Department of Mechanical and Aerospace Engineering

Electrification of heating: elevating the pressures of the low voltage network while maintaining thermal comfort within domestic homes.

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Abstract

As the UK moves into its tertiary stage of fossil fuel use and incentivise for electrification, there are concerns of stability within the ageing infrastructure of the National Grid. In particular, this instability will be most visible within the domestic sector where, currently, gas accounts for 28% of the total energy consumption of the UK. The extensive gasification of the residential sector contributes to 80% of the total carbon emissions in the UK. In line with Sustainable Goal Seven of the Sustainable Development Goals for Cleaner and Affordable Energy, the domestic sector needs to change.

The shift towards electrification in the residential sector will be a task fraught with techno-economic challenges. This thesis tackles the challenges of affordability, user comfort and stability of the grid through a course of iterative simulations. Using ESP-r- a building simulation software- three algorithms for load scheduling were created, evaluated and cost analysed on both current and future housing stock models. From the research conducted in this thesis, current housing stock models can be cost saving while maintaining thermal comfort levels with a gradual load scheduling strategy. Meanwhile, the future housing stock details that insulation construction plays a vital role in reducing heat loss and as such load shifting can be as restrictive as user affordability will allow.

Overall, this study emphasises the need for social acceptance of load scheduling and stresses the importance of upgrading the UK's ageing transmission and distribution lines to make way for a cleaner, reliable energy mix.

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List of Terminology

Abbreviation	Definition
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning
BRE	Building Research Establishment
CAD	Computer-aided design
CIBSE	Chartered Institution of Building Services Engineers
DSM	Demand Side Management
ESP-r	Building simulation software
EU	European Union
GHG	Greenhouse Gases
HVAC	Heating, ventilation and air cooling
ISO	International Standardisation Organisation
LED	Light-emitting diode
PHI	Passive House Institute
PHPP	Passive House Planning Package
PMV	Predicted Mean Value
PPD	Percentage Person Dissatisfied
SAP	Systems applications and products
SSE	Scottish and Southern Energy
TRNSYS	Transient system simulation tool
UK	United Kingdom
UN	United Nations
Unit	**Definition**
£	British currency
°C	Temperature
AC/h	Air changes per hour
clo	Clothes thermal insulation
Hrs	Hours (time)
kWhrs	Heating energy
lux	Illuminance
m^2	Area of space
W	watts
W/m^2	Casual gains per area of space
$W/m^2/lux$	Normalised lighting power density
W/m^2K	U-value

1. *Introduction*

1.1 Background

As fossil fuels enter their tertiary stage of use and the UK incentivise for an 80% reduction in Greenhouse emissions by 2050 (*Climate Change Act 2008*), a great deal of attention has been directed to the potential of future energy supply. This pursuit is a task fraught with techno-economic difficulties and differing views on the eventual objective between renewable deployment, demand management, sustained economic growth and ultimately the security of supply (Clarke, 2013).

There is a national urgency for decarbonisation, the electrification shift from gasification in heating and the variable nature of solar and wind poses a threat to the low voltage network (Péan et al, 2017). Demand Side Management (DSM) has been identified to help balance the energy production and demand at any time. This major expansion to the energy industry brings with it the drive to improve the energy efficiency in all areas of the economy, with particular focus within the building sector. This sector accounts for 40% of the UK final energy consumption (28% of this being domestic use) and 80% of this energy consumption uses gas, which in turn contributes to 36% of Carbon Dioxide emissions (UK Government, 2018). This mix is shown in Figure 1 which portrays the extent of the gas use within the domestic sector in comparison to any other sector of the UK.

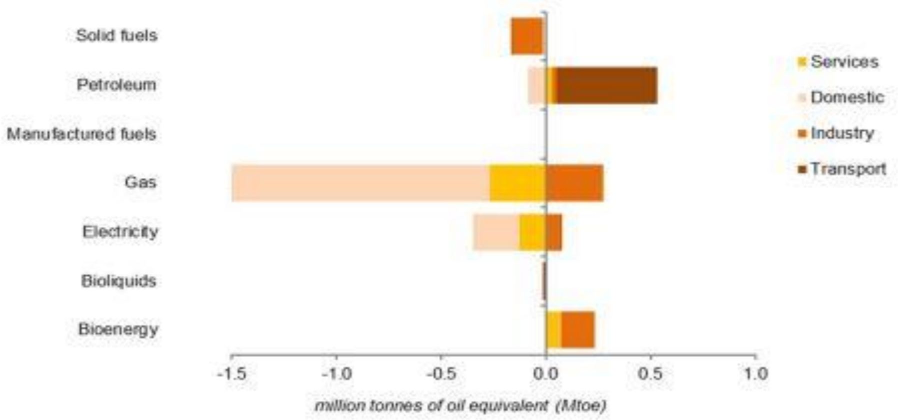


Figure 1: Energy mix in the UK (image from UK Government, 2018)

This thesis will delve into the need for change within the domestic building sector to meet the incentives laid down by both the UK Government (*Energy Act 2003* and *Climate Change Act 2008*) and United Nations (UN) in their Sustainable Development Goals; in particular Goal Seven for Affordable and Clean Energy and Goal Eleven for Sustainable Cities and Communities (United Nations, 2015).

1.2 Motivation

When making the shift to electrification for UK decarbonisation within the domestic building sector, there will be serious implications on the electrical network. The infrastructure will require a substantial, costly overhaul in order for the renewable and building sector to contribute to electrical demand. This infrastructure change will not only be an essential maintenance improvement for electrification from gas network in domestic homes, but also for the radical change of involving enormous amounts of renewables into the network.

The motivation for this study is to investigate how to elevate the pressures placed upon the load network with the impending heating transition from gasification to electrification. The need to decarbonise heating systems within domestic homes comes with the heightened pressure placed on the active peak hours of the electric network, and as such incentivises the need to mitigate the stress placed on of the UK's ageing Transmission and Distribution networks.

Within this investigation, this thesis will evaluate the extent to which the heating demand has the ability to flexibly move around outside peak times. This flexibility will focus on the how occupants within dwellings of both current and future housing stocks are affected by a DSM approach to load shifting of their heating and to what extent the thermal comfort levels can be stretched.

1.3 Aims and Objectives

Aim: To evaluate the extent in which heating has the ability to shift into off-peak time without impacting current thermal comfort levels within UK domestic dwellings.

Objectives:

- To understand current heating requirements and review literature on why the UK needs a decarbonised domestic heating supply;
- To adapt validated building models with current and future building regulations utilising building performance simulation software;
- To build a set of models/scenarios that give evidence to shifting the load of electrical heating requirements;
- Evaluate to what extent loads can be flexible with minimum impact to thermal comfort in varied typologies and building regulations;
- Conduct a cost analysis to assess the simulations cost saving attributes.

1.4 Thesis Structure

To achieve the aims and objectives of this research study, this thesis comprises of eight chapters that are outlined as follows:

- ***Chapter 1 (current)***: Introduces the background and motivation for the thesis, presenting aims, objectives and a summarised methodology for the study.
- ***Chapter 2***: Literature review of domestic building regulations and the concept of load shifting and thermal comfort guidelines.
- ***Chapter 3***: Describes the software used in the study and a description of the models.
- ***Chapter 4***: Defines the simulation and different modelled scenarios taken place in the study of load flexibility and discusses the reason for each iteration of heating shifts.
- ***Chapter 5***: Investigates and portrays the results from the simulations, with emphasis on the thermal comfort levels affected both annually and on seasonal timescales.
- ***Chapter 6***: Analysis on the energy costs attributed with each shift.
- ***Chapter 7***: Discusses the results on the impact of thermal comfort and goes on to confer the social implications of load flexibility and limitations to the climatic differences observed in relation to Global Warming.
- ***Chapter 8***: Draws conclusions and recommendations for further study, specifically the analysis of future heating guidelines and building standards.

1.5 Modelling Methodology

This section is written to give a summarised version of the methodology in which the simulations were undertaken for this study. A summarised version will give a base line to refer to throughout the thesis and ensure the study is focussed with a strict outline.

Three scenarios (below) have been established based on a combination of background research and iterative simulations.

Initial Set Up

The base case dynamic simulation model was adapted in ESP-r- a building energy simulation tool- from pre-modelled dwellings of both a Standard 2010 House and a Passive House (representative of current and future housing stock regulations). Pre-modelled dwellings were gratefully provided from the University of Strathclyde which were used within a previous study of heating, ventilation and air cooling (HVAC) systems. It was deemed unnecessary to create models due to the time constraints and the objective of the thesis not focussing on the construction methodology of a simulation software. The base case was given casual gains in both living and non-living zones and a heating controller within the living zone. The heating controller will regulate the temperature within the dwellings to a given value. Casual gains within the dwellings remains the same throughout each simulation.

Base Case: Current Requirements

The heating controller given for the base case represented the standard heating requirements within the UK based on the Household Electrical Survey report from Zimmermann et al (2012). The base case was modelled to provide an overview of the current energy demands of the domestic building sector and how current levels of thermal comfort are assessed.

Shift One: Restrictive

Reviewing the heating requirements within the dwellings, the heating controller strategy was shifted forward so that the load doesn’t fall into the peak times. This simulation was modelled to show the extreme for load flexibility and energy saving and how this restrictive heating shift impacted the thermal comfort and convenience of the occupants.

Shift Two: Gradual Shift

An iterative approach for this shift reviewed the previous two models and simulated shifting the heating load to the boundary constraints effecting thermal comfort requirements. These iterations resulted in the heating controller strategy being edited to have a gradual incline and decline on either side of the restrictive load shift.

2. Literature Review

The background research for this thesis has been sub-sectioned due to the many different aspects covered prior to running and investigating simulations. This literature review will evaluate the history of buildings and legislations which have shaped the motivation for electrification and go on to analyse previous studies of load flexibility and thermal comfort within domestic dwellings.

2.1 History of the Housing Stock

To get an understanding of the how the current building standards have adapted, this thesis delves into their history, starting with the Great Fire of London.

The Great Fire of London in 1666 single-handedly shaped today's building legislation. The accelerated growth of the fire highlighted the need to reconsider timber framed buildings and protect possible spread of fire between properties. This implemented the first building construction legislation of the *London Buildings Act 1667*, which imposed fire related restrictions. The Industrial Revolution, almost two hundred years later, highlighted poor living and working conditions in rapid growing, densely populated urban areas. The poor living standards resulted in outbreaks of cholera and typhoid due to meagre sanitation, damp homes and lack of ventilation ultimately resulted in the *Public Health Act 1875 (c55)*, meaning that Building Control would need to greatly consider health and safety. This Act has had many revisions over the years and in 1985, *the Building Act 1984 (c55)* introduced statutory guidance in Approved Documents. This made standards more flexible, supported innovation and made the system more efficient and effective. Today, the building standards fall under the legislation of *The Building Regulations 2010* and include health, safety, welfare, energy efficiency, sustainability, water contamination and waste. These regulations are set as national standards and cover all aspects of construction; including the overall stability of the building, construction, damp-proofing, fire protection and ventilation.

As building engineering has grown and adapted, building standards have reflected this. A notable housing standard that has emerged from energy saving is the Passive House concept.

The Passive House Standard originated in Sweden approximately 20 years ago courtesy of Professor Bo Adamson (Webster, 2015). He studied the feasibility of Passive House in China where he first proposed to improve passive design by eliminating any need for auxiliary heating systems. With his PhD student, Wolfgang Fiest, Adamson developed the Passive House concept, including the crucial components of thermal insulation, airtightness and heat recovery ventilation. In 1990, his first official Passive House was erected in Germany (Lozanova, 2014).

In 1996, Feist founded the PassiveHaus Institut describing Passive House as one "*that is truly energy efficient, comfortable and affordable at the same time*" (Passive House Institute, 2015a). Passive House Standards are a voluntary standard for energy efficiency in a building and today are mostly seen applied to Central European climates in an aim to seek high thermal comfort and indoor air quality with minimal energy use. However, there is a need to be able to apply passive house standards to any climate.

According to the Passive House Institute (PHI) (2015b), for a building to be considered as a "Passive House", it must meet certain criteria in association with the Passive House Planning Package (PHPP):

1. *"Space Heating Energy Demand must not exceed 15kWh per square metre of net living space per year or 10W per square meter peak demand;*
2. *The Renewable Primary Energy Demand states that the total energy used for all domestic applications cannot exceed 60kWh per square meter per year;*
3. *For Airtightness, a maximum of 0.6 air changes per hour at 50 Pascals pressure- verified with onsite pressure test;*
4. *Thermal comfort must be met for all season with no more than 10% of the hours in a given year over 25°C."*

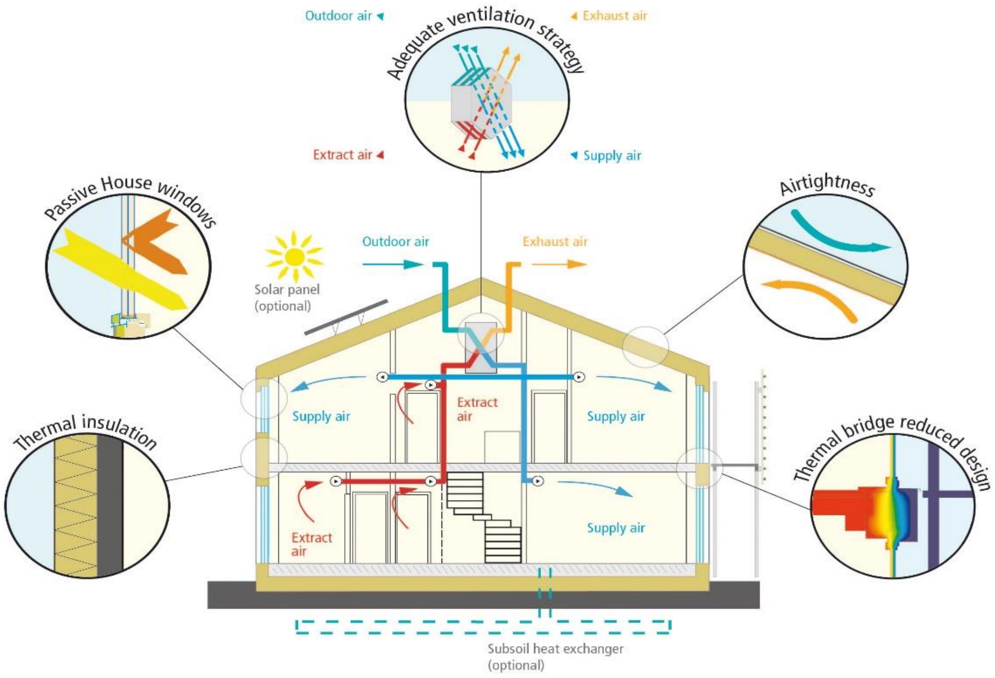


Figure 2: Regulations for Passive House (Passive House Institute, 2015b)

These criteria can be achieved by the implementation of the five Passive House principles (as depicted in Figure 2). The principles include thermal bridge free design; superior windows; ventilation with heat recovery; quality insulation and airtight construction (Passive House Institute, 2015b).

2.2 Energy in the Building Sector

According to the Eurostat (2016), domestic buildings in the European Union are responsible for 25.4% of total energy consumption, with 36% contribution from greenhouse emissions. The extensive use of fossil fuels and their resultant use within the domestic building sector has highlighted the dependence for these limiting supplies. Nations have realised that their crucial dependence on fossil fuels was responsible for socio-political dilemmas during the 1973 Oil Crisis (Hedley, 1981). This “first oil shock” was an embargo of the oil resources, so heavily relied upon by nations such as Canada, Japan, the USA, the Netherlands and the UK as a result of the Yom Kippur War (Smith, 2006). Hence, strict actions and legislations have been adapted and stabilised to promote alternative methods and measures for energy conservation as well as ways to enhance energy security and independence from the conventional energy sources (COM, 2005).

With the aforementioned transition from the heavy dependence of fossil fuel use and the UK desire to reduce Greenhouse Gas emissions, the breakdown of energy use within domestic dwellings was evaluated by Eurostat in 2016. This discovered that 37.1% of the EU's final energy consumption is covered by natural gas. Further to this, the main use of energy within a household in the UK is stated to be for heating which accounts for 61.4% of the final energy consumption of the residential sector. The breakdown of energy type used by space heating in the UK is shown below in Figure 3.

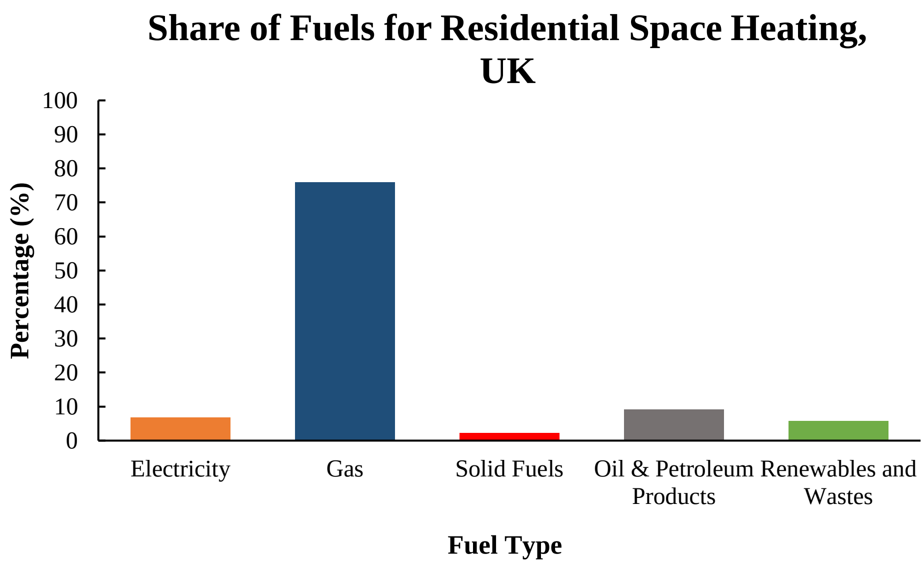


Figure 3: Breakdown of Space Heating Fuel Use in the UK -values, source: Eurostat (2016)

The UK is one of the highest Gas users for space heating fuel use (alongside the Netherlands, 87.2% and Italy, 60.6%). This emphasises the need to migrate from fossil fuel dependence to more energy efficient methods of heating. The legislations below play a vital role in the shift towards electrification of UK and EU housing stock.

2.3 Legislations

The *Climate Change Act 2008 (c27)* forms the basis of the UK's incentives to tackle climate change and their response to reduce emission of carbon dioxide and other greenhouse gases responsible for climate change. The UK government has set a target of 2050 to significantly reduce UK carbon emissions to 80% lower than the 1990 baseline figures. This requires the government to set legally binding carbon budgets to aid in the route towards the 2050 target. These legally binding documents are set 12 years in advance to allow policy-makers and businesses enough time to prepare. It is the significant contribution from the current space heating usage towards GHG emissions, aforementioned, that sparked the *Energy Act 2013 (c32)*.

The *Energy Act 2013* brings together all documentation in reference to the Energy and Climate Change Committee and establishes a legislative framework for "*delivering secure, affordable and low carbon energy"* (*Energy Act 2013).* Decarbonisation of the electricity sector gives rise to a drastic shift from dominantly gasification of heating to electrification. To cope with this shift, the *Energy Act 2013* provisions the Energy Market Reform (EMR), which emphasises the need to replace the current generating capacity and upgrade the Grid by 2020 in order to cope with the rising electricity demand put in place from the decarbonisation section of the Act (UK Government, 2013).

2.4 History of Load Scheduling

A Load Scheduling Control (LSC) describes the basic principle to shift the operating time of equipment either automatically or manually during the high peak prices in order to benefit from low-cost electric bills (Luo et al, 2015).

The first insight into load schedule was addressed by Hoskins and Rees (1970) where load shifting was proposed to address a nuclear fuel management approach. This was further endeavoured by Grossman and Reinking (1975) to understand the short-term issues of nuclear reactor fuelling cycles and they went on to propose overnight scheduling to maintain nuclear capacity. An optimum load scheduling of nuclear thermal systems was then adapted by Nieva et al (1981) to iteratively investigate the limits to the flexibility of the reactors.

Load shifting then remained stagnant over the next few decades with minor changes to the optimum load scheduling for base line nuclear requirements. This emphasises the heavy dependence for fossil fuels that the UK has.

With the increase of renewables into the grid and the inevitably of electrification of the nation’s heating network, there has been increasing research to the understanding and need for load scheduling over the past five years. Dang and Ringland (2012) were first to propose an algorithm for optimal load scheduling to minimise energy cost in residential homes, while Chen (2014) analysed the approach for Load Scheduling Control based on behaviour within dwellings.

Recent findings from Qin and Li (2018) develop different scenarios of electrical domestic load scheduling for cost saving. They propose several different algorithms given different living situations and conclude that the problem of load scheduling has a non-deterministic polynomial time- hardness (NP- hardness). The simulations were validated in efficiency and performance but yet, the research has not been put into real-time practise.

2.5 Load Flexibility

As the UK proceeds to migrate heating demands towards electrification with the ambition to reduce CO_2 emissions, the overall electrical demand will increase and with it brings technical challenges to the variability and security of the voltage network (Wilson, et al, 2013). The electrification of heat will be a gradual process rather than an overnight switchover and even a small percentage upgrade to the National Grid infrastructure will have serious implications on ageing transmission networks.

Péan et al (2017) express the increasing importance for energy flexibility on the demand side within the residential sector and the significance of control strategies for smart buildings and as such the flexibility of heating loads needs to be assessed.

A group of methods which will be looked at within this thesis is the simple Rule-Based Controls (RBC) which aim to avoid peak periods of demand with fixed schedules (Carvalho et al, 2015). This will reduce the peak power exchange between buildings and the grid, which should ultimately reduce energy costs. Figure 4 depicts load shifting within a domestic dwelling.

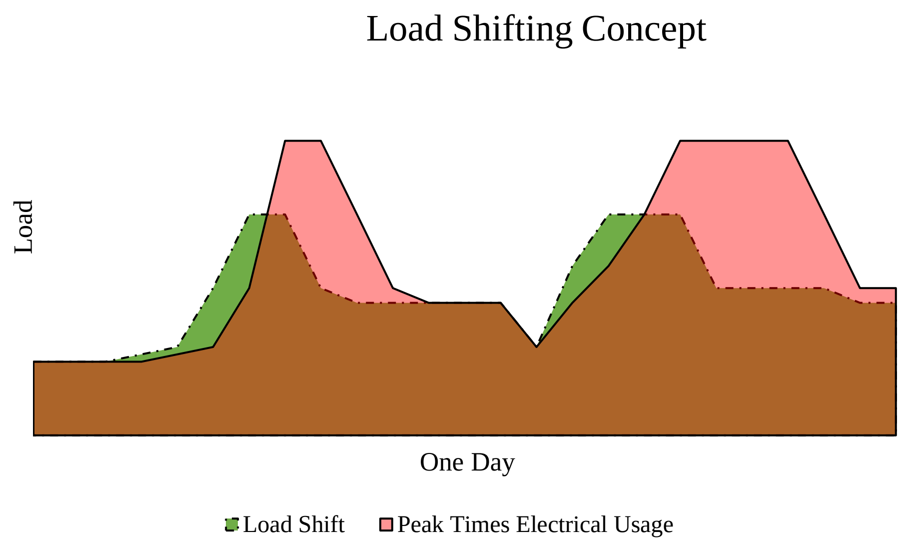


Figure 4: Concept of Load Shifting (adapted from Intertek, 2012 report on Household Electrical Survey)

Another method of control, which is worth noting but will not be analysed in this thesis, is the Model Predictive Control method which uses optimisation techniques orientated around decreasing the energy bill when variable energy tariffs are in place. However, Péan et al (2017) states that there are still a lot of issues with this model and requires extensive computational efforts and therefore lacks the simplicity required in this thesis to analyse the thermal comfort effect.

Using RBC method of load flexibility, load shifting can be achieved through rescheduling activities and switching to storage during high peak times. In this thesis, shifting will be applied to heating operating activities, however the use of storage will not be considered. The aim is to ensure that the objective of load flexibility does not jeopardize the satisfaction of the building's occupants and thus the evaluation of comfort levels is crucial in this thesis. Flexibility control strategies often aim at operating the building systems close to the boundaries of any major changes to occupant behaviour or comfort (ISO Standard 7730) and thus thermal comfort boundaries must be defined.

2.6 Thermal Comfort

Thermal comfort is considered a state of mind which expresses the satisfaction of the thermal environment (Halawa and van Hoof, 2012). In the late 1960's Povl Ooof Ole

Fanger developed the Predicted Mean Vote (PMV) model in attempt to standardise a thermal comfort model. Referred to as a static model (Halawa and van Hoof, 2012), the PMV model combines all thermal factors in the environment (any activity, any clothing insulation) for which the largest possible percentage of people in a given group experienced thermal comfort. Fanger stated in his research on "Thermal comfort and the human body" that the human body should meet several conditions: the body is in heat balance; mean skin temperature and sweat rate which influence the heat balance, are within given limits; and no local discomfort exists prior to experiment. Figure 5 schematically shows the thermal comfort interactions with the body, as taken from Taleghani et al (2013).

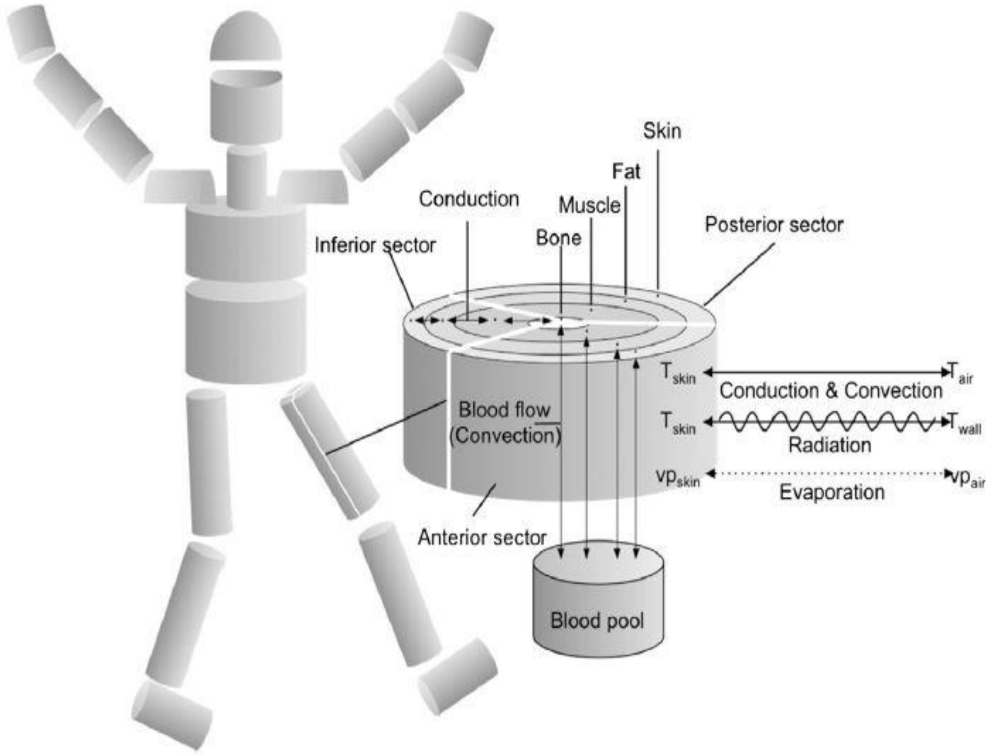


Figure 5: Schematic view of human body conditions applied to Fanger's equation for thermal comfort boundaries (source Taleghani et al, 2013)

Within the PMV model, there are six factors which can be said to influence thermal sensation: air velocity, air temperature, mean radiant temperature, clothing insulation, metabolism and relative humidity. These are input into Fanger's thermal equation

(Equation One) and thus gave fruition to the American Society of Heating, Refrigerating and Air- Conditioning (ASHRAE)'s seven-point model for analysing thermal comfort as shown in Table 1 (ASHRAE, 2013):

Equation 1: Equation for the thermal interaction of the body with its environment (Fanger, 1970)

$$\boldsymbol{S = M \pm W \pm R \pm C \pm K - E - RES}$$

Where S = heat storage
M= metabolism
W= external work
R= heat exchange by radiation
C= heat exchange by convection
K= heat exchange by conduction
E= heat loss by evaporation
RES= heat exchange by respiration (from latent heat and sensible heat)

Table 1: ASHRAE thermal sensation scale (ASHRAE, 2013)

Index	**Description**
3	Hot
2	Warm
1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Gungor (2015), Raw and Oseland (1994) and Teleghani et al (2013), to name a few, criticise the validity of the PMV-PPD model. The limits to the PMV model are emphasized in the study by Raw and Oseland (1994) where they state optimum validity when clothing insulation is measured at 0.7 clo, and Gungor (2015) expressed the errors in different sizes of data sets giving varying thermal sensation votes of 1.3 ASHRAE-scale units. It is expressed that the PMV model should be applied with caution due to errors within the large group model for small data sets. However, the model is adaptive when combined with behavioural adjustments and shows correlation between thermal comfort and other aspects of the sampled space which are inter alia, heating requirements, casual gains and shading (Péan et al, 2013). Refer to the table below shows thermal comfort levels which are in line with the Environmental Change Institute (Darby and White, 2005) for UK domestic dwellings.

Table 2: Modified terms for PMV thermal comfort index

Index	**Temperature °C**	**New Description**	**ASHRAE Description**
3	27+	Very Uncomfortable	Hot
2	25-27	Unpleasant	Warm
1	22.5-25	Acceptable	Slightly Warm
0	19-22.5	Pleasant	Neutral
-1	16-19	Acceptable	Slightly Cool
-2	11-16	Unpleasant	Cool
-3	11-	Very Uncomfortable	Cold

For ease of clarity, the index and descriptive models has been adapted to represent zones of thermal acceptability for human occupancy in line with Percentage Dissatisfied terms of use (Table 2) and as modified by Charles (2003).

2.7 Literature Review Summary

From this research, dwellings with current and future building regulations will be applied to this study. To keep the scope neat, there was two typologies of dwellings modelled and adapted with these building standards: flat and detached. A rule based styled controller strategy was applied to the models heating loads.

Legislative incentives have emerged to improve dwelling thermal efficiency, with building regulations across the UK radically strengthened. As reviewed above, assessment of PMV-PPD levels were evaluated with iterative shifts to heating operating times. The simulations discussed herein combined current thermally acceptable comfort levels within UK dwellings and the ability to flexibly move heating into off-peak operating times, keeping or mitigating change to the comfort levels.

3. Model Description

3.1 Energy Systems

Energy systems are attributed as dynamic, systemic and non-linear. Building simulation tools give understanding to complex problems such as energy consumption, retrofits and thermodynamic properties of built materials. This enables engineers to make informed decisions within their field and make changes dependent on the results.

While simulations can only predict within the results given, it is with verification and validation that the uncertainties and errors in the data are minimised. It is important for the user of simulation tools to consider the input parameters and climate effects of the built environment within the models; the better quality of the validity of the inputs, the better the accuracy of the outputs.

3.2 ESP-r Software

The ESP-r software is a modelling software licensed from the University of Strathclyde and has been subject to development since its debut in 1974. The software currently aims to emulate building performance that corresponds to reality; allows integrated performance matrix in both intermodal comparison and measured data in order to be assessed and support all stages of design application (Clarke, 2001). Figure 6 shows the opening screen of the ESP-r software which can allow the user to import a previously constructed CAD file, create a new model or choose from one of the many different exemplar models.

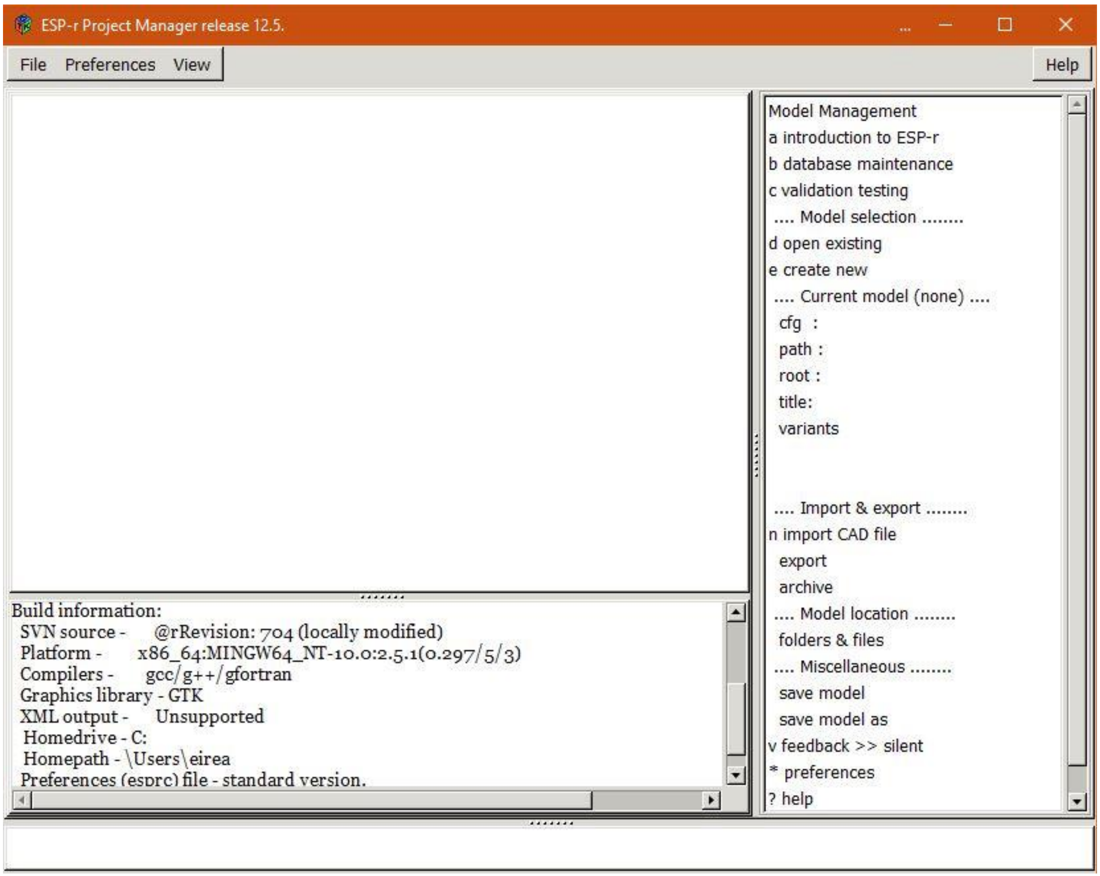


Figure 6: Start screen of ESP-r Software

ESP-r is used for the simulations involving load shifting in this thesis. The software has a powerful capability to simulate dynamic and systemic building design, calculate energy conversions within the models and integrate at successive time steps in response to occupant, thermal comfort, climate and control systems. ESP-r will also allow both annual and seasonal analysis for, in response to this thesis, correlation of thermal comfort.

However, with many modelling software, there comes weaknesses. While ESP-r will be the modelling software regardless of its weaknesses, it is worth noting that the software retains the look and feel of a tool still very much in its development stages as well as uses heavy jargon that can limit the type of user-friendly feel a lot of other modelling software have (such as EnergyPlus or TRNSYS).

3.3 Climate

The climate data used within this model is based from UK climate data 2005. The data associated with ESP-r has been static for a number of years but are used to emulate a typical climate within the northern hemisphere. For cost assessment and assumptions within this model, Glasgow in central Scotland is used as the reference point.

3.4 Dwellings

There are two dwellings that are analysed in comparing thermal comfort levels where building standards, base floor area and exposed walls differ.

The dwellings are representative of typical typologies of the period from 1997 to 2010. Both typologies have been modelled to have the constructional standards of 2010 ISO in one version and Passive house in another- in other words, there are two versions to each scenario and each dwelling.

3.4.1 Living and Non-Living Zones

Within the modelling context of ESP-r, two zones have been set up within the model parameter: living and non-living. While this isn't typical of an architecturally real building, the models can replicate the thermodynamic behaviour needed for the purposes of this energy analysis (Hong et al, 2012). Living refers to a zone of active occupancy involving frequent movement, rooms such as living room, kitchen and bathroom are in this zone. Non-living zone refers to a zone of inactive occupancy, such as sleeping within the bedroom. For the sake of clarity in examining results, the same casual gains for lighting and occupancy are applied to both zones.

3.4.2 Flat Model Description

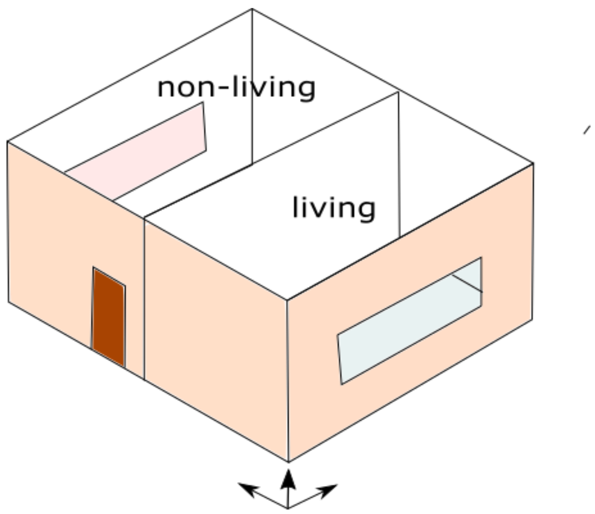


Figure 7: Modelled Flat edited from ESP-r model

The flat is representative of a tenement typology and is on the upper level of the tenement with two external facades orientated north and south as Figure 7 shows. The total floor area of the flat is 84m^2, with a 5m^2 window in both zones.

The flat is divided into two zones, living and non-living which has been classified by their use and defined in section 3.3.1. The building has been modelled in ESP-r, including the external environment. The dwelling is assumed to be occupied by two adults and the occupancy profile has been adapted according to the habits of the adults during a typical week, this can be viewed in the casual gains from Table 3. This table describes the building characteristics, and the corresponding U-values for both building standards.

3.4.3 *Detached Model Description*

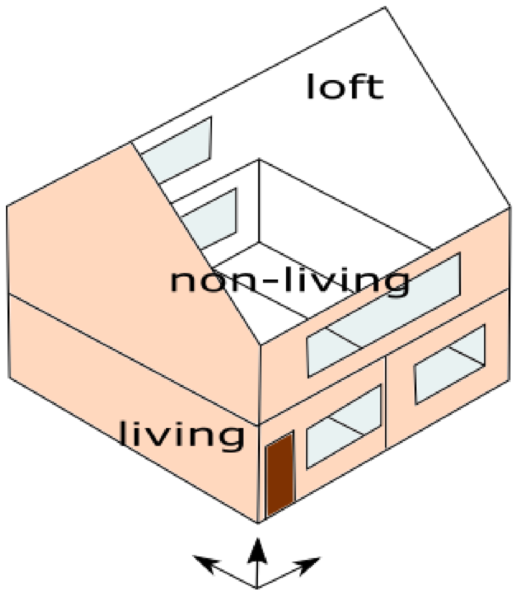


Figure 8: Modelled Detached dwelling edited from ESP-r Software

The detached dwelling (Figure 8) has all four walls exposed with two-storeys. The total floor area of the two active zones in the dwelling is 254.5m^2 with a total window surface area of 33m^2 (only 6m^2 of this is in the living zone).

The dwelling is divided into three zones: living, non-living and loft which are defined as relatively open and allow for good ventilation, these are defined in section 3.3.1. For the purposes of thermal comfort analysis, the zone for loft has been excluded in results due to lack of occupancy or significant casual gains within this zone. The building has been modelled in ESP-r, including the external environment. The dwelling is assumed to be occupied by two adults and two children and the occupancy profile has been adapted according to the habits of the family during a typical week, this can be viewed in the casual gains from Table 4.

Table 3: Casual Gains for the flat including timeline for both weekday and weekends

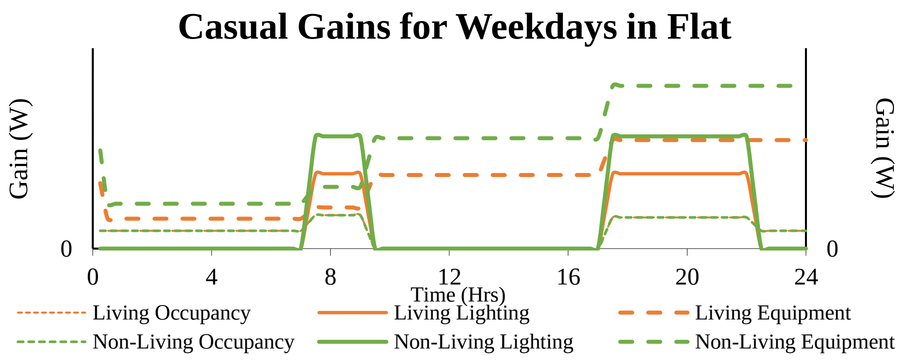
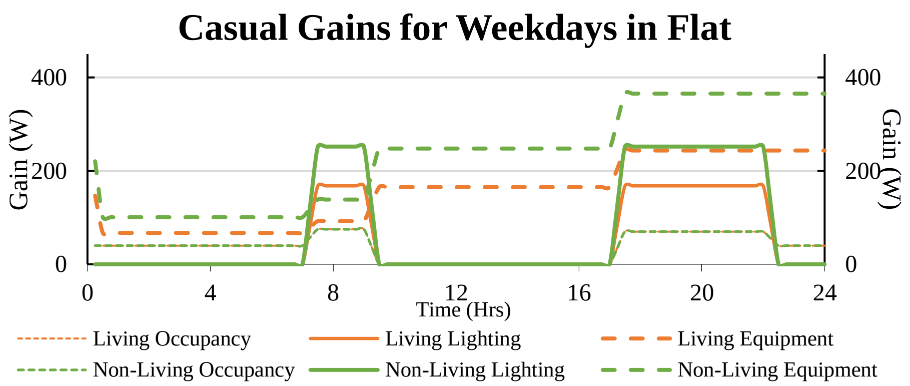
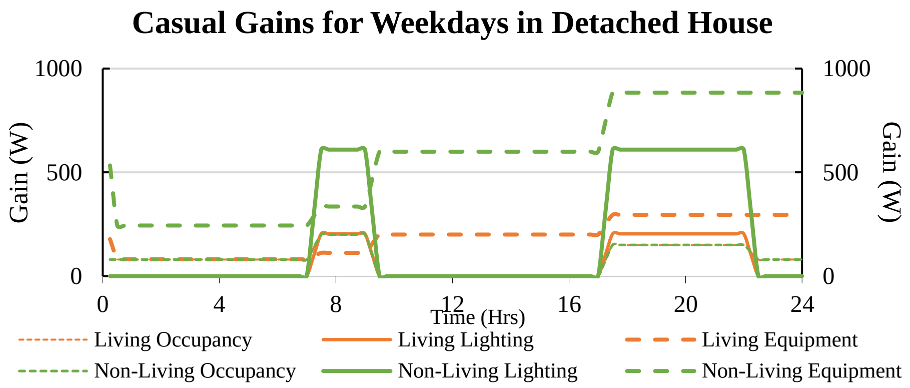
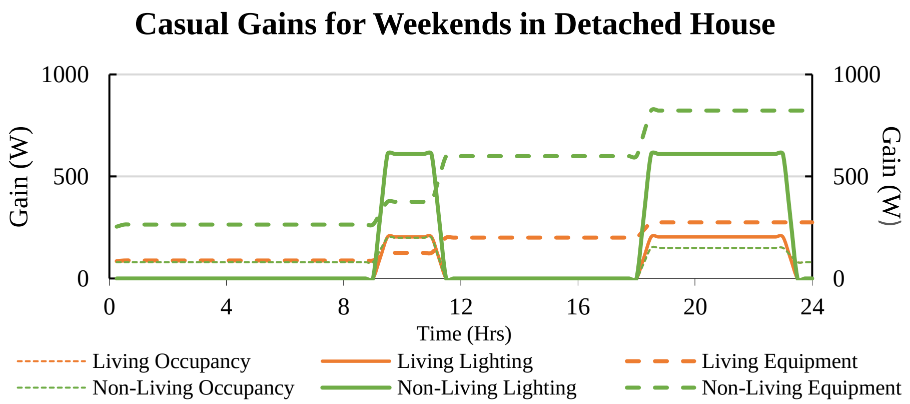
<table>
<tr><th colspan="4">Casual Gains for Flat</th></tr>
<tr><th>Type</th><th>People</th><th>Lighting</th><th>Equipment</th></tr>
<tr><td>Max Sensible</td><td>75W</td><td>6W/m^2</td><td>10W/m^2</td></tr>
<tr><td>Max Latent</td><td>55W</td><td>-</td><td>3W/m^2</td></tr>
<tr><td>Occupancy</td><td>1-2 People</td><td></td><td></td></tr>
<tr><td>Radient Fraction</td><td>0.3</td><td>0.6</td><td>0.4</td></tr>
<tr><th colspan="4">Gains Profile</th></tr>
<tr><td>Weekdays</td><td colspan="3">
</td></tr>
<tr><td>Weekends</td><td colspan="3">
</td></tr>
</table>

Table 4: Casual gains for detached dwelling including timelines for both weekday and weekend occupancy and other heat gains

Casual Gains for Detached House			
Type	**People**	**Lighting**	**Equipment**
Max Sensible	200W	6W/m^2	10W/m^2
Max Latent	100W	-	3W/m^2
Occupancy	4 People		
Radient Fraction	0.3	0.6	0.4
Gains Profile			
Weekdays			
Weekends			

3.5 Construction

In accordance with Building Regulation 2010, the U-value assesses the rate of heat loss/ gain through the thicknesses of the combined elements that make up a building, including wall, floor and roof. Measured in W/m^2K, it is used to calculate the insulating properties of the building element. A lower U-value indicates a better insulated building component. Passive House standard (which has been defined in Chapter Two, Section 2.1) has lower U-values due to the high insulation materials used within the dwellings. These can be found in Table 5 where the U-values for both the flat and detached dwellings are given with the standardised values.

Table 5: U-Values of typical and modelled typologies

Construction	**U Values ($W/m^2.K$)**			
	Typical Standard	**Modelled Standard**	**Typical Passive**	**Modelled Passive**
External Wall	0.94	0.450	0.15	0.150
Windows	1.2-3.7	3.304	0.80	0.754
Floor	0.59	0.620	0.14	0.142
Ceiling	0.39	0.250	0.13	0.139
Average infiltration rate	0.5	0.5	0.035	0.07

ESP-r defaults the value for air changes per hour (AC/h) of 0.5, which is typical air tightness rating associated with a 2010 Standard Building (*The Building Regulations, 2010*). Infiltration (air leakage) is defined as the movement of air from the outside through to the inside through leaks, cracks and/or holes in the building construction and materials (ASHRAE 2013) and is the only form of air flow considered in this study, i.e. ventilation is not recognised.

3.6 Casual Gains

Casual gains are applied to the models as a form of excitation that impact air temperature in the dwellings and as such influence the thermal comfort. The casual gains for both living and non-living zones have been kept the same across the zones to provide clarity in the results for thermal comfort, however there are some variations where area size changes between the zones. To estimate the casual gains from occupants, lighting and appliances for the dwellings, data was collated from ASHRAE fundamentals, SAP and Code of Lighting resources. From these resources, a causal gain profile was created and can be seen in Table 3 and Table 4. It is assumed that the flat has an occupancy of one/two people while the detached house occupies four people. The equipment and lighting are kept the same as measured in W/m^2 and is adjusted by the simulation tool dependant on the base area. Times of occupancy is based on a household survey by Zimmermann et al (2012) which is reflected in lighting use (CIBSE, 2012). Equipment (or appliance) use is estimated by Damaskou (2016) and theoretical assumptions from ASHRAE (2013). For further information of the full casual gains used within ESP-r model, this can be found in Appendix A.

3.6.1 Occupancy

Comfort Gains for Occupancy are in accordance with ASHRAE 2013 for analysing metabolic rates for thermal comfort. A conversion calculation is applied within ESP-r to convert the metabolic rates to occupant sensible and latent gain.

For sensible gain, the default options for radiant and convective fraction were considered and applied to the model for occupancy, equipment and lighting gains.

Occupancy was modelled in terms of the heat the inhabitants in the dwelling emit. The thermal interaction of the human body with its environment (with environment in this study being a dwelling) is determined by the total metabolic rate within the body and activities plus the rate of shivering (if this were to occur) (Figure 5). Heat can dissipate from the body to the immediate surroundings by several modes of heat exchange which have been modelled under the occupancy section of casual gains in ESP-r as sensible and latent gains. Sensible heat gains have been mathematically calculated within the model to include sensible heat flow from the skin and during respiration. While latent heat gains are described as the heat flow from heat evaporation and from evaporations of moisture diffused through the skin, as well as loss from moisture during respiration. Sensible gains are complex and incorporate a mixture of conduction, convection and radiation for a clothed person, however the metabolic rate of heat through the clothing level can differ depending on the thermal qualities of the clothing. See Table 6 below for definition on thermal clothing levels:

Table 6: Metabolic clothing rate for assumed clothing worn in the home

Clothing Description	Garments Included	Icl (clo)	Average clo
Underwear	Men's Briefs	0.04	
	Bra	0.01	0.04
	Pants	0.03	
	Socks	0.03	
Tops/Shirts	T-shirt	0.08	
	Long Sleeved Shirt	0.25	
	Thin Sweatshirt	0.25	
Trousers	Sweatpants	0.28	
	Thin Trousers	0.15	
Outfit Description			
Lounge Wear	Sweatpants, Sweatshirt	0.68	**0.62**
Work Wear	Trousers, Shirt	0.55	

3.6.2 Lighting

Heat gains from lighting can significantly impact the overall casual gains within a dwelling, with standard incandescent bulbs contributing to a heat emission coefficient of 0.95 (Suszanowicz, 2017). Over the past four years, there has been a switch to LED lighting within the home, not only due to its energy efficiency but its low heat emission attribute (0.08) means it is also safer within the home.

To calculate the casual gains from an LED bulb, a series of simple equations are used. Firstly, from BRE (2011), it is assumed that a standard living area operates with an LED light of 1600lumens (equivalent to a 75W incandescent bulb). This is applied to an equation from Code of Lighting (CIBSE, 2012) to convert lumens to lux (Equation Two). This conversion is required to show that the lighting meets the relevant performance standards associated with EN 12464-1, whereby the lighting installed in the living zone must not exceed the maximum lighting power consumed in the space (BRE, 2011). For the living zone, the maximum lighting power consumed (Equation Three), divided by its total floor area and by its illuminance in units of 100lux must not exceed 6W/m^2/100lux. This calculation is shown in Equations Two and Three.

Equation 2: Conversion of lumens to lux to calculate heat gains from LED

$$1lux = \frac{1lm}{m^2}$$

$$lux = \frac{1600}{28}$$

$$lux = \mathbf{57.14}$$

Equation 3:Caluation of heating gains from LED bulb within living zone

$$Normalised\ lighting\ power\ density = \frac{Lighting\ power\ consumed\ (W)}{\frac{Total\ floor\ area\ (m^2)}{Illuminance\ of\ 100lux}}$$

$$= \frac{75}{\frac{28}{0.5714}}$$

$$= \mathbf{4.70W/m^2/100lux}$$

The results from equations above, normalised power density is well within the maximum boundary for rooms of this type and is applied to the casual gains for these models.

3.6.3 Equipment

In reference to equipment use within the dwellings, appliances mainly in the kitchen are considered for this casual gains section. Based on research from Damaskou (2016), equipment gains for sensible and latent gain are given in Table 7. The use of these appliances throughout the day are then based on theoretical assumptions and each given a day factor which are applied to the sensible gains. Sensible gains are considered in this study over latent as humidity from latent gains are not used in the contribution to thermal comfort levels.

Table 7: Casual heat gains for standard appliances in the home (Damaskou, 2016)

Appliance	Sensible Gain (W)	Latent Gain (W)	Total (W)	Day Use Factor	Recalculated sensible gains per day (W)
Toaster	469	293	762	0.02	9.77
Oven	410	-	410	0.10	42.71
Washing Machine	539	882	1421	0.13	67.38
Laptop	23	-	23	0.29	6.71
TV Screen	90	-	90	0.33	30.00
Freezer	323	-	323	1.00	323.00
Fridge	352	-	352	1.00	352.00
Kettle	147	-	147	0.04	6.13
Shower	-	303	303	0.03	-
Other	200	-	200	0.08	16.67
			4031	**TOTAL**	854
			95.9762	**TOTAL/ m^2**	20.34

The equipment use was further divided throughout the day to represent the active occupancy times in association with equipment use (Damaskou, 2016) and the total heat gain/m^2, calculated in the above table, was then multiplied by the day use fractions as shown in Table 8.

Table 8: Equipment use throughout the day and their subsequent heat gains

Time Period	Equipment Use throughout day (fraction)	Heat Gain (W/m^2)
Weekdays		
0-7	0.12	2.4
7-9	0.16	3.3
9-17	0.29	5.9
17-24	0.43	8.7
Weekends		
0-9	0.13	2.6
9-11	0.18	3.7
11-18	0.29	5.9
18-24	0.40	8.1

The heat gains calculated in the above table is applied to the model's casual gains, as shown in the timelines in Table 3 and Table 4 for the dwellings.

3.7 Model Controllers

Heating is provided to the indoor space through the means of a controller- in ESP-r this is defined as a configuration control file. Within ESP-r, there are a myriad of heating controllers to choose from to customise the heating requirements in the building and for this thesis, the modelling of the dwellings has been used with two of the controls: basic controller and free-floating. According to the ESP-r Cookbook (2008), when no configuration control file is implemented within the zone, such as in the non-living zones, then the system is defined in "free-floating" throughout the simulation period- this is simply described as the heating being off. During the periods of active heating, a basic controller mode is implemented to living zone only within set time periods.

Within the configuration control file, the zones in which the controller exists, there is a sensor and actuator. A sensor exists to measure the flux variable to the control law of the basic controller in place with the sensed property in this study being temperature. The actuator is in place to transmit the output, or heat, to the living zone.

The basic controller (used in this thesis) uses a rule-based strategy and offers different heating and cooling set point, which when invoked will cause the sensor to activate and the actuator to attain the set points. The specific heating points are detailed for each scenario is described in Chapter Four.

While it was assumed that there is likely a hot water system within the dwellings, this has been omitted from this study due to the hot water system not contributing to the thermal environment of the model.

3.8 Modelling Summary

By evaluation of the modelling software and inputs into the ESP-r software, the flat and detached dwellings were modelled to represent as close to real dwellings as the software allows. This includes the casual gains associated with occupancy, lighting and the equipment use within the properties combined with the external environment climate. The subsequent stage of this thesis is to create simulations which model load shifts to heating loads to gauge thermal comfort constraints.

4. *Simulations*

This section of the thesis describes the changes to the controller strategies over the three simulations. The controllers have been dictated around the operational hours in which the inhabitants in the dwellings occupy. Morning operational times coincide with the occupants' wake times and getting ready for their day, while the evening operational times are in accordance to the occupants returning from their out of home activities.

There are three simulation cases for this analysis: Base Case with current UK heating requirements, Shift One with restricted heating and Shift Two with gradual heating- all of which are described in sections below. The simulations are invoked for week-long periods to compare seasonal differences: 9^{th} -15^{th} January (Winter), 17^{th} -23^{rd} April (Transitional/Spring) and 3^{rd} -10^{th} July (Summer) using a simulation time step of 15 minutes. The simulations also run for the full course of a year in each case to analyse the heating requirements and effect on thermal comfort annually.

4.1 Base Case: Current Typical UK Heating Demand

The base case represents the standard and current requirements of heating during peak times in the UK (Zimmermann et al, 2012). A combination of a basic controller and free-floating heating is applied to the living zone while non-living zone is always set to be in free-floating state - in other words, there is no heating controller in this zone. The timeline of peak electrical usages for heating is graphically represented in Figure 9:

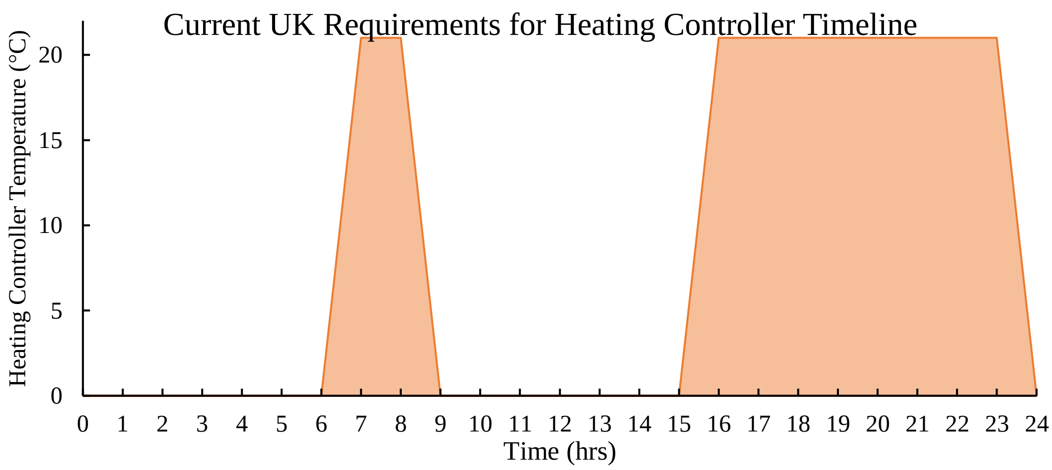


Figure 9: Controller strategy for Base Case scenario

Within the basic controller settings, the heating set-point is configured at 21°C which will be met if there is sufficient capacity within the time set boundaries. The heating controller occupies 8 hours of the day, with no heating being active in the considered inactive sleeping hours (between 10pm and 6am). It is worth noting that the cooling set point is set to 29°C to represent there being no air conditioning in the dwellings as standard for UK dwellings and temperatures not in exceedance of 25°C in an average Summer season (see Chapter Seven, section 7.3 for discussion on recent Summer temperatures).

4.2 Load Shift One: Restricted Heating

The first load shift to the model comes by reducing the hours of the required heating load and activate during off-peak hours. This heating controller strategy was modelled to establish the extent of load flexibility given an extreme limited heating contribution (Figure 10):

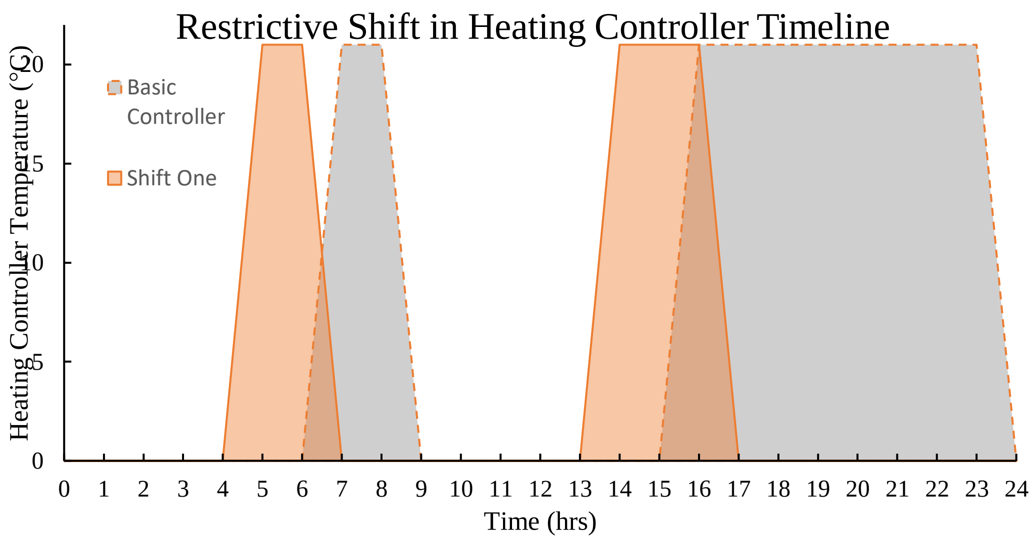


Figure 10: Controller strategy for Shift One: restrictive heating

Restrictive heating used a heating set point of 21°C which was met given sufficient capacity within the limited time. Figure 10 shows the shift in the heating loads (orange area) compared to the original base case (grey area) and shows a reduction in heating strategy by three hours with a two-hour shift in the morning and evening into off-peak heating times. This strategy was used within both dwellings to compare the different housing stocks (Passive House or 2010 Building Standards) and the contribution that casual gains have to the dry bulb indoor temperature which ultimately effects the thermal comfort levels. Seasonal differences were analysed to determine if heating was required at these controlled periods throughout the warmer months in addition to the colder periods. Significant analysis will look at effects on thermal comfort to reduction of heating and if load has the flexibility to maintain suitable thermal comfort levels.

4.3 Load Shift Two: Gradual Heating

The gradual heating shift was determined through a series of iterative simulations to determine the maximum boundary in which the heating load can be shifted. The simulations were compared against the extreme shift of restrictive heating load whereby the heating is shifted by two hours from required demand and the base case for current UK requirements. This gave rise to a gradual incline and decline to the heating loads with a shift of two hours in the morning, but with a longer heating operative period and a shift of one hour in the evening with a reduced operating time as graphically displayed in Figure 11:

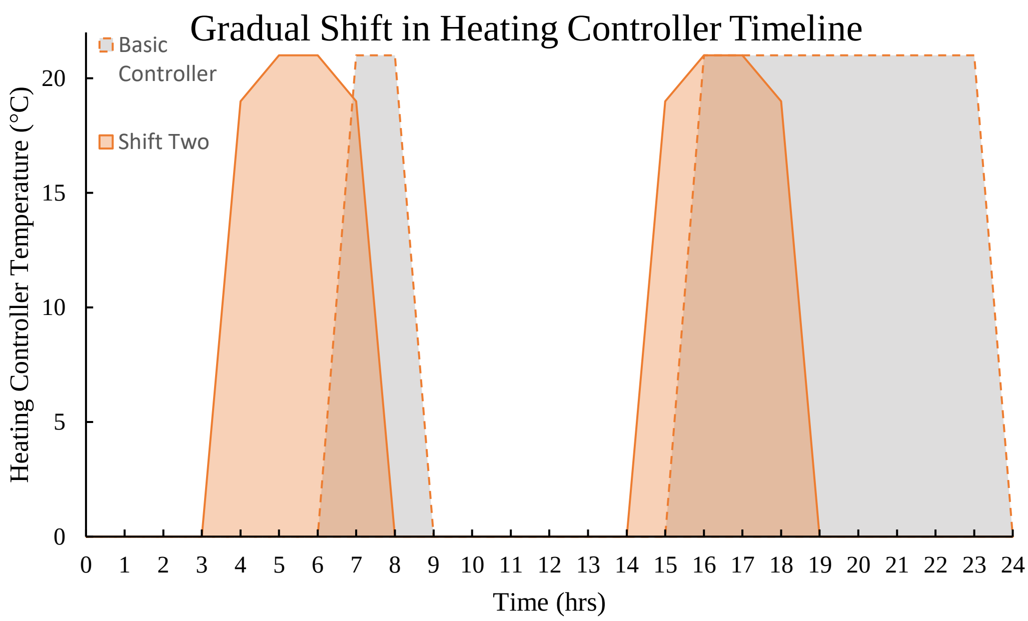


Figure 11: Controller strategy for Shift Two: gradual heating

This shift took form from Restricted Shift in the aspect of time zones in off-peak demand times for electrical usage. Instead of heating controller activating at 5am and immediately requesting a room temperature of 21°C, an instep incline and decline of

19°C was applied to the restrictive case. This will show the effects of load flexibility by having a reduced temperature that can be maintained instead of a rapid request for a high heating load. The iterative process which was applied to this control strategy emphasises the limits in which load has the flexibility to shift where thermal comfort is marginally affected.

4.4 Simulation Summary

Each of the three simulations modelled within ESP-r were adapted based on the results of the previous simulation. The first model exhibits the current UK heating requirements if there was a heating shift to electrification and all remained the same with heating operative times and thermal comfort levels. The second simulation pushes load scheduling to the extent of cost saving and as such the thermal comfort levels were poor. This meant that the third model is created with the interest of cost, thermal comfort and occupancy convenience in mind.

5. *Results*

Each of the three simulations gave rise to a large set of data results, showing the capacity and in-depth facilities of the ESP-r modelling software. The data sets relate to different elements of the building fabric and system components and were processed to extract the key information for this analysis of load shifting and thermal comfort. This was namely in the form of the dry bulb temperature within the dwelling, energy consumption and thermal comfort levels. Other excitations such as internal and solar gains have contributed to the effects for PMV-PPD analysis. The results section of this thesis focusses mainly within the Living Zone of the dwellings where the heating controller was set. There are some comparisons made to the non-living zone of the dwellings and the graphs which represent these can be found in Appendix B.

To gauge the results extracted from the ESP-r simulations, there have been certain heating and PMV criteria set in place to aid in the analysis of thermal comfort. These are explained in Chapters Two and Three for the controller and PMV levels, respectively. Long-term and short-term comfort conditions (seasonal and annual simulations) are used to check whether the implementation of load flexibility strategies creates discomfort over the long and/or short term. Further analysis is reviewed into these seasonal differences within this chapter.

There is a comparative results section (section 5.4) which combines the results of all three scenarios for specific situations, such as thermal comfort and heating loads. The results are discussed by grouping the results from the flat dwelling and comparing to the detached dwelling.

5.1 Base Case, Current Heating Results

The following results in this sub-section highlights the current energy requirements within the UK in both typology dwellings against the different building regulations. This gives a baseline in the areas of current high energy consumption when switching the UK gas heating supply to electric, highlighting what areas are to focus improvements. This section also portrays the current accepted thermal comfort levels in the form of pie charts, which represents the percentages of the different levels of thermal comfort experiences in the properties in both long and short time scales.

Table 9: Current UK heating requirements given electrification

	Sensible Heating Energy (kWhrs)		**Number of hours required (Hrs)**	
Flat	2010 Standards	PassiveHouse	2010 Standards	PassiveHouse
Annual	876.97	4.09	1607.8	81
Winter	52.47	0.53	66.5	10.5
Spring	6.75	0	42.8	0
Summer	0	0	0	0
Detached				
Annual	1380.5	5.75	1933.5	89.5
Winter	63	0.84	66.5	6.5
Spring	21.48	0.09	63.8	0.5
Summer	0.03	0	1	0

In the initial viewing of the above results (Table 9), it was deemed pertinent to view the values for heating energy output and hours required tabularly and make visual representations later. Any assumptions made at this stage may change when the results of thermal comfort and heating loads are compared in the following sections.

Initial suggestion of the heating requirements is that they are standard for the current heating energy usage within the UK domestic sector, contributing to ~40% of total home electrical energy usage for both dwellings-43% and 44% for flat and detached, respectively (based on an energy study carried out by OfGem, 2015). The results in the above table represent higher usage in winter in all three scenarios, for both typologies and building regulation types which is to be expected.

The results for the future housing stock, as like the nature of a passive dwelling has air tight insulation and minimal to no air leakage (more information about passive house standards can be found in Chapter Two, Section 2.1). Therefore, heating is well maintained inside the property and as such requires a significantly lower amount of heating compared to the 2010 building standard- this equates to 99.5% less heating energy required over a full year across both dwellings.

The number of hours required over the course of a year if the heating were needed every day would be 3650 total hours (see base case control strategy time line for more information on heating hours per day in Chapter Four, Section 4.1). Thus, the total amount of hours actually required in the flat is 44% less than that of the total possible heating demand (3650 hours) and 54% less sensible heating energy for the detached property.

For the seasonal simulated weeks in the flat, the most interesting result is the transitional (or spring) week which requires a higher number of hours compared to the given energy used (kWhrs) to the homes. This is likely due to the cold spring mornings requiring the heating to work like a winter morning but the solar (Appendix C) and casual gains (Ch3, section 3.5) throughout the rest of the day requiring less heating in the evening to meet the controller strategy set point of 21°C.

In the detached dwelling, the heating loads are higher due to the larger floor area meaning more energy is required to reach the living zone’s controller set point. The results for 2010 building regulations standards of both sensible heating energy and the number of hours required in the spring week show that the heating demand is higher when compared against the flat in the other two simulated seasons: 68.6% more kWhrs and 21 more hours of heating within the dwelling during this one week. The winter week simulation has a 16.7% kWhr increase compared to the flat, yet the required hours remains the same. Summer simulation results have negligible comparison.

As this is the current requirements for the UK, these results create a baseline when comparing against the two shifted heating requirements in the following sections with the ideal to be reducing the total heating requirements.

The following results depict the thermal comfort levels within the dwellings against the two different housing stock models. Pie charts were chosen to represent the data as they visually display the proportion of time in which the thermal comfort within the dwellings would be considered as suitable and the time in which it is not. The key for the following pie charts is shown in Figure 12 below:

Figure 12: Key for thermal comfort pie charts

As the figures in the Base Case and following iterations will show, the colours of the pie charts (Figure 12) indicate a thermal comfort zone of "Very Uncomfortable". This level is not an outcome in any of the simulation results and is shown in the key to illustrate the four levels of thermal comfort and to emphasise that the result of "Unpleasant" is not the worst case that ***can*** be observed.

Future Housing Stock

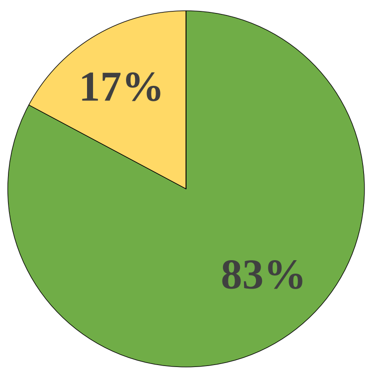


Figure 13: Annual base case Passive House thermal comfort levels in flat dwelling

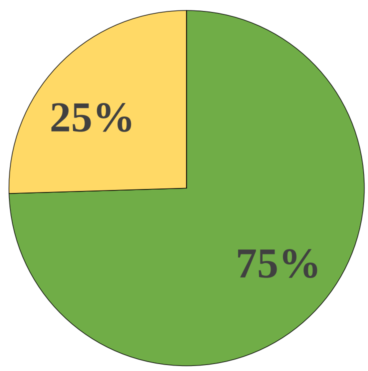


Figure 14: Annual base case Passive House thermal comfort levels in detached dwelling

Current Housing Stock

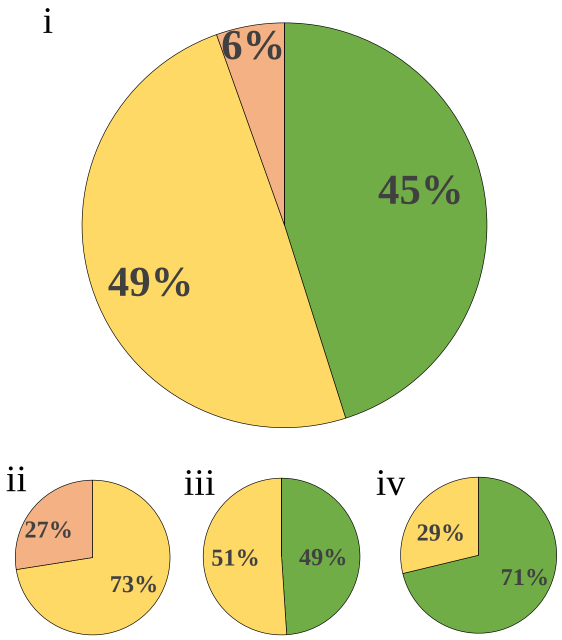


Figure 15: Base case thermal comfort levels for flat with 2010 Standard Building regulations for i) annual, ii) winter, iii) spring, iv) summer

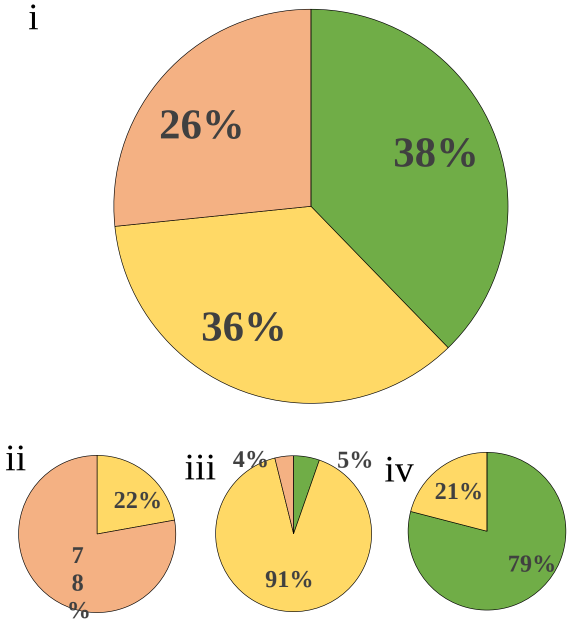


Figure 16: Base Case thermal comfort levels for detached with 2010 Standard Building regulations for i) annual, ii) winter, iii) spring, iv) summer

The annual pie charts (Figures 13, 14, 15i and 16i) give an overview of the thermal comfort over the course of a year and for more in-depth analysis for this thesis, seasonal pie charts are reviewed for the 2010 building regulation dwellings. This gives an insight to the thermal comfort levels inside a typical, current UK dwelling. Passive House building regulation dwellings give negligible seasonal differences between the seasons and hence they are omitted from the results. The values for each simulation in future house stock models can be viewed in Appendix D.

The results for the Passive House dwellings show that thermal comfort levels inside both property typologies are well-maintained in the “Pleasant” thermal zone throughout the year, with just 17% of the time considered as “Acceptable” in the flat and one-third of the year in the detached dwelling. In contrast to this, the 2010 standard dwellings give rise to a varying set of results in thermal comfort levels.

The first significant result when compared to Passive House dwellings is that there is a substantially lower amount of time within the year considered as “Pleasant”- 38% less in the flat and 37% less in the detached house. As a result, there is a greater proportion of the year when thermal comfort is below this zone of ideal comfort.

Annually, the flat has better thermal comfort levels than the detached dwelling, with 49% of the time being considered as “Acceptable” and only 5% of the year being considered as “Unpleasant”. Meanwhile, the detached dwelling has approximately one-third of the year within the “Unpleasant” thermal comfort zone.

Looking further into seasonal variations (Figures 15i-iv and 16i-iv) depicts that winter inside both dwellings contributes to the annual “Unpleasant” thermal values. The detached building is considered as being “Unpleasant” for 78% of the winter week simulation.

The base case scenarios represent the current UK and so the objective is to improve or maintain these thermal levels, while reducing the heating requirements. This will be evaluated over the next two scenarios.

5.2 Shift One, Restrictive Heating Results

The results for the restrictive heating operating times are shown in this section. The simulation for this shift is modelled on an extreme movement on the heating operating activity to evaluate the limits to thermal comfort and load flexibility. Following structure from the Base Case results section, this section will cover the numeric values of the heating within both dwellings and then analyse the effects this shift has on the thermal comfort levels compared to those results from the UK current heating requirements.

This simulation features a reduced number in heating hours and the heating controller is set to occupy only 21% of the day, or 5 hours.

Table 10: Restrictive heating operating activity energy outputs

	Sensible Heating Energy (kWhrs)		Number of hours required (Hrs)	
Flat	2010 Standards	PassiveHouse	2010 Standards	PassiveHouse
Annual	660.73	3.26	1033	69.2
Winter	34.8	0.49	38.5	8.8
Spring	8.14	0	30	0
Summer	0.04	0	1.5	0
Detached				
Annual	888.56	0.54	1292	22.8
Winter	35	0.89	38.5	9.5
Spring	20.68	0	38.2	0
Summer	0.13	0	4	0

Table 10, as like in the base case, shows the Passive House regulated building to have a significant reduction in heating output and heating hours required. Compared to the Base Case, the annual Sensible Heating Energy (kWhrs) outputted to the dwelling is reduced by as much as 35.6% in the detached dwelling (24.6% in the flat) with hours of required heating reduced, on average, by 25 days between the two dwellings. This is a significant reduction which could reduce costs within the properties by a large amount. This is analysed in Chapter Six.

Interestingly, there is a significant decrease in the annual and winter reductions within this scenario. The spring simulation week poses very little differences in the results, with only a few kWhrs reduction in the week. The hours required for the heating differing very slightly, or on par, to the winter week simulation. This could be a result of the heating hours required occurring in the colder mornings of spring and therefore, with the heating controller being shifted to earlier in the morning before solar, occupancy or significant equipment gains are present, the temperature within the living zone is below the set point temperature of 21°C and as such the controller is activated. Solar levels can be observed in Appendix C. To view how the heating controller impacts the living zone temperature compared to no heating present in the non-living zone, see Appendix B.

When comparing the three Passive House cases, this scenario (restricted heating) presented a higher number of required hours in the detached dwelling compared to the other two simulations. This is likely due to the nature of Passive House relying heavily on solar gains which are unavailable during the morning hours of a spring season. The summer results, as like in Base Case are considered negligible in the contribution to annual or seasonal requirements.

The following pie charts portray the thermal comfort levels extracted from the results of the restricted shift simulation (see Figure 12 for key). In comparing the Passive House results for Shift One (and Shift two) to the Base Case, it was found that there was no difference to the values of thermal comfort levels, annually or seasonally, and therefore from this point is was deemed unnecessary to include in the results section. The percentage and numerical values of thermal comfort parameters can, however, be found for each iteration in Appendix D.

Current Housing Stock

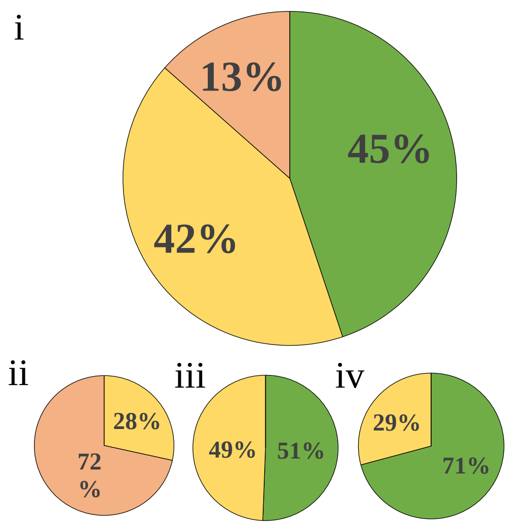


Figure 17: Shift One thermal comfort levels for flat with 2010 Standard Building regulations for i) annual, ii) winter, iii) spring, iv) summer

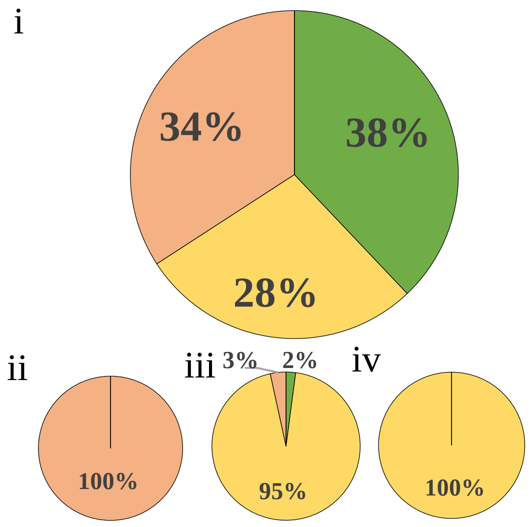


Figure 18: Shift One thermal comfort levels for detached with 2010 Standard Building regulations for i) annual, ii) winter, iii) spring, iv) summer

A first overview of the thermal comfort results above in Figure 17 and Figure 18 shows minor differences to the annual thermal environment for each dwelling compared to the first simulation. The most obvious difference in these results is seen within the seasonal evaluations. The winter pie chart (Figure 17ii), in comparison to the base case winter (Figure 15ii), depicts that the zones for “Unpleasant” and “Acceptable” thermal levels have switched, instead of the week being dominantly “Acceptable”, the week is now considered as mainly “Unpleasant”.

The thermal comfort results for spring and summer for the flat do not differ from the Base Case results. However, there is a drastic change in the thermal comfort levels observed in the detached property. The thermal comfort levels are reduced in all three simulated seasons. The biggest difference occurs in the summer week where 100% of the week is considered as being “Acceptable” as opposed to 21% in the Base Case simulation and the rest of the week remaining in the “Pleasant” thermal comfort zone. While “Acceptable” suggests a suitable thermal environment, in these simulations, it highlights the negative effects that thermal comfort has undergone by this reduction and shift of the heating strategy.

5.3 Shift Two, Gradual Heating Results

The final iteration, as defined in Chapter Four, section 4.3, combines the need for load shifting with more flexibility. This is done by gradual inclines and declines in the heating on either side of shift one control strategy.

The control strategy for this iteration equates to controlling the heating within the dwellings for one-third of the day.

In reference to Table 11, the annual changes in the standard building construction models, show a ~12% reduction in Sensible Heating Energy output for both dwellings compared to the current UK requirements. The table indicates a reduction in heating hours required by nine and seven days for the flat and detached dwellings, respectively.

Table 11: The heating outputs for a gradual heating system

	Sensible Heating Energy (kWhrs)		**Number of hours required (Hrs)**	
Flat	2010 Standards	Passive House	2010 Standards	Passive House
Annual	759.92	2.56	1389	53.5
Winter	44	0.5	59.5	8.2
Spring	7.67	0	30	0
Summer	0.03	0	1.5	0
Detached				
Annual	1220.43	0.59	1775.2	23
Winter	55.5	0.84	59.5	8.5
Spring	21.03	0	46.2	0
Summer	0.13	0	4	0

In the Passive House results, both dwellings coincide with the description from the previous two simulations: significantly less than 2010 standards due to high insulation and air tightness in the dwellings. The shift to early morning hours in the model controller and the larger floor area is likely the reason for a higher number of hours required in the summer months in the detached typology than the 1hour only required within the Base Case scenario. This is considered a negligible number of hours for a week of simulations. Taking this into account, there is a decrease of eight days of heating requirements annually, with a greater proportion of the year requiring heating.

The following pie charts (Figures 19 and 20) represent the thermal comfort levels experiences in the ESP-r model for the gradual heating iterative simulation. The key for the pie charts is referenced in Figure 12.

Current Housing Stock

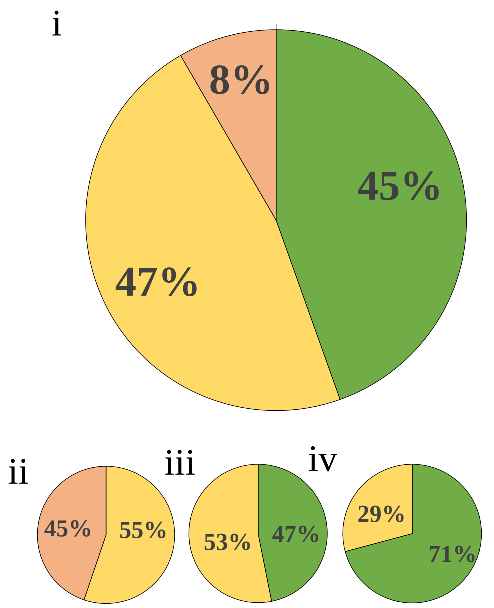


Figure 19: Shift Two thermal comfort levels for flat with 2010 Standard Building regulations for i) annual, ii) winter, iii) spring, iv) summer

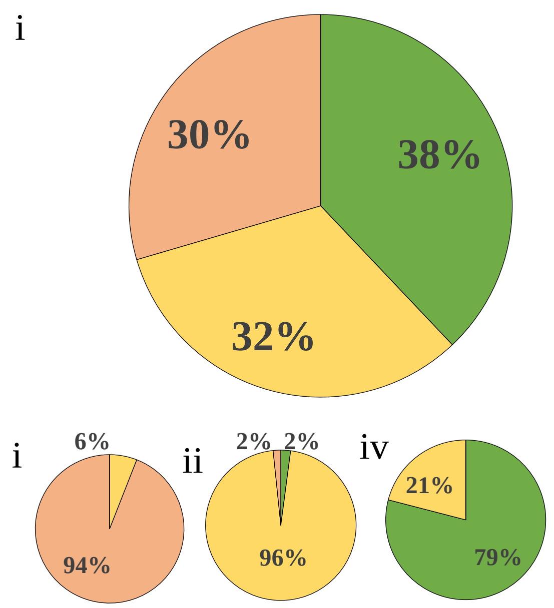


Figure 20: Shift Two thermal comfort levels for detached with 2010 Standard Building regulations for i) annual, ii) winter, iii) spring, iv) summer

Overall comparison to the current UK heating requirements (Base Case) in Figure 19 and Figure 20 depicts that there are similar correlations in thermal comfort levels for the two simulations and in both dwellings.

Differences which are noteworthy are the higher proportion of “Unpleasant” thermal rating in winter flat and detached dwelling (Figures 19ii and 20ii) for gradual heating than in the Base Case. The results for the detached home show that, annually, there is a one-third split between the three dominating thermal comfort zones. From the seasonal pie charts, it is clear as to which season effects which zone: dominantly “Unpleasant” in winter week, “Acceptable” in spring and “Pleasant” in summer.

There is a slightly higher proportion of “Unpleasant” in both dwellings compared to Base Case, with an overall increase of 3% in both dwellings, and a 17% increase in winter across both dwellings. In comparison to the restrictive shift (Figures 17 and 18), the thermal levels have improved, particularly in Summer where the presence of "Pleasant" comfort level is increased from 0% to 79% occurrence.

5.4 Comparative Results

For result comparison within this thesis, it was deemed necessary to compare the scenarios for each dwelling as well as the individual analysis in the previous sections of this chapter. This meant that thermal effects could be studied with occupancy times rather than from the brief overview in the pie charts. For this, a weekend day (Sunday) and a weekday (Monday) were analysed during a winter season. Winter was chosen as from the individual pie charts depicted above, Shift One and Shift Two show that this season's effects thermal comfort the most significantly when loads are moved around off-peak hours.

5.4.1 Flat

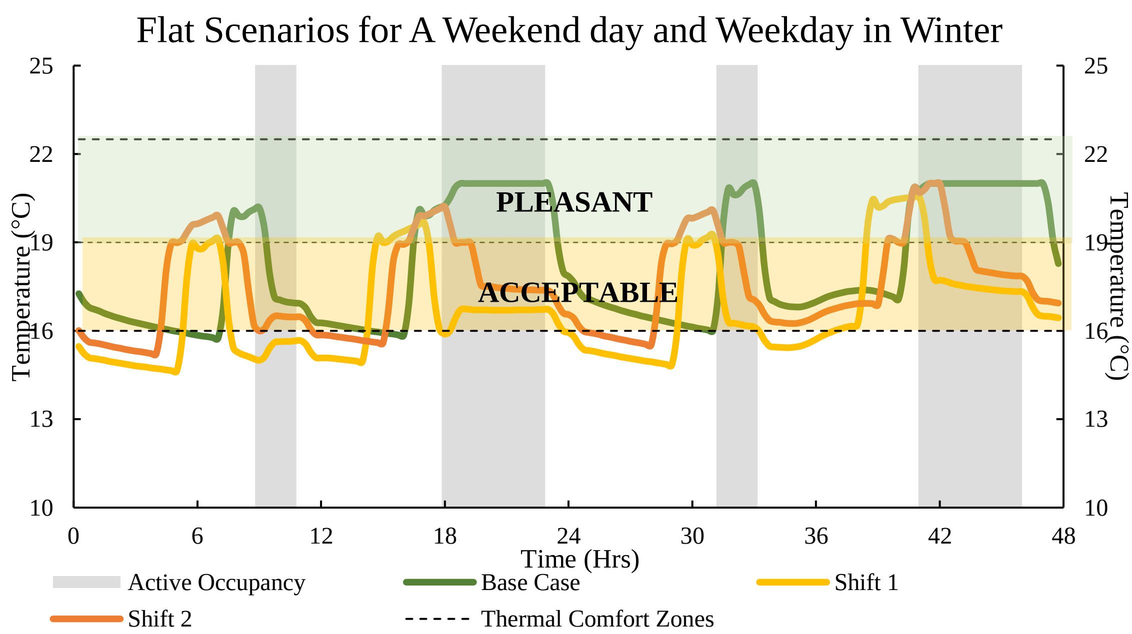


Figure 21: Comparative graph of all three scenarios graphically displaying active occupancy hours with times of suitable thermal comfort within the flat

From the graph above (Figure 21), it can be a seen that the Base Case scenario presents the most comfortable environment, with thermal comfort being within the pleasant zone for much of the occupancy times. The exception to this is the weekend, when heating controllers maintained the same timings as through the week, but occupancy levels differ (see Ch3, Sec3.5.1 for occupancy). In reference to the thermal zones definition in Chapter two, Section 2.5 and the zones given in the graph above, the two zones which were considered as thermally suitable are “Pleasant” and “Acceptable”. Where the temperature drops to out with these zones, the thermal level is measured to be unsuitable for the occupants.

Restrictive heating, as represented by the yellow line on the graph, shows that a small amount of time is spent within the pleasant zone of thermal comfort and when within this zone, it is during inactive occupancy hours. For the two days graphically displayed, Shift One falls within the acceptable thermal zone for 12 of the 14 hours of active occupancy. This gives a further level of detail at the first look of thermal comfort from the pie charts where all hours of the week in winter are combined as one output. The graph in Figure 21 predicts a pattern, that for a full week, active occupancy for Shift One will be considered as acceptable for 45 of the 49 hours, with the other four hours considered as an unsuitable thermal environment for inhabitants.

The gradual heating results (orange line on Figure 21) show that ~10% of the active occupancy hours in these two days falls within the pleasant comfort zone window, with the other 90% of the active occupancy times falling within the acceptable zone. The stepped increase and decrease of 19°C to and from 21°C shows a better flexibility in the ability for the heating load to coast through the active occupancy hours. The best outcome for the heating with a gradual shift is at the start of the evening (4pm) during the week where comfort levels are within the pleasant zone for the first 1.5hours of occupancy and drops to the acceptable zone when the heating is turned off.

The flexibility of the load within the flat has positive attribute for a gradual heating strategy. This shift shows that, while thermal comfort levels drop below pleasant, they are considered as acceptable for the majority of the time. The issue is that there is a significant loss of heat through the insulation within a 2010 standard dwelling where the temperature line graphs show significant drops by around 2-3°C within the first hour of the heating being turned off. This can be further analysed in Appendix B where there is a comparison of the temperatures of the living and non-living zones. Any ability to hold temperature within the dwelling is likely due to the casual gains present-throughout the evening in particular-which accounts for ~ 40% of the total casual gains of the dwellings (see casual gains graph in Table 3 and Table 4).

5.4.2 Detached

Figure 22 shows that the detached dwelling spends a significant amount of time out of the pleasant comfort window for all three scenarios. This could be due to the larger floor area of the detached dwelling compared to the flat- 33% larger- meaning that more heat is lost to the surroundings and that heat cannot be retained within the dwelling given 2010 building regulations.

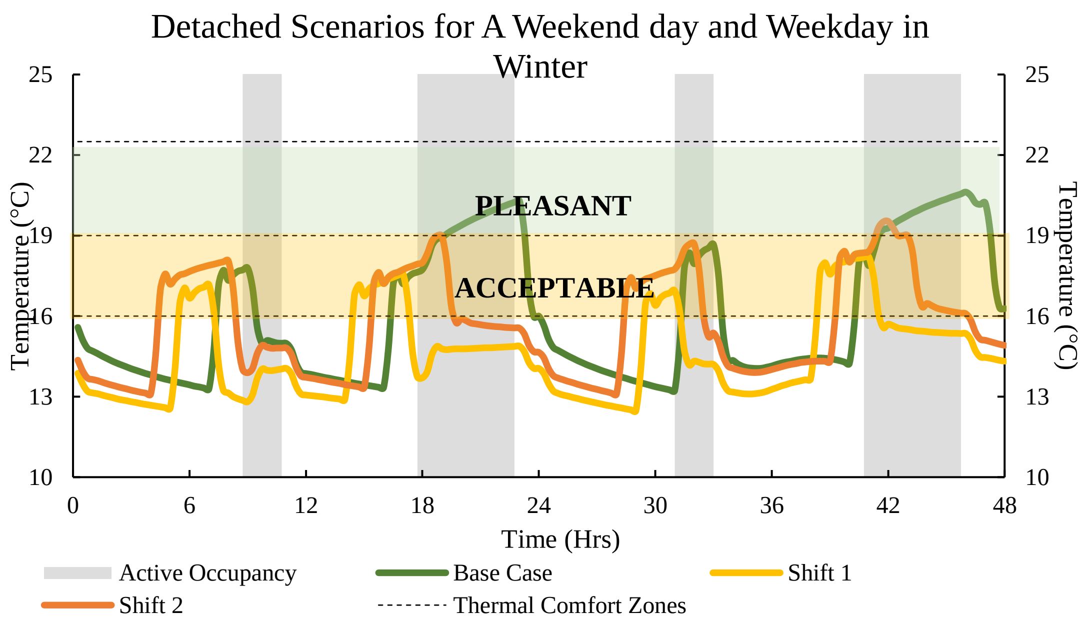


Figure 22: Comparative graph of all three scenarios graphically displaying active occupancy hours with times of suitable thermal comfort within the detached property

As in the flat, the Base Case, or current UK heating demand, gives the best thermal comfort outcome, with eight of the fourteen active occupancy hours within the pleasant zone. For the three scenarios, Figure 22 indicates that the heating load struggled to reach the desired upper temperature of 21°C, with the Base Case scenario hitting this peak temperature in the last hour of the heating controller timeline during each day.

Similar to that in the flat scenarios, Shift One shows the most detrimental effect to thermal comfort of all three scenarios with only one hour of the active occupancy time being within an acceptable thermal environment zone and the other thirteen hours falling within unsuitable thermal comfort conditions for inhabitants.

In the gradual heating strategy (Shift Two in Figure 22), the reduction in heating load from the Base Case scenario resulted in a fall of thermal comfort to within the acceptable window for all hours of active occupancy. The exception is in the morning during the weekend when the controller is not set to represent occupancy changes during these times.

Further investigation would need to be made for the detached scenario and these are suggested in Chapter 8, Section 7.2

6. *Cost Analysis*

While analysing thermal comfort levels in the ability for load flexibility is the main focus of this thesis, it was also considered necessary to consider if these shifts really resulted in cost saving. Thus, a cost analysis was carried out on both dwelling typologies with the results from the sensible heating energy output in Tables Nine, Ten and Eleven.

The results in Table 12 are based on tariffs set by SSE (2018) for a Pay As You Go metre and Economy metre situated in Glasgow City Centre. The results are purely based on electric heating output and do not consider any other electricity use within the homes. These two tariffs were decided by comparing a standard tariff applied to many homes- Pay As You Go, which is easily managed at one flat cost- and an Economy tariff which is tentative towards peak hour usage.

For the Pay As You Go tariff, the standing charge is £110.99 per year with a standard electricity price of 14.32p per kWhr. The Economy metre has a higher standing charge of £116.91 and peak times (7am-1.30pm and 4pm -11pm) have an electrical price of 15.34p per kWhr while the off-peak times are priced at 7.99p per kWhr.

Table 12: Energy tariffs (SSE, 2018) applied to the Sensible Heating Energy results from ESP-r

	2010 Standard		**Passive House**	
Flat	Pay As You Go	Economy	Pay As You Go	Economy
Base Case	£236.57	£251.44	£111.58	£117.54
Shift One	£205.61	£179.41	£111.46	£117.22
Shift Two	£219.81	£205.56	£111.36	£117.21
Detached				
Base case	£308.67	£328.68	£111.81	£117.79
Shift One	£238.23	£200.97	£111.06	£116.96
Shift Two	£285.75	£259.28	£111.07	£116.98

Table 13: Cost savings for the 2010 Building Regulated dwellings

	Shift One	Shift Two
Flat		
Pay As You Go	£30.96	£16.76
Economy	£72.03	£45.88
Detached		
Pay As You Go	£70.44	£22.92
Economy	£127.71	£69.40

In the Base Case for each dwelling typology, the current UK heating operating times represent the peak times defined by SSE and as such, the Economy tariff would be an unsuitable cost saving solution for current heating demands. However, the Economy tariff does have substantial cost saving attributes for both the restricted heating shift (Shift One) and the gradual shift (Shift Two), whereby the heating load falls into peak times just 20% of the time (or one hour a day) for the first shifted scenario and a 50/50 split for the second shifted scenario. The Economy tariff for the two shifts compared to Pay As You Go has ~15% cost savings (Table 13), even with a higher standing charge and peak cost per kWhr.

The higher standing charge for Economy tariff results in a higher cost in all three scenarios for the future housing stock compared to Pay As You Go tariff. This is because the Passive House results have an almost negligible output of kWhrs so that the high standing charge of Economy is more noticeable than within the current building standard housing stock models.

Overall, the results for the cost analysis show that with a reduction to the heating operating times and the flexibility of the loads to be able to move into off peak hours, the Economy tariffs will result in substantial savings year on year. The savings table

(Table 13) could be the turning point for convincing communities to the need for demand side management of their heating loads.

However, to encourage consumers to op in to a load shifting scheme would require inducements more than the cost saving attributes. It is likely that the current tariff prices will change with the overload of the electric network to persuade homeowners to make a voluntary switch in their heating schedules.

7. Discussion

This chapter of the thesis will summarise the results and cost analysis of the study as shown in Chapters Five and Six and go on to discuss the social impacts of load shifting and the effects the UK climate will have on the future of electrical heating (and cooling) demands.

7.1 Results Summary

To summarise the results in the previous two chapters, it is evident that while the current UK housing stock models satisfy the majority of thermal comfort requirements, the cost to run heating is an expensive commodity for either a Pay As You Go or Economy tariff customers. This work emphasises the need to change. The shift to electrification is required due to the urgent need to decarbonise and reduce the UK's Green House Gas emissions. Nevertheless, gas has high volatility, high seasonal variations and is less predictable than that of electricity (Wilson et al, 2013). Therefore, the need for electrification brings substantial positives, which makes it seem unusual that the UK has not made the shift before now. This is another example of the heavy dependence the UK has on fossil fuels.

It is apparent that the improvements to the insulation levels seen in the future housing stock models have little to no difference in the overall thermal comfort levels of shifting the heating requirements. This is due to the passive nature and the self-sufficiency of Passive House buildings whereby the construction and materials used within the dwellings result in negligible heat loss. This emphasises the need for significant improvements to air tightness and insulation in current housing stock to both improve thermal comfort environments for the short and long term and reduce overall energy demands. In the detached dwelling, the floor area is substantially larger than that of the flat and, as such, there is significant heat losses associated with the former typology which lessens the acceptable to pleasant thermal comfort results in all three scenarios.

The two shifts in the heating demand were simulated to study the effects of thermal comfort where heating demand needs to be shifted as to elevate pressures to the low voltage network given electrification. Firstly, a restricted shift was applied to the heating loads whereby the load is shifted into off peak hours and reduced hours. This was simulated to show the effects of thermal comfort and energy requirements in an extreme cost saving shift. The cost of electric for heating was, as Table 11 shows, significantly reduced compared to current standards in both Pay As You Go and Economy tariffs for each typology and building stock type. However, as Figures 17 and 18 show, the thermal comfort levels are expressively impacted by this shift resulting in a poor thermal comfort environment. Thermal comfort levels are heavily affected in the current housing stock due to the inability for heating to be retained within the dwelling and heat being lost through gaps in the construction materials. As discussed above, Passive House types for both dwellings saw negligible variations, annually or seasonally, for this shift.

The second shift in heating operative activity came by iteration whereby the shift was simulated to the extent where energy and cost can be saved but thermal comfort is retained/ minimally affected to that of current levels. This resulted in a gradual shift of the current heating requirements. As the results show in the previous chapter, thermal comfort is only slightly affected. This would be expected in the current housing stock, but overall thermal comfort levels vary only marginally different compared to Base Case model and significantly better than the restrictive shift case. Alongside this, the gradual shift of this model reduces the energy required (Table 11) and the associated saving costs- especially in Economy tariff (Table 13).

Therefore, to summarise the results:

- ***Base Case*** represents current UK heating operative times and as such is expensive to run but with sufficient thermal comfort levels;
- ***Shift One*** (restrictive heating) is low cost but poor thermal comfort;
- ***Shift Two*** (gradual heating times) has a lower cost than Base Case (higher than shift one) but thermal comfort closer to that of current UK requirements.

This thesis focusses on the current standards of housing stock compared to future housing stock, however there are a significant proportion of the UK population living in poor housing conditions. Three in ten people live in “bad housing” from a 2013 English Housing Survey. This emphasises that acceptable thermal comfort is a more pertinent focus for all housing in the UK, particularly in those pre-1970 builds, before modifying the heating loads in those sub-par dwellings.

7.2 Social Impact

There are many social implications to consider with any idea regarding energy- these include inter alia security of supply, sustained economic growth, fossil fuel replacement and climate change mitigation (Clarke, 2013). Within this study occupants' acceptance is the upmost important factor as shifting heating out of the current heating operative hours can have a negative effect on the end-user's convenience (Hategekimana, 2015). Nicol (1993) states that the requirements for understanding the importance of thermal comfort are:

- To provide a satisfactory condition for occupants; and
- To control energy consumption.

While this study incorporates both within the gradual shift change, it is the acceptance of demand side management to heating requirements that raises issues going forward. Electrification is essential moving forward to satisfy the *Climate Change Act 2008* and the Sustainable Development Goal Seven of Cleaner Energy. However, the strain placed upon the ageing transmission and distribution networks of the UK associated with the electrification shift is concerning. From a social perceptive the shift in heating operating times will come with a need for the public to understand the instability of the grid of they don't turn to load flexibility and demand side management.

Load shifting may be unacceptable for vulnerable groups such as the elderly (Hong et al, 2012) where the lower boundaries of "Acceptable" thermal comfort is experienced as "Unpleasant" for those sensitive to colder temperatures. Shifting heating demands is also unsuitable for homes in poorer conditions whereby the insulation is poor, and the air leakage is weak (Wilson et al, 2013).

A positive outcome to the community is the results from the cost analysis (Tables 12 and 13) where there are substantial savings to be had with load flexibility in a gradual shifting model where thermal comfort is also only marginally affected. In a time where people are being influenced to retrofit their homes for renewable penetration gain, demand side management for heating is even more important to the effects on the low voltage network, electrical bills and thermal comfort.

The challenge always facing society is to select the appropriate solution from the plethora of options while accommodating conflicting viewpoints and ensuring end-users comfort and convenience is maintained (Clarke, 2013).

7.3 Future for Heating (and Cooling)

The simulations for this study are based on climate data from 2005 and used as the base line for climate data representing the past 15 years. However, global warming is contributing to higher Summer temperatures and colder Winters as experienced in the first half of 2018. This is seen with the "Beast from the East" in March 2018 where the UK saw temperatures drop to minus 12°C in some rural areas and put much of the nation in lockdown. According to Twidale (2018), the prices for gas consumption surged 146% to 190p per therm and 30% increase than standard usage within the first day of the "Beast from the East". Britain's ability to be able to supply short term demand stocks is pertinent in times of extreme weather. Storage of electrical supply is a developing concept which, with the increase of renewables into the voltage network, will see improvements year on year to give energy security while keeping costs low.

On the other hand, this year's Summer (2018) has seen a surge in temperatures as high as 35°C (Heathrow, 27 July as recorded by Met Office) which has seen the hottest month of July in southern regions of the UK since records began. The Summer Heat Wave has seen major discussions concerning the lack of air conditioning present in most residential homes in the UK. With Global Warming, it is expected that these hot Summers' may be a thing of the future and as the UK experiences average summer temperatures in the high 20s, the future to the domestic building trade will need to change. This will contribute to a shift in the electrical usage throughout the year with many homes being fitted with air conditioning to satisfy thermal comfort levels with improved insulation levels.

The first half of 2018 has already seen two extremes (for the UK) in weather conditions. There is potential to be both high electrical use from cooling in Summer and high electrical use from heating in the Winter if Global Warming is to continue to contribute to these high seasonal variations. It is further pertinent that renewables are used to their full potential to contribute to this increase in electrical demand. Arbnco (2018) stated that this Summer has broken solar energy records, generating 75GWh on five of seven days between 21st and 28th June 2018 and emphasises the need for storage of renewable energy to take UK into the cold winters.

8. *Conclusion*

The objective of this thesis was to examine the potential for shifting operating times for heating requirements in current and future UK dwellings, avoiding discomfort or inconvenience to the occupants. The enhancement of flexibility to the heating demand given its steady shift from gasification to electrification gives the ability to be able to manipulate operation times and prove useful in the future stock of stochastic renewables entering the energy mix.

From the results given in this thesis, conclusions are drawn which give rise to heating demands that have semi-flexible attributes. Within the current housing stock, the insulation levels do not give sufficient air tightness for heat to be retained in the dwelling for hours during peak times (even more prominent in large floor area of the Detached dwelling) and gives rise to a moderate thermal comfort situation. The results showed that in the need to maintain the thermal comfort, shifting heating loads by a factor of its current situation (as shown in restrictive heating) bares no positive outcome on the thermal comfort of the occupants and as such was dismissed. A shift of displacement of one-two hours with gradual incline and decline of heating temperatures (as shown in the gradual heating shift) is the best outcome for this study. This shift also reduces costs by ~20% and satisfies thermal comfort levels to be that of similar to current moderate levels.

Within the Passive Housing stock models: thermal comfort levels, energy use and subsequent cost savings were ideal. The future stock exhibits a promising outcome in all shifts of the heating load and as such the boundaries of thermal comfort can be extended. It is therefore suggested that load scheduling needs to be adaptive to the housing in which it will take place, assessing the insulation and air tightness of the properties before addressing the algorithm and scenario needed to schedule loads.

The modelling work carried out in this thesis highlighted the difficulty in load scheduling when considering end-user comfort and convenience. The software emulates as close to real dwellings as the inputs to the system will provide. However, without testing the strategies in real dwelling, it is hard to draw a definite conclusion on the algorithm of convincing load scheduling.

On a final note, load shifting alone cannot be relied upon to deal with the future increase of electrical demands and subsequently will not be an overnight process. Ultimately, the infrastructure of the UK's transmission and distribution lines needs to be upgraded to deal with the urgent need to decarbonise the UK, meet legislation and policies and be prepared for the future of a changing energy mix.

8.1 Limitations

The limitations to the study are stated below. These cover the assumptions that were made throughout the study and how these limitations may have impacted the overall results and conclusions drawn in this thesis.

Firstly, the dwellings were pre-modelled from a previous study which meant the construction, materials and geometry were assumed to be typical of dwellings of their type. While the occupant behaviours were researched, overall the number of occupants and their final behaviours were assumed as generic based on theoretical study.

Secondly, there was every attempt to simulate the models as close to real dwellings as possible- with extensive research on casual gains and controller strategies- the results were taken from ESP-r software where there are some limitations to the reality of the results.

Lastly, within the model the boundaries for PMV-PPD can differ dependent on size of study carried out and thus the results should be analysed with caution. The heating controller in the models is set the same for 365 days of year and not altered for weekends or holidays which affects the results in occupant behaviour and thermal comfort levels.

8.2 Future Work

This section of the thesis suggests some areas which require further study. Some of the suggestions are due to the time constraints on the thesis while others were raised during the results of the study.

8.2.1 Modelling Improvements

From the results given in this thesis, it is clear that the control strategies applied to the detached model would not be suitable to maintain thermal comfort within the dwelling. A suggestion for improvements to the model would be to reconsider the casual gains within the property that might better represent the heat gains to the occupants.

It would also be worthwhile to reconsider the control strategy of the heating demand, as the results in Chapter Five show that there is difficulty in the heating rising to the upper desired temperature. This could be reconsidered by increasing the wattage load able to be supplied to the controller or increasing the temperature, so the rooms have more flexibility to warm up if there is a wider temperature range. This could be done by incorporating not only rule-based controls but the Model Predictive Control where several weighted objectives can be considered and optimised.

A further suggestion to improve the research into load flexibility would be to further the ability on demand side management. This would mean giving the heating controller different settings determined by weekends or holidays which the current modelled case for the controllers do not mirror.

8.2.2 Further Study

This thesis focussed on how a shift would affect the current thermal levels, but a further study could be to try and improve thermal comfort levels to as close to passive house standards as possible, with minimal costs- comparing the costs of upgrading to the savings of energy usage.

The aggregation potential of flexibility should also be studied, since only two types of dwellings were considered in this study, a larger data set of results would give a more definitive conclusion on load shifting.

Further iterations to the flexibility to load shifting should also be considered. Given time constraints within this study, iterations were run on 30-minute time shifts but further study could recognise a more specific time shift for the constraints on load flexibility.

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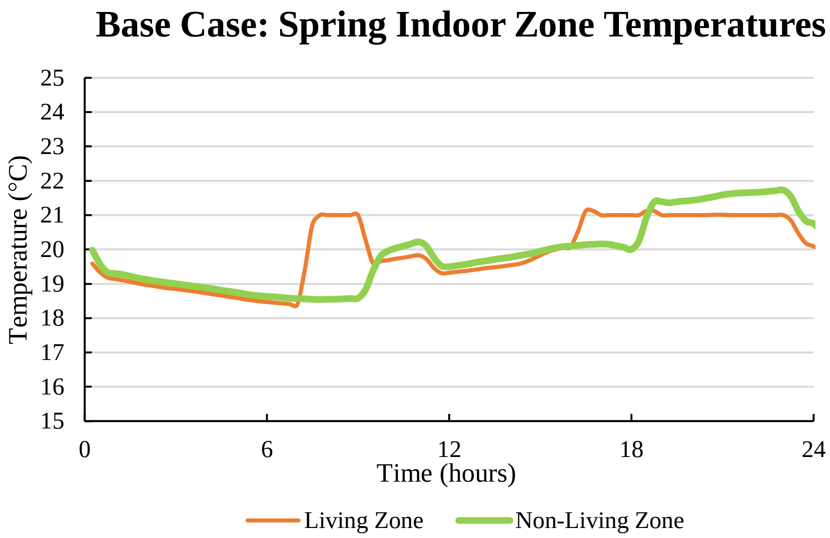
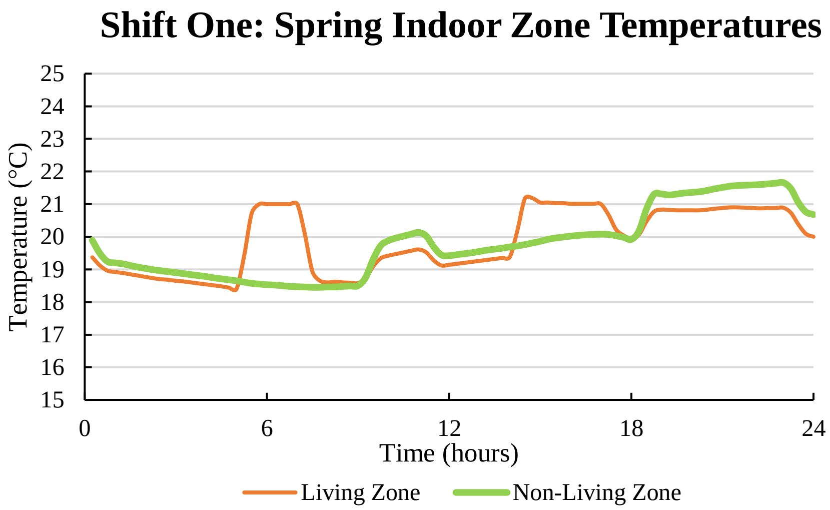
Appendices

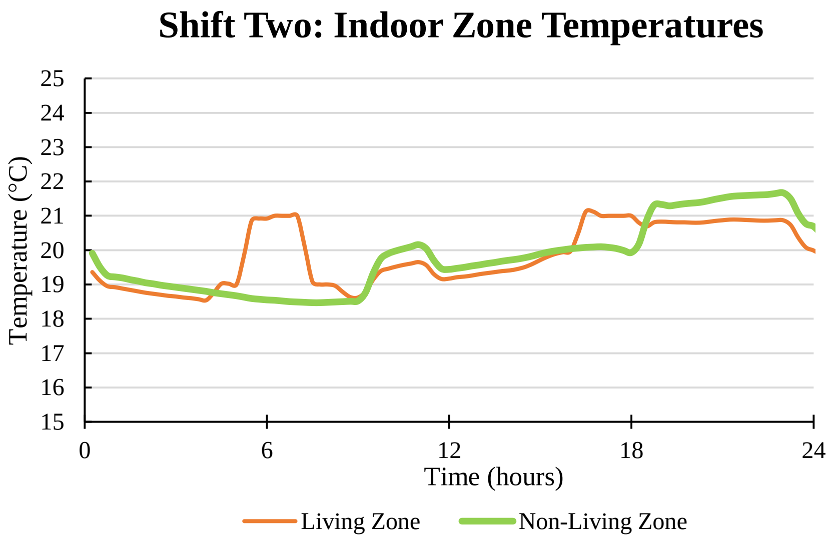
Appendix A: Casual Gains by type extracted from ESP-r

Daytype	Gain No.	Label	Unit	Period Hours	Sensible Magn.(W)	Latent Magn.(W)	Radiant Fraction	Convec Fraction
Weekdays								
	1	Occupt	W	0- 7	40	40	0.6	0.4
	2	Occupt	W	7-9	75	55	0.6	0.4
	3	Occupt	W	9-17	0	0	0.6	0.4
	4	Occupt	W	17-22	70	45	0.6	0.4
	5	Occupt	W	22-24	40	40	0.6	0.4
	6	Lights	W/m^2	0- 7	0	0	0.3	0.7
	7	Lights	W/m^2	7-9	4.7	0	0.3	0.7
	8	Lights	W/m^2	9-17	0	0	0.3	0.7
	9	Lights	W/m^2	17-22	4.7	0	0.3	0.7
	10	Lights	W/m^2	22-24	0	0	0.3	0.7
	11	Equipt	W/m^2	0- 7	2.8	0	0.4	0.6
	12	Equipt	W/m^2	7-9	3.7	0	0.4	0.6
	13	Equipt	W/m^2	9-17	6.8	0	0.4	0.6
	14	Equipt	W/m^2	17-24	10	0	0.4	0.6
Weekend								
	1	Occupt	W	0- 9	40	40	0.6	0.4
	2	Occupt	W	9-11	75	55	0.6	0.4
	3	Occupt	W	11-18	0	0	0.6	0.4
	4	Occupt	W	18-23	70	45	0.6	0.4
	5	Occupt	W	23-24	40	40	0.6	0.4
	6	Lights	W/m^2	0- 9	0	0	0.3	0.7
	7	Lights	W/m^2	9-11	4.7	0	0.3	0.7
	8	Lights	W/m^2	11-18	0	0	0.3	0.7
	9	Lights	W/m^2	18-23	4.7	0	0.3	0.7
	10	Lights	W/m^2	23-24	0	0	0.3	0.7
	11	Equipt	W/m^2	0- 9	3	0	0.4	0.6
	12	Equipt	W/m^2	9-11	4.2	0	0.4	0.6
	13	Equipt	W/m^2	11-18	6.8	0	0.4	0.6
	14	Equipt	W/m^2	18-24	9.3	0	0.4	0.6

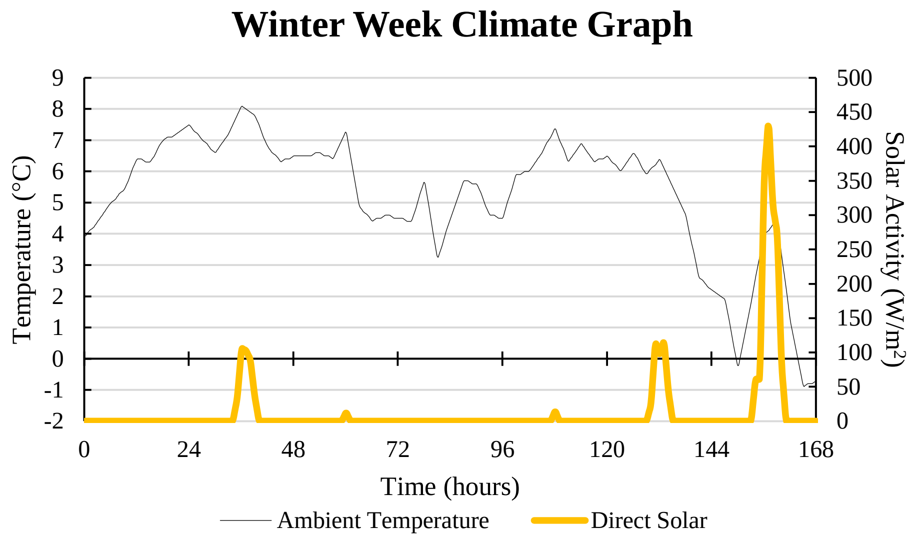
Appendix B: Living and Non-Living Zones Ambient Temperatures

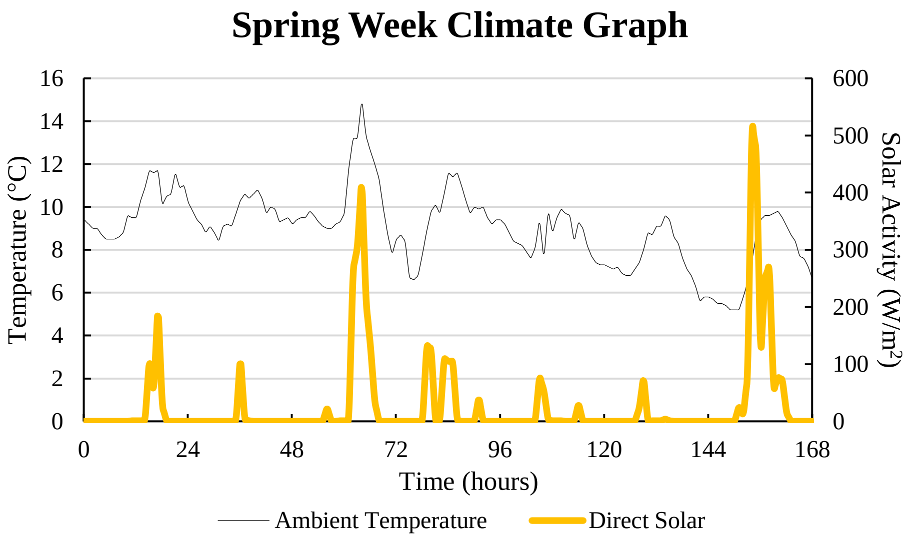


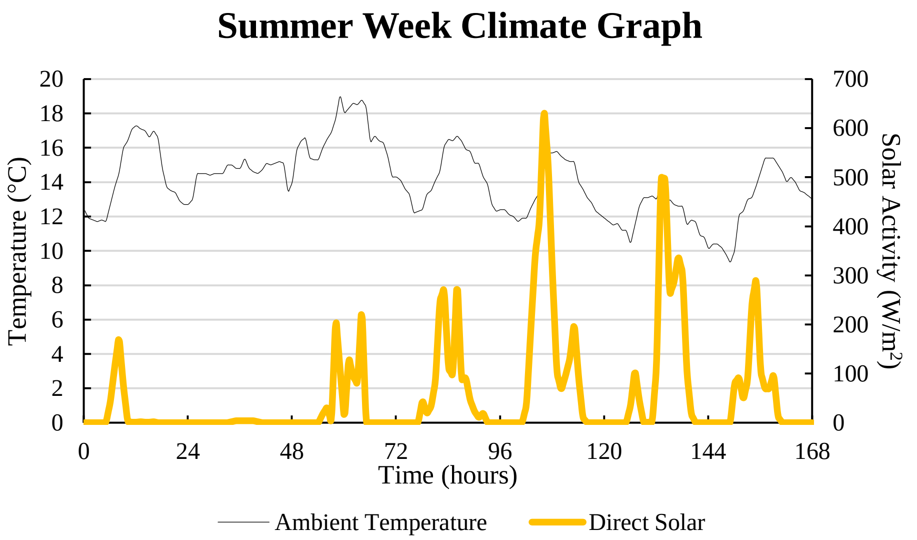




Appendix C: Seasonal Climate Data







Appendix D: Passive House Annual and Seasonal Thermal Comfort Values

	Pleasant	**Acceptable**	**Unpleasant**
Flat			
Annual	83%	17%	0%
Winter	100%	0%	0%
Spring	100%	0%	0%
Summer	73%	27%	0%
Detached			
Annual	75%	25%	0%
Winter	100%	0%	0%
Spring	100%	0%	0%
Summer	52%	48%	0%

Note: values are the same for each load shift