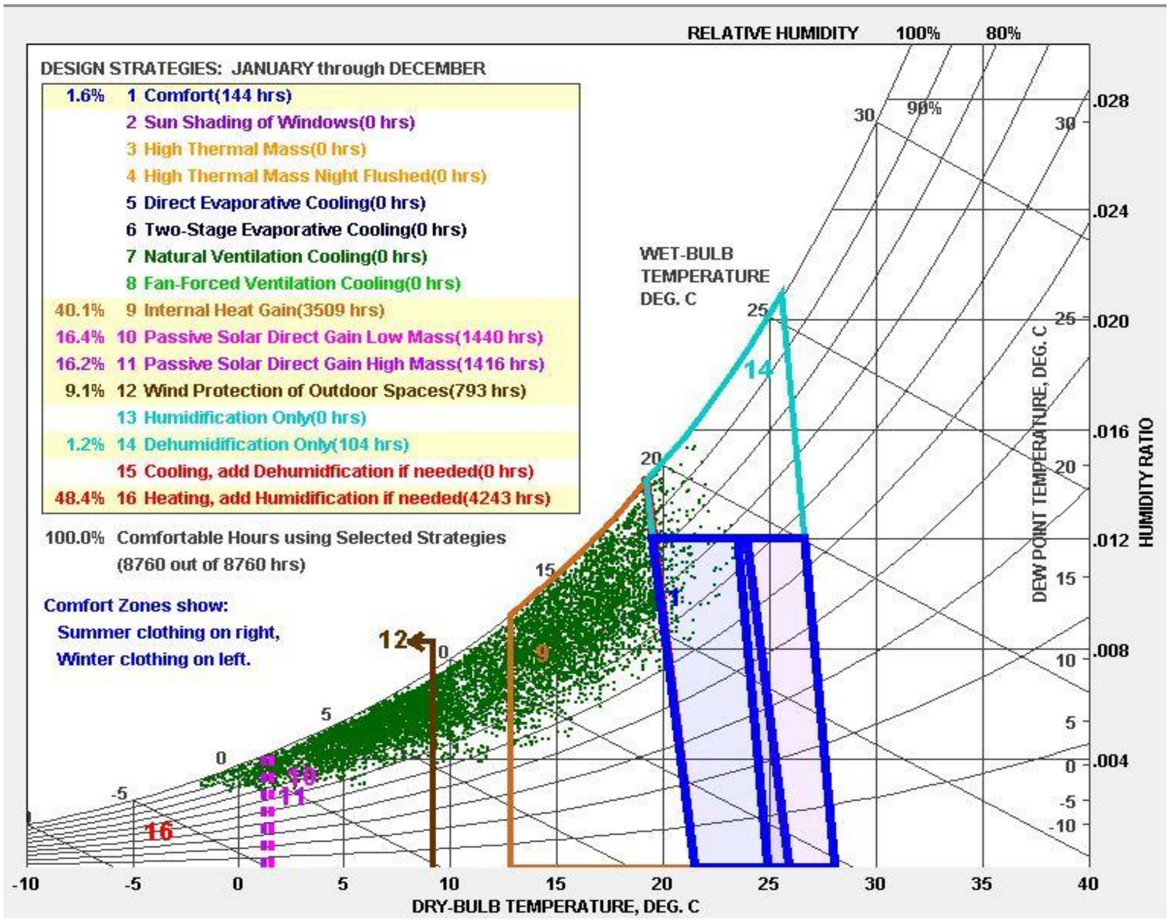
Appendix 1. I: UK Passivhaus Designing for Summer Comfort in the UK.



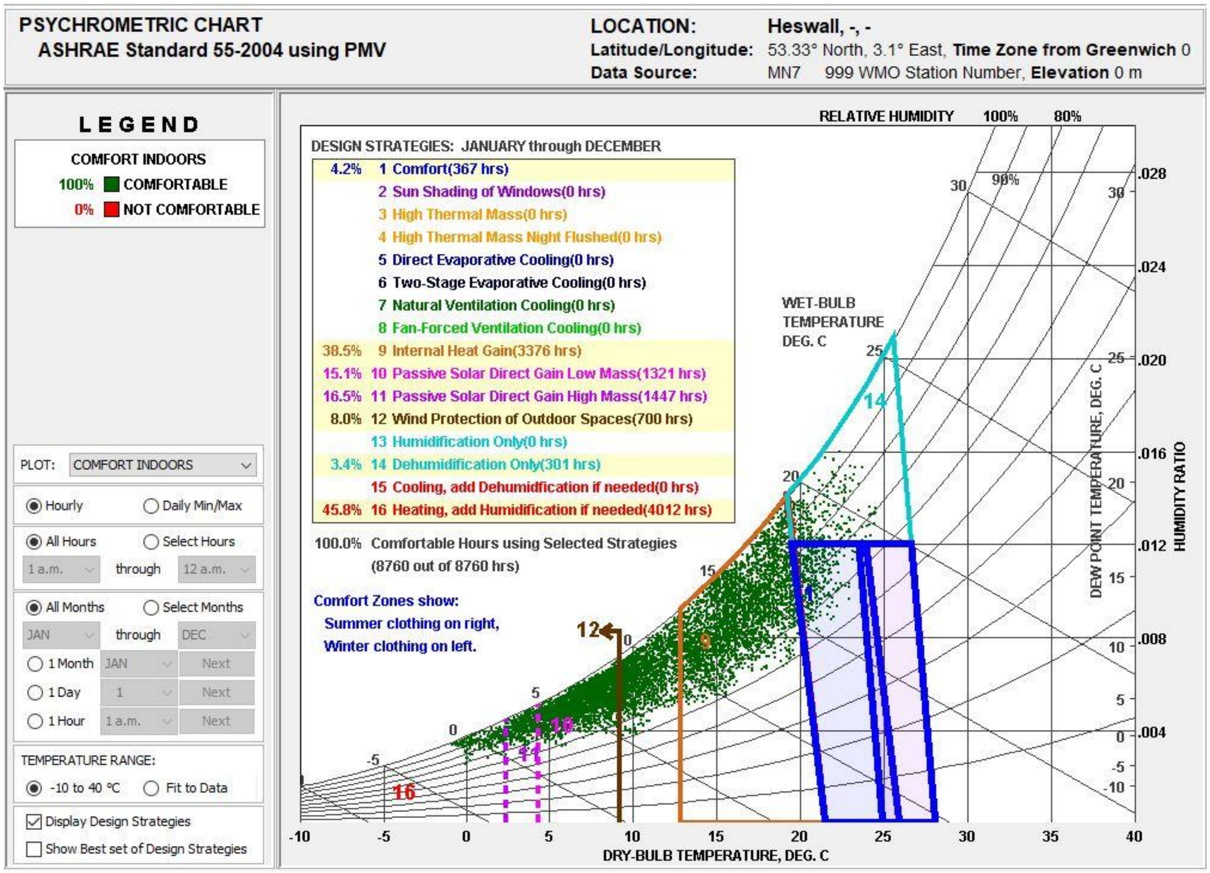
Appendix 1. J: Schneider's comfort chart.



2030 Psychrometric chart

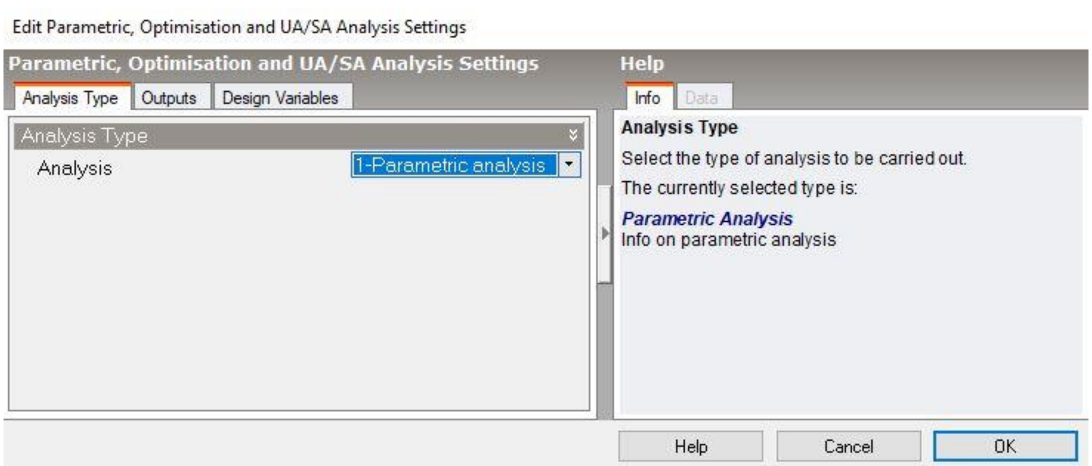


2050 Psychrometric chart

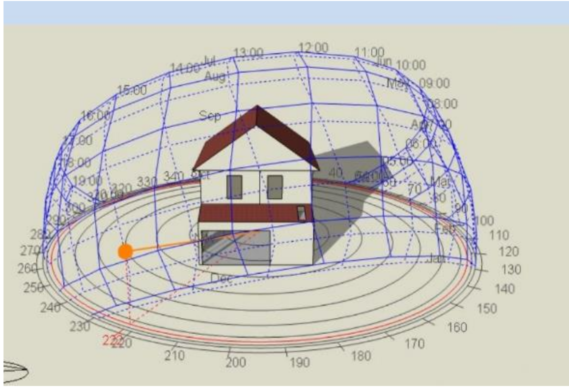


2080 psychrometric chart

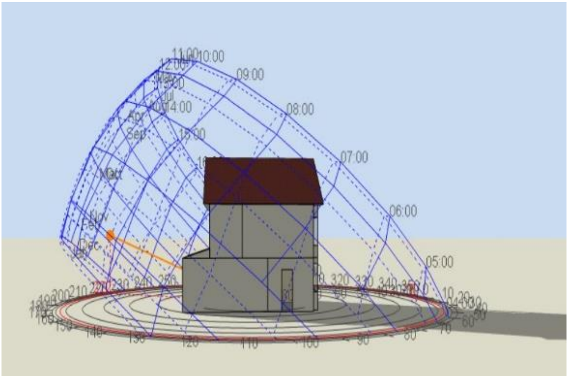
Appendix 1. K: Climate consultant design strategies for 2030,2050 and 2080



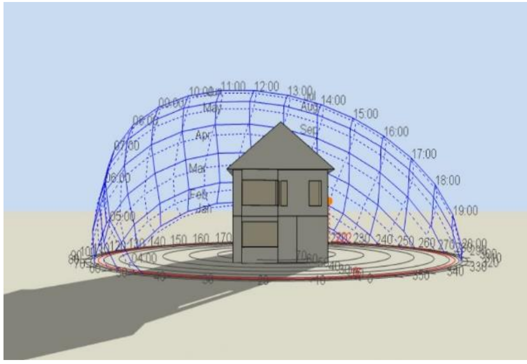
Appendix 1. L: Parametric study in Design builder



Main glazed area facing South



Main glazed area facing East

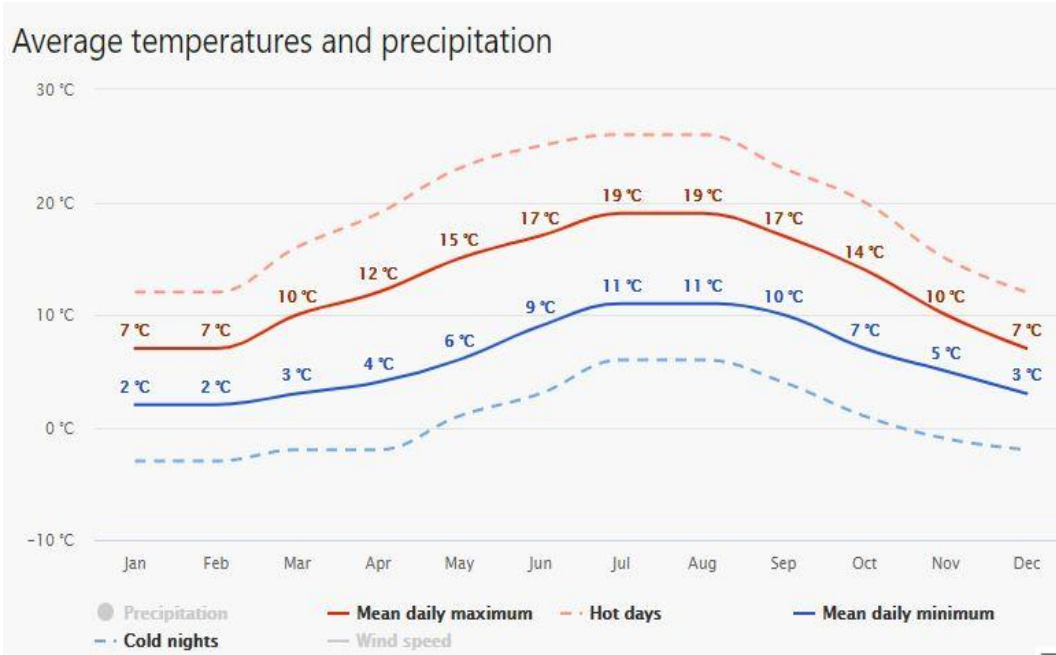


Main glazing area facing North

Appendix 1. M: Sun orientation in wintertime studies for the SIPs House, illustrated in DB.

Country	2021 nZEB standard kWh/m²/year	Country	2021 nZEB standard kWh/m²/year
Austria	160 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Italy**	Available with no specific values set
Belgium	45 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Latvia**	95 (D'Agostino and Mazzarella 2019), (BPIE 2010)
Bulgaria	30-50 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Lithuania**	Under development
Croatia	33-41 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Luxembourg**	Under development
Cyprus	100 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Malta**	40 (D'Agostino and Mazzarella 2019), (BPIE 2010)
Czech Republic	Under development	**Netherlands**	Under development
Denmark	20 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Poland**	60-75 (D'Agostino and Mazzarella 2019), (BPIE 2010)
Estonia	50-100 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Portugal**	Under development
Finland	Under development	**Romania**	93-217 (D'Agostino and Mazzarella 2019), (BPIE 2010)
France	40-65 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Slovakia**	32-54 (D'Agostino and Mazzarella 2019), (BPIE 2010)
Germany	Under development	**Slovenia**	45-50 (D'Agostino and Mazzarella 2019), (BPIE 2010)
Greece	Under development	**Spain**	Under development
Hungary	50-72 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**Sweden**	30-75 (D'Agostino and Mazzarella 2019), (BPIE 2010)
Ireland	45 (D'Agostino and Mazzarella 2019), (BPIE 2010)	**UK**	**44** (D'Agostino and Mazzarella 2019), (BPIE 2010)

Appendix 1. N: *nZEB standards across the EU.*



Appendix 1. O: Average temperature of Wirral source

List of published/unpublished papers from this research

Al Derbi, B., & Finnegan, S. (2020). 'The embodied carbon analysis of a Nearly Zero Energy Building (NZEB/NZC) MgO SIPs House in the UK.' *Planning Post Carbon Cities*: *35th International Conference on Passive and Low Energy Architecture, Coruna, Spain.* https://livrepository.liverpool.ac.uk/id/eprint/3116924

Finnegan, S., Al Derbi, B., Campbell, I., Fulton, M., Edwards, R., & Forster, R. The potential of Modern Methods of Construction to supply Zero Energy Housing in Europe [Unpublished manuscript].