Department of Mechanical Engineering

Investigation into the Time-Shifting Of Domestic Heat Loads

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Energy: Renewable Energy Systems and the Environment

2011

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Signed: Bryan Wyse Date: 09/09/2011

Abstract

The aim of this thesis is to investigate through the use of thermal storage how this could be used to enable a time-shift in the operation of the heating system. This would enable the limits of time-shifting to be identified, by analysing the results this has on the space and water temperatures delivered during occupied periods. Therefore the focus of this research is in the area of demand-side management through the technique of load shifting.

Such a study is important as current policy is to encourage the use of small-scale low carbon devices, to replace current methods of space and water heating in our homes. Heat pumps are just one technology which has been identified as offering great potential, however whilst being a heat source, they require drawing electricity from the electricity distribution network. Therefore, they would be using electricity to heat our homes and water during peak times. Using a modelling approach, this thesis investigates the possibility of time-shifting the operation of the heating system, to shift the loads away from peak periods. A typical UK detached dwelling was modelled with three different levels of building fabric. In addition, a mathematic model of a domestic hot water tank was also developed. The storage mechanisms examined here were the basic thermal inertia of the building fabric and sensible and latent storage materials in the hot water tank. The on/off times of the heat input were then back-shifted and the limits of time-shifting were identified.

The findings from this investigation showed, that time-shifting the on/off times of the heat input for the lower standards only allowed for between 1 and 1.5 hours, while the highest standards allowed for 6 hours without causing serious discomfort. However, the effect of the time-shift on the temperature of the water delivered only allowed for a time-shift of around 2 hours and thus was the limiting factor here. Phase change materials were then added to provide latent thermal storage and this significantly improved the conditions. However, it did not fully eliminate the problem of low temperatures of water being delivered during occupied periods.

Acknowledgements

Firstly, I would like to thank my supervisor Dr Nick Kelly for his patience, support and guidance throughout this project. His help throughout has been vital, providing encouragement, sound advice and direction. This ensured the project went down the correct the path.

I would also like to thank Aizaz Samuel for his help with ESP-r during my group project in the second semester. His help back then really helped me when it came to carrying out my ESP-r investigations this time round. Furthermore, I would like to thank Tom McCombes for his help in setting up a virtual machine with a linux based operating system on my computer at the beginning of the project.

I would also like to thank my family for their continued support throughout my education. Finally, I would like to thank nucleargraduates for ensuring I have a graduate job come October. Their job offer came at the right time and gave me the drive to complete this thesis and took the pressure off from job searching.

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A. Introduction

Securing future energy supplies and reducing greenhouse gas emissions are the two biggest challenges that we are currently faced with in the 21st Century. Global population is continuing to increase and with this, an inevitable increase in energy consumption is evident. The UK has a broad energy mix made up of: coal, oil, natural gas, nuclear, hydro and various types of renewable energy. Recent developments have seen stricter emission restrictions and a push for increased generation from renewable technologies at both local and national levels.

The traditional method of space and water heating in our homes here in the UK is through the use of producing heat by the means of finite resources such as fossil fuels. This means that the energy is supplied by the gas distribution network, which is adequately set up to cope with fluctuations in supply and demand. To move away from our dependency on fossil fuels, there has been significant research and development in alternative low-carbon technologies that could be implemented. These technologies could deliver significant energy efficiency and also greenhouse gas emission reduction benefits and thus helps meet the emission targets, through the use of renewables.

Two technologies that have been identified which offer the greatest potential are: heat pumps and micro-CHP (combined heat and power). However, both these technologies pose challenges for two very different reasons. Heat pumps, whilst being a heat source, require drawing electricity from the electricity distribution network to operate and therefore are moving the demand away from the gas network and on to the electricity network. This would mean the heat pump would be using electricity to heat the house and hot water during peak times and thus adding to the large demand we already place on the network during these times. Micro-CHP generates electricity by burning fossil fuels, so this puts electricity into the network. The ability to control when the electricity is being put into the network could offer benefits financially to the consumer, but also help to achieve a balance of supply and demand on the network.

In the future it is likely that our electricity distribution network is going to have to be managed to accommodate for the inevitable variations in supply that is characteristic from electricity generated from large scale renewables (on-shore and off-shore wind). If there is to be a significant increase in the installations of heat pump and micro-CHP technologies, to ensure a reliable and safe supply of electricity to consumers, the ability to manipulate supply and demand and offer greater demand side management is going to be important. Therefore this thesis is an investigation into one method which could be used for demand management; load shifting.

Load shifting is a technique that aims to move demand from the peak hours to the off-peak hours of the day, in order to offer more control into demand-side management. Properly done, load shifting can help improve energy efficiency and reduce emissions by smoothing the daily peaks of generation that occur during peak times. One way load shifting can be accomplished is by controlling (time shifting), the operation of the heating system and removing the electrical loads they pose at maximum demand times. Therefore this thesis will investigate the use of various thermal storage methods to time-shift the operation of the heating system, in order to find out the maximum allowable time-shift without causing occupant discomfort. This will enable greater control over both supply and demand.

The first investigation will look at the how the thermal storage capacity in a typical detached dwelling, through the quality of building fabric, could be used to facilitate a time shift in the heating systems operation. The effects of back-shifting the start and stop times of the heating system would then be analysed against the space and water temperatures delivered to its occupants during the occupied period. This would help determine what the limits of time-shifting would be. Once the maximum time-shift allowance was identified, the final investigation involved increasing the storage capacity of the water tank through the use of phase change materials, to improve the conditions of the water delivered to the occupants.

B. Methodology

The aims and objectives of the project were to:

- Investigate through the use of buildings thermal storage capacity how this could be used to enable a time-shift in the operation of the heating system.
- Determine the limits of time-shifting by analysing the results showing the effect it has on the space and water temperatures delivered during occupied periods.
- Investigate increasing the storage capacity of the hot water tank through the use of latent thermal storage.

An outline of how the aims and objectives were defined and the project plan followed is listed below. It also explains the path the content in this thesis will follow.

1. Background Information

A literature review was carried out to gain an understanding of heat pump and micro-generation technologies. This helped to identify the problems that implementation of these technologies could have, if applied on a larger scale. The identified problem was one of demand management. Heat pumps require electricity to operate and if they are to be used to heat our homes and water, they would be using peak electricity to do this.

2. Defining Project Aims and Objectives

Once it was identified that demand management was the problem, the project was defined as being one of load shifting. Load shifting is one method that can be used to aid demand side management as this involves moving the demand from peak hours to off-peak hours. One way load shifting can be accomplished is through controlling (time-shifting) the operation of the heating system. From here it was decided to investigate how using thermal storage could be used to facilitate time-shifting.

3. Additional Research Carried Out

Additional research was carried out to gain knowledge of how thermal storage could be applied in this case. This also involved looking at work that had been carried out by others, to understand what they had discovered and establish a plan to carry out own investigations.

4. Modelling Approach

A modelling approach was identified as being the most effective method in carrying out the investigations in this thesis. This was achieved by using both ESP-r and Microsoft Excel software packages. ESP-r would enable a thermodynamic representation of a typical UK detached dwelling to be modelled. Excel would be used to develop a mathematic model to calculate and analyse the temperature inside a domestic hot water tank.

5. Develop Models and Carry Out Analysis

Three models were constructed on Excel and set up to represent three different standards of buildings and taking into account gains from the occupants, lighting and equipment based on intermittent occupancy. Numerous simulations were then run and if the desired results were not obtained, the simulations were repeated. Mathematical model of a domestic hot water tank on Excel was developed, taking into account various heat losses and an input of heat.

6. Results Analysis

The output from the simulations was used to analyse the results. The effect of the applied time-shift was investigated by looking at the environmental temperatures in the house and the temperature of water delivered to the occupants from the tank. This enabled the limits of time-shifting to be identified.

7. Further Research and Investigation Carried Out

In order to increase the storage capacity of the hot water tank, latent heat storage materials were identified as being a method of thermal storage to further investigate. In order to fully understand how they could be applied in this case; further background research was carried out. The mathematical model on Excel was then expanded to take into account the addition of Paraffin Phase Change Material modules.

8. Conclusions and Further Work

Conclusions were drawn from the results of the analysis carried out. Finally, recommendations for further work related to this investigation were made.

C. Project Background

The current UK targets for electricity generation and Carbon Dioxide emissions by 2020 are 15% and 34% respectively. [1] The major advantage seen for installing low-carbon technologies is, consumers can make a contribution to the current renewables targets and also cut Carbon Dioxide emissions. Other benefits include: [2]

- Generating electricity onsite can reduce energy bills
- Could tackle the inevitable future rises in energy prices
- Help to ensure security of safe and clean energy supplies
- Various schemes are available that offer financial benefits associated with their installations

These low-carbon technologies are classified under the name Microgeneration, this covers electrical generation from: micro and mini wind turbines, solar photovoltaics (PV) and micro-hydro. In addition, it also includes heat generation from biomass, solar thermal and two technologies which have been identified as offering the greatest potential; heat pumps and micro-CHP. For these low carbon technologies to really make an impact on the UK electricity system, consumers would need to be within their millions. In 2005, published figures show that we are currently way off this figure. The total number of installations was found to be just over 107,000 and a breakdown of the installations can be seen below in Table 1. [3] This fact and the aforementioned future generation from large-scale renewables, is going to require a new approach to energy planning and policy.

Technology	**Number**
Solar Water Heating	78,470
Community CHP	25,000
Solar PV	1,300
Micro-CHP	990
Ground Source Heat Pumps	545
Biomass Boilers (Pellets)	150
Micro-Hydro	90
Fuel Cells	5
Total	**107,200**

Table 1: Number of Microgeneration Installations in the UK

The next section will give a brief overview of the identified low-carbon technologies that offer the most potential of being installed in large numbers; heat pumps and micro-CHP.

1. Heat Pumps

Heat pumps are seen as one technology which could be used as the main heat source in our homes. A heat pump is a device which transfers heat from one location (the heat source) at a lower temperature to another location (the heat sink) at a higher temperature using a mechanised system. It is not a new technology, but has previously never been extensively used to provide space heating in domestic properties in the UK. Their use has become more popular in the UK in recent years due to their potential of providing high seasonal heating efficiencies, long life expectancy, low maintenance costs and financial benefits of using the technology. [4]

The heat pump system is a fairly complicated device which consists of four main components; the compressor, condenser, expansion valve and evaporator. The setup is shown below in figure 1.

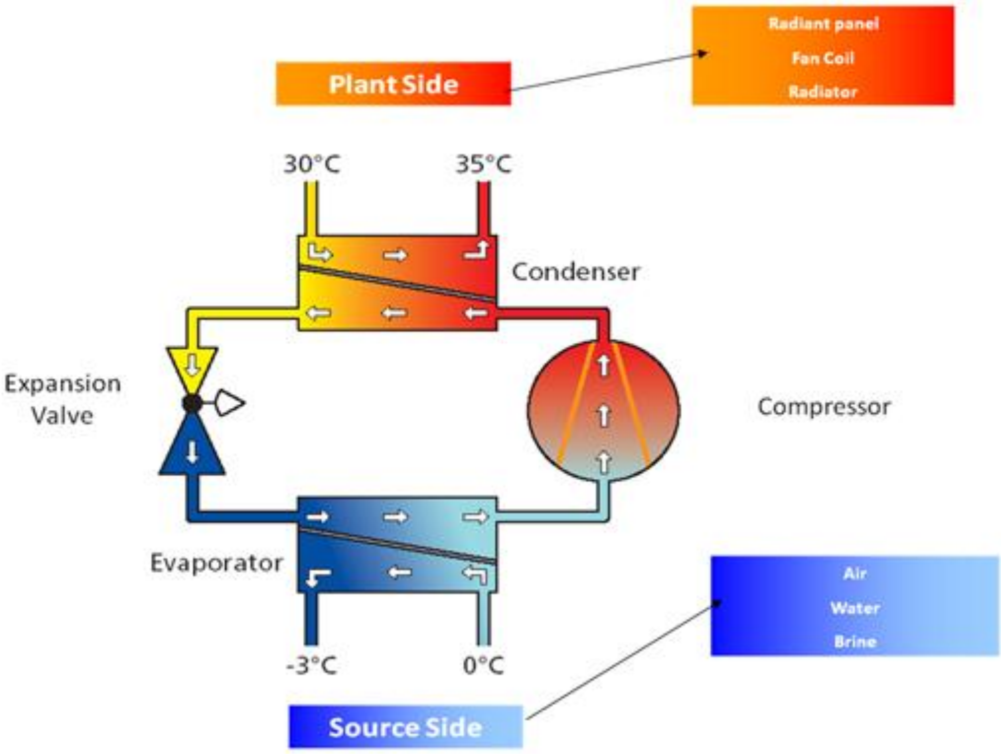

Figure 1: Components that make up a heat pump [5]

They operate by adopting thermodynamic principles involved in heat transfer and in order to do this, they use a refrigerant or working fluid inside the heat pump. They operate in a similar way to a refrigerator at home, but in reverse. Heating and cooling is achieved by moving the refrigerant through various indoor and outdoor coils and components.

There are five main stages that make up the heat pump process and they are:

1. The liquid refrigerant passes through the outdoor evaporator coil at a low temperature.
2. Liquid from the ground loop then enters the unit and heat is transferred from the liquid to the refrigerant. As a result, the refrigerant boils and changes state to a vapour.
3. The vapour is then drawn into the compressor, where the temperature of the vapour is increased to a high temperature.
4. From here the vapour then enters the condenser heat exchanger and heat from the vapour is transferred across the coils. As the vapour cools it condenses back to a liquid, which results in a release of latent heat to the air passing over

the heat exchanger. It is at this stage that the heat is transferred to the buildings heating, cooling and hot water systems.

5. The refrigerant, which is now a very cold liquid and at a high pressure, passes through the expansion valve, which reduces the pressure so that the cold liquid can re-enter the evaporator and begin the cycle again. [6-7]

There are many possible refrigerants that could be used and this includes: CFCs (Chlorofluorocarbons), HCFCs (Hydrochlorofluorocarbons), HFCs (Hydrofluorocarbons), Ammonia (NH_3), Hydrocarbons (HCs) and Carbon Dioxide (CO_2). Each possesses different qualities and some are more suited to certain applications than they are to others. The required properties of an ideal refrigerant state that: [8]

- The refrigerant should have a low boiling point and freezing point.
- It must have a low specific heat but a high latent heat to reduce the mass flow of the refrigerant.
- It should have a high critical pressure and temperature to avoid large power requirements.
- It should have a high thermal conductivity value to reduce the area of heat transfer in the evaporator and condenser.
- It must not be flammable, explosive, toxic or corrosive.
- It should also be readily available and cheap

The most common form of heat distribution system in a domestic dwelling is by using water as the heating medium in either a wall hung radiator heating system. Therefore, the types of heat pumps that are being predominantly implemented into the domestic sector are air and ground source heat pumps.

1.1 Air Source Heat Pumps

Air source heat pumps (ASHP) systems operate by using fans to draw air across the evaporator component of the heat pump system. The ASHP extracts heat from the outside the same way that a fridge extracts from the inside. It can extract heat from the air even during adverse winter conditions when the outside temperature is at -15^{o}C. Figure 2 below shows how an ASHP would be set up in a domestic dwelling.

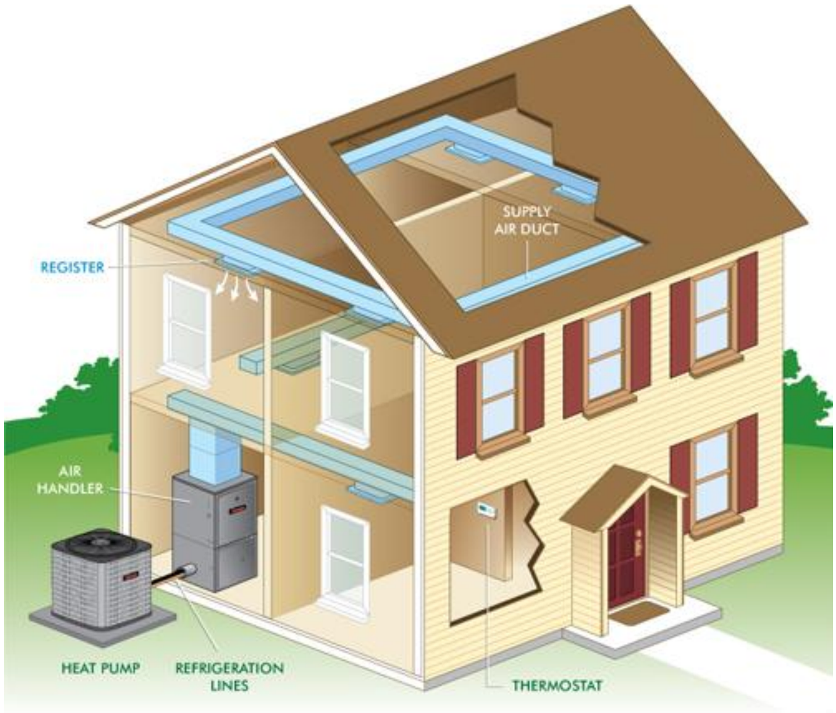

Figure 2: Air source heat pump installation [9]

The system has two units which are connected together through the house by copper piping. The outdoor unit contains a coil that acts as a heat exchanger and compressor, while the indoor unit contains a coil and a fan. The fan is used to circulate air through the house ventilation system. The refrigerant used acts as a coolant as it passes through the copper piping between the two units and heat is absorbed from the air by the refrigerant gas.

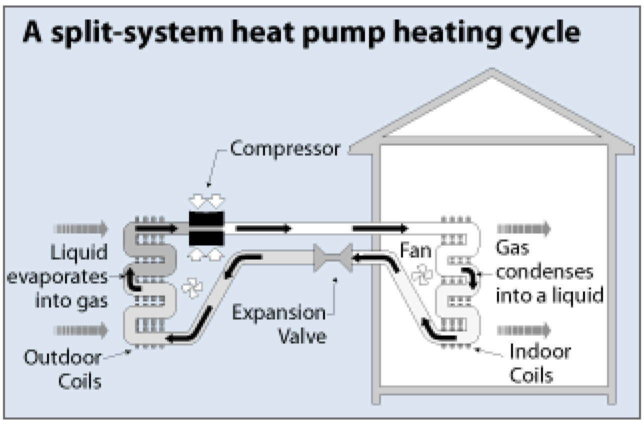

Figure 3: ASHP heating cycle [10]

The refrigerant gas absorbs the heat from the air moving over the coil in the outside unit. The compressor in the outdoor unit, then heats up the gas to a high temperature. This gas passes into the indoor coil via the copper piping. The fan in the inside unit, draws the heated air through a grill and the air moves through the coil in the inside unit. While the gas is in the copper piping, its heat is transferred through the metal of the coil and the air from the fan passes over the coils, and carries the heat to the ventilation ducts in the house. [10]

Advantages and Disadvantages

ASHP offer the advantages of reducing carbon emissions and the fact that it utilises a natural heat source which is inexhaustible. They require minimal maintenance and are relatively easy to install. They are also ideal for new-build or retro-fit installations where space is limited. However, they have the disadvantage of being quite noisy, relatively high installation costs, (£4,500-£8,500 depending on size) and having a lower efficiency that ground source heat pumps. They also require the installation of a large box on the side of the property which could be deemed as unsightly or subject to vandalism. [11]

1.2 Ground Source Heat Pumps

A ground source heat pump (GSHP), sometimes called a geothermal heat pump, is a central heating and/or cooling system that utilises heat to or from the ground. In the winter period it uses the earth as the heat source and in the summer as a heat sink. GSHP's use pipes which are buried in the garden that extract the heat from the ground. They are ideal for use in both domestic and commercial environments and can be used for both underfloor and radiator heating systems and hot water. GSHP can be used all year round, even in the middle of winter, as the temperature of the ground remains fairly constant all year round.

A GSHP circulates a water/antifreeze mixture around the underground copper or metal loop of pipe, which is called a ground loop. The heat which is absorbed from the ground into this fluid is pumped through a heat exchanger in the heat pump. Low grade heat passes through the compressor which increases the pressure and is concentrated into a higher temperature and a more useful heat, which is capable for being used in the heating and hot water circuits of the house. The now cooler fluid in the ground loop is passed back to the ground, where further heat absorption from the ground takes place, resulting in a continuous process while heating is required. [12]

There are two types of configurations for the ground loop in GSHPs; horizontal and vertical loop. These are shown in figure 4 below.

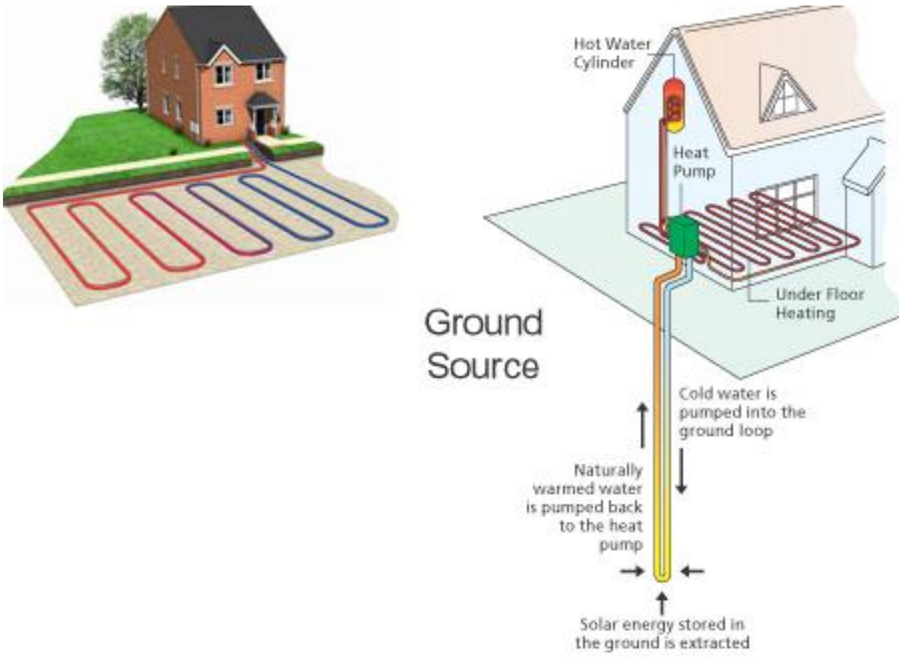

Figure 4: Horizontal and vertical loop configurations [13-14]

Horizontal loops are genuinely the most cost-effective option for residential installations, particularly for new house builds where there is sufficient land available. It requires digging trenches that are normally 6-8 feet in depth. The most common layout is a slinky ground loop which is a coil of plastic tubing spread out and overlapped in the trench. This method concentrates the heat transfer surface into a smaller volume, meaning less land area is needed for trenches. Vertical loops are installed when there are limits to the land area for the installation, or when the soil is too shallow for trenching. This type of system is particularly suited for large commercial buildings such as schools, but can also be used in the domestic sector. With this type of configuration, bore holes of around 150mm in width are drilled to around depths of around 100 metres and the loops of pipe inserted in each borehole, which is then filled and sealed with a thermally enhanced grout. The number of boreholes is dependent on the geology of the area, the heating required by the dwelling and the size of the GSHP. [15-16]

Advantages and Disadvantages

GSHP heat pumps offer the advantages of having lower CO_2 emissions than fossil fuels. Because it has few moving parts it is highly reliable and has low maintenance costs. It also has a long life span (20-25 years and up to 50 years for the ground coil). In addition, there is no boiler or fuel tank so this frees up the space which that would have taken up. However, it does have the drawback of having relatively high installation costs (£9,000-17,000). It also requires using electricity to operate and the heating performance is dependent on the weather conditions and is least effective when the ground temperature is low. [11]

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2. Micro-CHP

Like heat pumps, micro-CHP is seen as a potential replacement for standard domestic gas boiler installations. Micro-CHP is a specific form of combined heat and power system that is designed for use on a domestic scale. The process generates power mainly for consumption in the home, but also creates heat which could be used for space and water heating. Although the electricity generated by the individual units is relatively small, [17] the significance of micro-CHP lies in the potentially huge numbers of systems that could be installed in millions of homes in the UK where natural gas is the current fuel for the heating system.

The 'Baxi Ecogen micro-CHP,' is the first widely available wall-hung domestic micro-CHP boiler in the UK. This type of boiler produces up to 1kW of electricity per hour which can be used throughout the owner's home. To break this down, 1kW of electricity could break down to power: 10 20W light bulbs, a TV, a computer and a washing machine. These appliances have a combined demand of 1kW. [18] In addition, any electricity that doesn't get used can be exported and sold to the national grid. So similarly to heat pumps, there are financial incentives to consider. With this incentive, users could expect an additional 13p on top of the standard sale price, for each kilowatt they sell. [19]Baxi claims that householders would save around £200-400 per annum in electricity bills. [20]

One other financial incentive which could shorten the pay-back time of both types of heat pumps and micro-CHP, is that set by the recently announced Renewable Heat Incentive (RHI) scheme. For every kilowatt-hour of heat that is estimated that your property requires, you will receive a payment of around 7 pence. This could work out at giving the owner of an average 3 bedroom semi-detached house, an annual payment of around £1000 and £2000 for a 5 bedroom detached house. [21]

The Baxi Ecogen is a type of Stirling engine micro-CHP unit. This type of engine is where the current technology is being concentrated. Stirling engines are external combustion engines and they allow continuous, but controlled combustion, which results in wanted low level pollutant emissions and a high combustion efficiency. The fuel for the system is natural gas, hence why it is seen as a direct replacement for conventional heating systems. In such a system, a total of around 70-80% GCU (Gross Calorific Value) of the energy value of the gas is converted into heat. This heat is principally in the form of hot water which is used for space heating and domestic hot water, the same as typical central heating systems. Between 10-25% is converted into electricity and the remainder is lost in the flue gases. This process is shown in figure 5 below. [22]

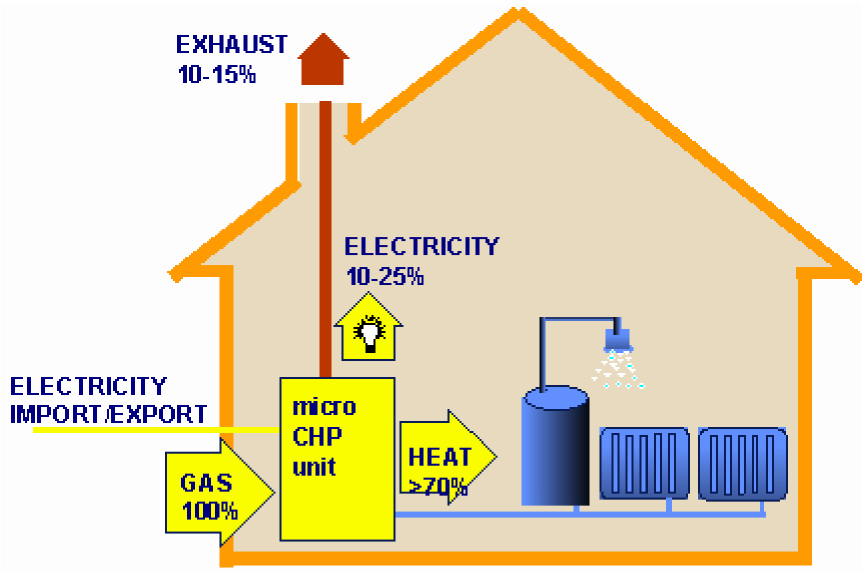

Figure 5: Micro-CHP process [22]

2.1 Other Types of Micro-CHP Technologies

There are other types of micro-CHP that are receiving significant research and are seen as potentials for the future. These include one that utilises internal combustion (internal combustion engine) and one that utilises fuel cell technology (fuel cells).

The internal combustion engine has been continuously developed for many years. It is a tried and tested technology, in larger residential developments, where power flexibility is required. However, the levels of emissions and also the noise it makes, results in it being particularly difficult to control. In addition, the regular need for oil lubrication and frequent servicing, points towards saying that this technology isn't well suited for micro-CHP applications. However, recent developments have resulted in lower emissions, noise levels and increased service intervals. Until significant improvements are made however, it is unlikely that all the desirable parameters for micro-CHP can be met with this technology. In addition, due to the low heat to power ratio, this technology is very sensitive to fluctuations in gas prices. [23-24]

Fuel cell micro-CHP also known as a home fuel cell is still very much a technology in the early stages of development and perhaps many years away from being commercially available worldwide. There have however been around 2000 installations in Japan. [25] Fuel cells convert hydrogen and oxygen directly into electricity via an electrochemical process. It offers very low emissions, a high efficiency and very low noise levels. In the process, the heat is produced as a by-product of the electrochemical process and water is also produced as the waste product. A lot of funding and research is currently going into this process and it is estimated that in around ten years' time it will be able to compete on a commercial scale. [24]

After reviewing both heat pump and micro-CHP technologies available that current policies are encouraging the use of, it is evident the biggest challenge is going to be managing the electricity distribution network. In the case of heat pumps, which require electricity to operate, they would be moving the demand from the gas distribution network and onto the electricity distribution network. This would mean we were using peak time electricity to heat our homes and hot water, putting more pressure on the electricity network during these periods. One method this pressure could be alleviated is through the use of energy storage. Energy storage can be one of the main solutions to ensuring a safe and secure supply of electricity. With energy storage, the energy can be stored and used at a later time. The next section will explore the potential energy storage methods which could be used to support the larger use of small-scale renewables.

3. Energy Storage Methods

In order to move away from our current dependence on fossil fuels and support the move towards renewable technologies, something has to be done to the way we store produced energy. It is known that renewable sources are intermittent in nature, but storage methods to conserve energy rather than waste it, could bridge the gap between generation and consumption. Without the use of energy storage methods, energy production systems would have to be designed to meet the peak load and the energy produced which was not used would be wasted at times when the demand is lower. Effective energy storage could mean the energy production system could generate energy when demand is low, store it and shift the excess energy when the demand is low to periods of higher demand when it is needed. The development of improved thermal storage could thus support the application of heat pumps, by operating them when demand is lower and using thermal storage to release the energy when the demand is higher. This would mean they wouldn't be operating during peak times and would take the pressure of the electricity distribution network. From the research carried out, it was found that there are three key types of energy that can be stored and these are: mechanical, electrical and thermal energy.

Mechanical energy is normally stored in water pumped to a higher elevation using pumped storage methods, in compressed air, flywheels, or as gravitational potential energy. Electrical storage is normally stored as chemical energy in the form of a hydrogen fuel cell or a battery. Thermal energy storage is the method which is of most importance in this thesis and this can be stored in three ways and this is illustrated in figure 6 below. The first method of thermal storage that will be looked at is through the use of sensible thermal storage.

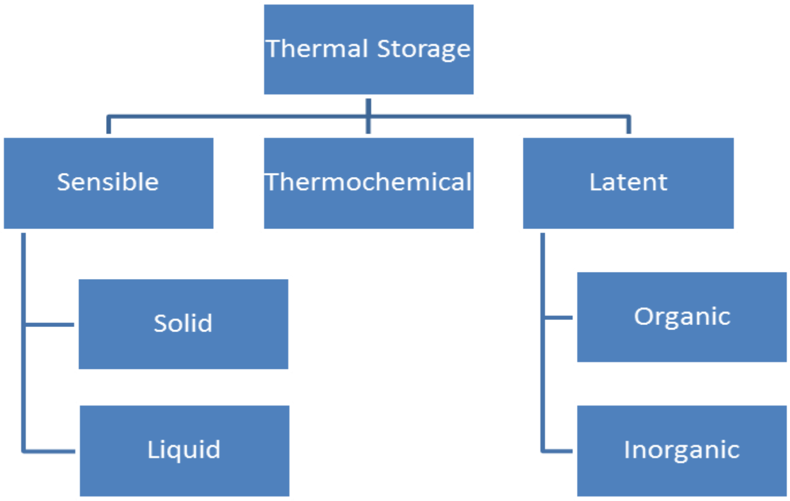

Figure 6: Thermal Storage Methods

3.1 Sensible Thermal Storage

Sensible heat storage is the most common method used for thermal storage. With this type of storage, thermal energy is stored by raising the temperature of a solid or liquid medium. A sensible heat storage system utilises the heat capacity of a material and the change in temperature during the charging and discharging process. The amount of heat that can be stored is dependent on the specific heat of the material, the temperature change and the amount of storage material. It is desirable for the storage medium to have a high specific heat capacity. As the diagram in figure 6 above shows, there are two methods of sensible storage: solid storage and water storage.

3.1.1 Solid Storage

The ways in which solid storage mediums could be used to reduce peak demand and potentially offer greater control in the flexibility of the operation of the likes of heat pumps is through storage in the building fabric and storage in the internal thermal mass of the house. In addition to reduced peak demand, it also offers reduced energy costs and Carbon Dioxide emissions.

Building Fabric

By improving the building fabric, you are effectively reducing the thermal exchanges to and from the environment and improving the air tightness of the building. This can either be from heat loss from the inside of the building to the outside, or from heat gain from the outside to the inside. The term 'building fabric,' which is also sometimes referred to as the building envelope, includes the external and internal walls, ceiling, roof, floors, windows and doors of a building and the materials they are made of. Improving the building fabric can be achieved in a number of ways; the addition or improvement of wall and roof insulation, or replacing old glazing systems (double or triple glazing installation).

The building fabric plays an important part in determining how energy efficient the building is. If the building is poorly insulated and draughty, it will mean more heating is required to keep the temperature at a comfortable level, which will result in a loss of money. The following measures can be adopted which could significantly reduce energy bills and also reduce carbon dioxide emissions. This is particularly a good investment in older buildings and retrofit projects. A fabric upgrade is also necessary to ensure your building qualifies for the renewable heat incentive. Table 2 below summarises the annual savings, installed cost, payback and CO_2 savings per year for each measure.

Cavity Wall Insulation

It is said that around a third of all heat loss in an un-insulated home is lost through the walls. Insulating a cavity wall means filling the gap between the two layers in the wall construction. Cavity wall insulation is a great way to significantly reduce the amount of energy needed to heat your home. [26]

Solid Wall Insulation

Solid walls differ from cavity walls as they don't have the air gap that cavity walls have. This construction is typical of many pre 1920s builds. External or internal insulation could be used if your home has solid walls. Again this could result in significant savings on energy bills. [26]

Floor Insulation

The addition of insulation between floorboards in your house could reduce heating bills and also improve the comfort of your home. Floors of timber construction can be insulated by lifting the floorboards and laying mineral wool insulation beneath them. In addition, gaps and cracks around the floor and skirting boards can easily be filled yourself by using a silicon sealant. This again could reduce heating bills. [26]

Loft Insulation

Without proper insulation, a lot of heat can be lost through the loft. It is said that around a quarter of heat lost in the home is through the roof. Loft insulation is an effective way to save energy and money. A recommended depth of 270mm mineral wool insulation, would keep the warmth in the house. [26]

Draught Proofing

The use of strips and draught excluders around leaky doors and window frames could also help to save money on heating bills. [26]

Glazing Upgrades

All properties loose heat through their windows. The installation of energy efficient glazing is an effective way of reducing energy bills and keeping the house warm. Double glazed windows use two sheets of glass with an air gap between them, which creates an insulating barrier. Triple glazed windows use three sheets of glass with an argon air gap between the sheets. Replacing all single glazed windows with more energy efficient glazing could save you around £135 per year on energy bills. [26]

Measure	Annual Saving Per Year (£)	Installed Cost (£)	Installed Payback	CO_2 Saving Per Year
Cavity Wall Insulation	Around £110	Around £250	Around 2 years	Around £560kg
Internal Wall Insulation	Around £365	£5,500-£8,500	Around 11 Years	1.8 tonnes
External Wall Insulation	Around £385	£10,500-£14,500	Around 22 Years	1.9 tonnes
Floor Insulation	Around £50	Around £100	Around 2 Years	Around 240kg
Filling Gaps Between Floor and Skirting Boards	Around £20	Around £20	Around 1 Year	Around 100kg
Increase in Loft Insulation Thickness to 270mm	Around £145	Around £250	Around 2 Years	Around 730kg

Table 2: Summary of expected annual savings from insulation improvements [26]

However there are also problems associated with fabric improvements. These are the increased risk of overheating and reduced air quality. Improving the fabric does keep the heat in, but when you have lots of equipment on with high internal gains, it is just going to build on the heat already present.

The application of using building fabric to shift the demand to off peak periods is off great interest. N.J. Kelly from the University of Strathclyde had previously been working alongside others and they produced a paper titled: "*The influence of Thermal Storage on Micro-generation Flexibility*." [27] In this report, different thermal storage mechanisms were investigated which could be used in order to determine the maximum possible temporal shift, in order to deliver flexibility in the operation of an air source heat pump. In order they to do this, they developed a model which represented a typical UK detached dwelling using the software package ESP-r, so that the house and its heating system could be modelled. The basic thermal inertia of the building fabric was used to analyse the possibility of time-shifting the heating system. The first situation they examined was where they altered the start and stop times of the heat pump, in half-hourly increments to a total time-shift of 3 hours. They then increased the heating setpoint, in order to boost the quantity of heat stored in the fabric. This would increase energy consumption, but it was investigated to see if it could offer more flexibility.

The results that were obtained were very interesting. For the first situation examined, the results showed that a time-shift of up to 1 hour had only a small effect on the comfort of the living space experienced during occupied periods. However, a time-shift beyond this point had a detrimental effect on the environmental conditions. Increasing the set point, as expected did offer more flexibility in regards to the time-shift potential, however only by a further half hour. Another observation they found was that for both situations there was a slight increase in energy consumption initially when time-shifting the start and stop times of the heat pump before it dropped again.

The conclusions they could take from the results of their investigation was that although it would be possible to shift the operating time of the heat pump by 1 hour with minimum disruption to the occupants comfort, from a large demand shifting perspective, it wouldn't seem that attractive initially for a lightweight building. It wouldn't flatten the peak loads of electricity that occur in the morning and evening periods. However, it could allow a local network operator to stagger the operation of heat pump installations in a local area.

Their study could be expanded to investigate the effect improvements in building fabric could have on the allowance of a time-shift. The building standards they based their modelling on was described as being of slightly above-average standards levels of insulation. Increasing the quality of building fabric would reduce the rate of decay of the internal temperatures once the heat pump was switched off. They also used wall-hung radiators as the space heating source, investigating what the effects of using underfloor heating would have on the allowance of a time shift, would also be interesting.

Thermal Mass

In addition to the buildings fabric, its internal thermal mass can also be used as a mechanism for sensible storage. The thermal mass of a building basically describes the ability of the construction materials to absorb and also store and release heat. This is a useful property as it helps to regulate the temperatures in buildings. Thermal mass is effective in improving the comfort in buildings in both winter and summer. When used well and combined with passive solar design methods, thermal mass can play an important role in reducing energy use in active heating and cooling systems. Ideal materials for thermal mass have high specific heat capacity and density values. The more dense the material (less trapped air) the higher the thermal mass value will be. Ideal materials will also have good thermal conductivity values associated with them, meaning the material must allow heat to flow through it.

Heavyweight material such as concrete provides a high level of thermal mass. An example of a high thermal mass construction is a typical brick and block wall with a plaster finish, which has a heat transfer coefficient of around 6 W/m^{2}K. Timber frame constructions with a plasterboard finish give a significantly smaller value of around 0.85 W/m^{2}K. [28] Illustrations of these constructions can be seen in figure 7 below. Thermal mass should not be confused with insulation and U-values, which are completely independent of thermal mass. Thermal mass is also not a substitute for building insulation. Insulation prevents heat from flowing into or out from the building, while thermal mass stores and radiates it.

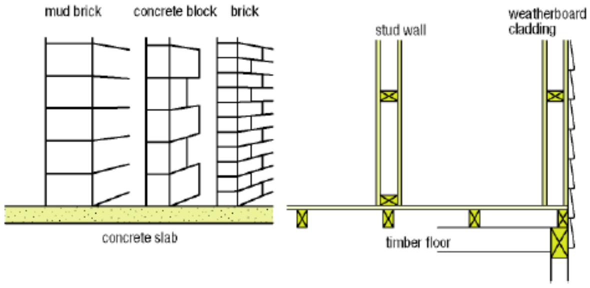

Figure 7: Materials with high and low thermal storage capacity [29]

3.1.2 Liquid Storage

Water has the largest specific heat capacity and density of all fluids and is cheap and readily available. At low temperatures it is one of the best storage mediums. The most common practice is via hot water tanks in our homes. The thermal store cylinders are used as a store of energy for the hot water and central heating systems. Thermal stores are ideal as they allow multiple heat sources to contribute to the entire heating system, which is good if you plan to have multiple renewable heat sources installed. Thermal store cylinders work on the principles of thermal stratification. Stratification is the process of the hotter water, rising to the top of the cylinder and the cooler water being towards the bottom. Therefore, at each level of the cylinder, there will be a different temperature and it's these zones that the heat source is connected too. The number of zones in the tank is dependent on the height of the tank.

Other types of thermal storage tanks include buffer tanks. Buffer tanks are combined with GSHP and ASHP to improve efficiency of the heat source. They are commonly positioned between the heat source (heat pump or micro-CHP), and the rest of the heating system. They allow the heat source to charge the tank with heat energy, which can then be extracted or taken away by the rest of the heating system. [30] The use of a buffer tank when using heat pumps maximises the run periods and therefore increases the performance of the device. [31] This was backed-up in the analysis from the work carried out once again by N.J. Kelly and D. Beyer. [32] Influenced by the results from field trials carried out on domestic cogeneration devices which did not include any thermal buffering between the device and the heating system, they decided to carry out analysis that takes this into account and paints an all-round bigger picture.

In order to investigate the performance Microgeneration devices could have on UK buildings, they constructed representations of four different types of buildings using ESP-r. These buildings included: detached, semi-detached and terraced dwellings and also flats. Two cogeneration devices were analysed during their investigation: a 5.5kWe Internal Combustion Engine unit and a smaller 1kWe Stirling Engine unit. Four different levels of thermal buffering were introduced: no-buffering, 200, 500 and 750 litres. Their results showed that the addition of thermal buffering has a major effect on the behaviour of the performance of the device tested. Backing up the earlier statement, the number of on/off cycles was reduced and resulted in maximising the run time and improving the efficiency of the device.

Similarly, thermal buffering was also introduced in the earlier mentioned temporal shift report. [27] This time a 300 and 500 litre buffer tank was introduced into the system. The results for the addition of a 300 litre tank showed that a time-shift of 1.5 hours would be allowable before significant deterioration of the environmental conditions. The results for the addition of a 500 litre tank showed that a time-shift of 2 hours would be possible. It is therefore evident that the addition of a buffering tank offers benefits. However, the capacity of the buffer tank is very much dwelling dependent on how much space would be available to facilitate it, as buffer tanks can be large in size.

The research carried out has identified that sensible thermal storage can be achieved by both solid and liquid thermal storage. The next section will look at the first set of investigations carried out. The first will investigate how improving the insulation quality of buildings could boost the thermal storage capacity, of a detached dwelling and how this could be used to enable a time-shift of the operation of the heating system. It would also enable the limits of time-shifting to be identified.

D. Investigation: Time-Shift of Space and Water Heating

This section will give detail on the modelling approach used and how the models were constructed in order to carry out the investigation, beginning with the model constructed to investigate the use of the thermal capacity of a typical detached dwelling.

1. Detached Dwelling Modelling

1.1 Modelling Approach

In order to carry out this investigation, a modelling approach was undertaken. Two software packages were identified which could be utilised for this investigation. The software that was used to analyse the space heating was ESP-r. This is an integrated building energy modelling tool, which models the internal environment of buildings dynamically. The modelling tool simulates the real world as close as it can and enables an in-depth assessment of the buildings energy and environmental performance. In order to make full use of the software and the ability to develop and run scripts to automate the associated simulations, a Linux based operating system in the form of OpenSUSE was used.

Before the model was constructed it was important to establish what was hoped to be achieved from using the software. The answers to this question were:

- To create a model that would give a thermodynamic representation of a typical detached dwelling.
- The building fabric could be varied to represent current and projected future standards.
- Heating system could be modelled in an abstract way, with a generic heat input which could be applied to a heat pump or micro-CHP system.
- The maximum possible time-shift without causing disruption to occupant comfort could be determined, by back-shifting the times it switches on and off.

- An underfloor heating system could be modelled in addition to wall hung radiators.

The Hypothesis prior to this investigation was that there wouldn't be much flexibility with the average standards model, in regards to the amount of time you could back-shift the on/off times of the heat input, before there was deterioration of the internal comfort. However, it was expected that as you increase the building standards there would be more of an allowance due to the reduction in the decay rate of internal temperatures, after the heating system is switched off. It was also expected that as you increase the building standards that the heating demand required would also decrease. An underfloor heating system will offer the benefit of the house taking longer to cool down, meaning there is potential here for flexibility with the applied back-shift.

1.2 Model Development

The first step in the development of the model was to decide what type of dwelling to model. A detached dwelling was chosen for this investigation as this was identified as a good starting point, as it makes up a large percentage of the UK housing stock and is a large energy consumer. The model developed however, could still be easily adapted to represent other types of dwellings. The area of the ground floor was 68.9m^2 and had the dimensions of the house 8.3m in length, 8.3m wide and 6m high. This information and the dimensions of the window enabled the construction of the skeletal model of the dwelling on ESP-r. The model was set up to only include one zone, which would be effective in giving a thermodynamic representation of a typical UK detached dwelling.

1.3 Building Fabric

Three models were developed, each one representing different levels of building standards. These included standards based on the UK Average, the published UK 2010 standards and projected future standards, based on the published standards for PassivHaus design. This was chosen as it is going to be difficult to better these standards. Table 3 below shows the associated U-values used for each model.[33-36] The average outside air infiltration rate was taken as 0.5 air changes per hour for the average and 2010 standards models and 0.07 air changes per hour for the PassivHaus standards model.

Component	Average Standards	2010 Standards	PassivHaus Standards
	Associated U-Values (W/m^{2}K)		
Roof	0.160	0.141	0.110
External Wall	0.450	0.224	0.100
Floor	0.200	0.170	0.110
Glazing	2.811	2.811	0.698

Table 3: U-Values used for each model

1.4 Occupancy Information

The model was set up to include heat gains based on intermittent occupancy that are typical from a family of four. The occupants were assumed to be active between the hours of 7am-9am and 5pm-11pm. Between the times of 11pm and 7am they are assumed to be sleeping and the house is assumed to be empty out with these times. In order to take into consideration the weekend period, the occupancy data for this period was taken from a domestic building occupancy model developed by I.Richardson.[37] Throughout the day, typical lighting and equipment gains were included that represented typical domestic usage profiles.

1.5 Heating System

Two different heating systems were used during this investigation: conventional heating system using radiators and underfloor heating. To replicate a wall hung radiator heating system, the heat injection occurred at the air point. In the average and 2010 standard models, the heat emitted was 70% convective and 30% radiant, but for the Passivhaus model it was 100% convective. The heating setpoint was set to 21^{o}C and was controlled by a basic on/off controller. Initially, the heating systems were turned on 1 hour before the occupants were active and off at the end of occupied periods, replicating what happens in real life.

Underfloor heating is becoming increasingly popular as an alternative to wall hung radiators and for this reason I decided to model an underfloor heating system. To replicate an underfloor heating system in ESP-r, the heat injection this time occurred in the cement screed. Underfloor heating is particularly popular in new builds as it is expensive to install. With an underfloor heating system, the heat radiates upwards and results in a more pleasant environment. The downside however is that underfloor heating is less controllable than radiator based heating systems. It can also take a long time to get the house warm as there is a lagging effect. For this reason, some people choose to leave the system on all day. It can also take an equally long time for the house too cool down, which is good for winter, but bad for other seasons as it can lead to overheating. [38]

1.6 Simulations

As previously, three different models were developed each with different levels of building standards. This was in order to investigate the potential temporal shift on different quality of buildings. The simulations were firstly carried out for a characteristic winter week, which was taken as the 9th – 15th of January, using a simulation time step of 10-minutes. This meant close analysis of the results was able to be carried out during this period. The on/off times of the heat input was then back-shifted in half hourly increments right back to 6 hours. The simulations were then carried out for a week in March and November, to carry out the same investigation in spring and autumn.

2. Hot Water Tank Modelling

2.1 Introduction

In order to model the effect that time-shifting could have on the temperature of the water delivered during occupied periods, a mathematical model was created using Microsoft Excel to calculate and analyse the temperature of the water inside a domestic hot water tank. The hot water tank was subject to time varying hot water draws, which represented that of intermittent occupancy from a family of four. Again, an input of heat was used to represent that of a heat pump and similarly to the previous modelling section, the on/off times of the heat injection was back-shifted in half hourly increments to analyse what effect this had on the temperature of hot water during occupied periods. Figure 8 below shows a schematic of the inputs and outputs of a typical hot water tank.

Time steps of two minutes were used. This was chosen because it would be small enough to show the changes in temperatures. Originally, time steps of ten minutes and then five minutes were used, but it was later decided that these were too big a time step to fully investigate the variations in temperature.

The hypothesis was that there wouldn't be much flexibility with the allowance of a potential time-shift, before the temperature of water in the tank became unacceptable. However, it would show potentially how much could be achieved.

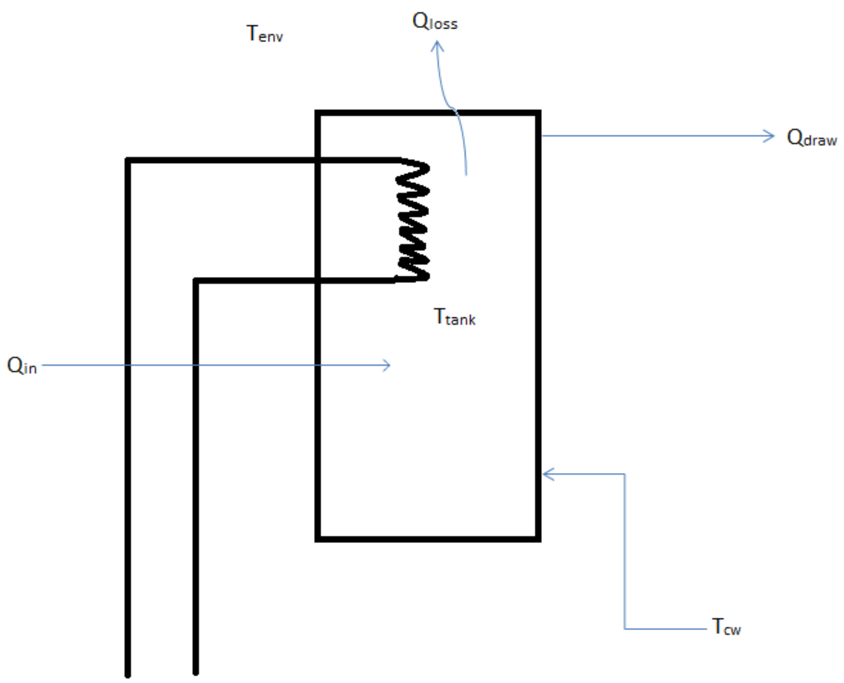

Figure 8: Schematic of a hot water tank

2.2 The Model

This section will give more detail on the developed model. The dimensions of the tank were taken for a 200 litre, hot water tank supplied by Albion. [39] The material of the tank was copper, as copper tanks reduce the risk of various bacteria that can exist in the warm water in the tank such as Legionella, MRSA, E-coli and Avian Bird-Flu. Copper also has a high value of thermal conductivity meaning that is a very efficient conductor of heat and maximises heat transfer. This is particularly important when getting the most out of renewable technologies, such as heat from ground source heat pumps, which require highly efficient coils to transfer their energy into hot water. [40]

2.3 Heat Input to the Tank

A heat input that represented the heat injection of that from a heat pump was used to heat the water in the tank. For simplicity an 'IF' function was created to input a maximum heat input of 10,000W, whenever the temperature of the water within the tank, dropped below the set point temperature during the periods of operation. Ideally, experimental heat pump test data would give more realistic results, but this method would still be effective in delivering desirable results.

2.4 Heat Energy Losses Due to Water Draw Off

There are several different sources available where typical domestic hot water draw off profiles have been produced. When testing out the model, the results were very dependent on what profile you use. Several were tried and the results for some of them will be detailed later in the results section.

The data from the draw profiles was in l/day and had to be converted to kg/s. Once this was done, the heat energy taken from the system was calculated using equation (1) below.

$$\dot{Q}_{draw} = \dot{m}_w C_{p(w)} (T_{tank} - T_{cw}) \quad (1)$$

Where:

m_w is the mass flow rate of water, C_p is the specific heat capacity of water and T_{cw} is the temperature of cold water feed. The temperature of the cold water feed to the tank varies between 5 and 15^{o}C depending on the time of the year and also the location. For this reason, a mean value of a constant 10^{o}C was used.

2.5 Heat Energy Losses Through the Tank Wall

Insulating the water tank is a simple and effective way to save energy and money. A British Standard 'jacket' of thickness 75mm is recommended to reduce the heat loss. [41] However, despite the inclusion of insulation, there will still be some losses from the hot water tank to the surroundings. These losses were calculated using equation (2).

$$\dot{Q}_{loss} = U_{tank} . A_{tank} (T_{tank} - T_{env}) \quad (2)$$

Where:

U_{tank} (which is calculated from equation (3) below), is the overall heat transfer coefficient in the hot water tank to the air outside the tank in the house. A_{tank} is the area of the hot water tank. T_{tank} is the temperature of the water in the tank and T_{env} is the temperature in the house. A temperature profile was used which was obtained from the first investigation. This added realism to the model rather than just using a constant temperature.

$$\frac{1}{U_{tank}} = \frac{x_c}{k_c} + \frac{x_i}{k_i} + \frac{1}{h_w} + \frac{1}{h_a} \tag{3}$$

Where:

x_c and x_i are the thickness of the tank and insulation respectively. The thermal conductivity of the copper, k_c was 401W/mK and insulation, k_i was 0.044W/mK. The convective heat transfer coefficient in water, h_w is 20-100W/m^{2}K and for free convection in air h_a it is 5-25W/m^{2}K, so mean values of 60 and 15W/m^{2}K were used for each respectively. [42-43]

2.6 Water Temperature Calculation

It was the temperature of the water in the tank that was off interest in this investigation. How the heat input, water draw-off and heat losses affect the temperature of the water in the tank, was calculated using equation (4) below. Where in this equation: M_w, is the mass of water in the tank.

$$M_w . C_{p(w)} \frac{d\theta_{Tank}}{dt} = \dot{Q}_{in} - \dot{Q}_{draw} - \dot{Q}_{loss} \tag{4}$$

The temperature of the water in the tank was initially estimated to be at 50^{o}C, this was a reasonable assumption to make. This meant that when the time, t=0, the temperature of the water was 50^{o}C. At every time step after that, the temperature was calculated using the forward difference method which is shown in equation (5) below.

$$\frac{d\theta_{Tank}}{dt} = \frac{\theta_{Tank} - \theta_{Tank'}}{\Delta t} \tag{5}$$

E. Results: Time-Shift of Space and Water Heating

1. Space Heating Results

The results obtained from both models will be discussed in this section beginning with the ESP-r model. Once all the simulations were complete, it was a case of sorting through the large detailed datasets that were produced by ESP-r and extracting the data that was of interest. This included: the internal temperatures in the building, so that they could be compared to the minimum allowable temperature to assess the comfort levels that would be experienced. As mentioned previously, three models were created for the analysis. The model constructed with Average building standards was treated as the worst case scenario and the results from the other two models should show improvement, due to the improvements in building fabric. A selection of graphs and tables summarising the results will be displayed in this section, but the majority of graphs and tables will be able to be found in Appendix A at the end of this thesis.

1.1 Winter Analysis

Initially the operation of the heating system was between the hours of 6am-9am and 4pm-11pm. The heat was also delivered to the living space via radiators. The graph in figure 9 below shows the typical data that was extracted from the data obtained from the ESP-r simulations. In this case it is showing how the living space temperature varies throughout the day, in response to the heat input from the heating system. In addition to the effects from the heating system, the temperature plots also take into consideration the effects from internal and solar gains, infiltration of outside air and also the heat exchanges that occur with the building fabric.

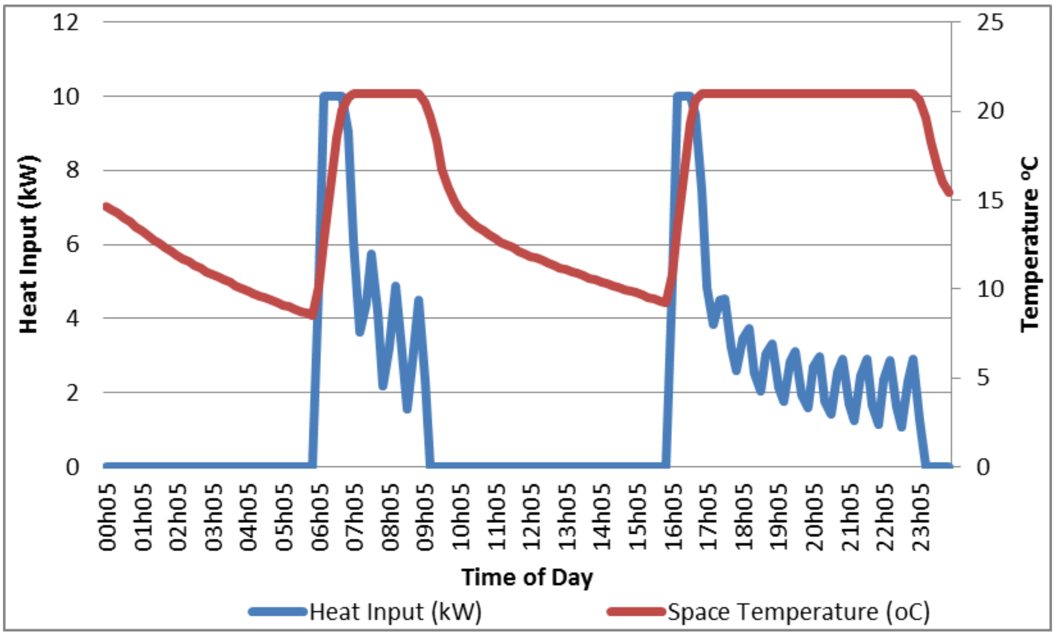

Figure 9: Graph showing temperature variation with heat input

Comparing the input of heat with this model required to keep the living space at the set point temperature of 21°C to that of the other two models. It would be expected that the heat input would be larger in the average model and lower in the PassivHaus model. This was indeed the case and is shown below in figure 10.

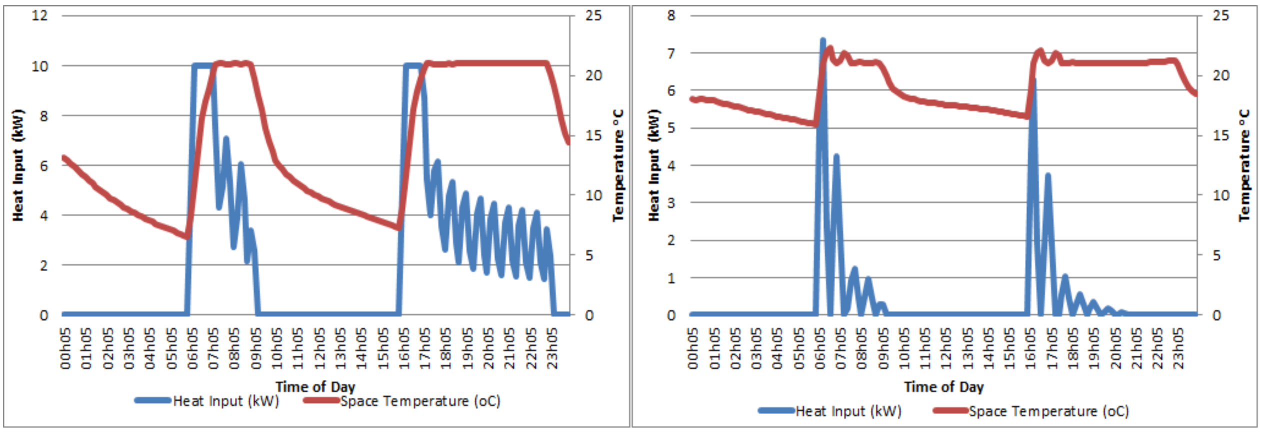

Figure 10: Graph showing temperature variation (Average and Passiv)

The heating operating times were then back-shifted in half hourly increments right back until the morning operational time started at midnight. This totalled a total back-shift time of 6 hours. Figure 11 below shows the effect of back-shifting the on/off time of the heating system from 0-3 hours, on a typical winter's day, for the first half of that day. Figure 12 shows the same information for the second half of the day. It was decided to split the day up and only show a few hours of the back-shift to clearly show what was going on. Graphs showing the full 6 hour back-shift can be found in Appendix A at the end of the thesis.

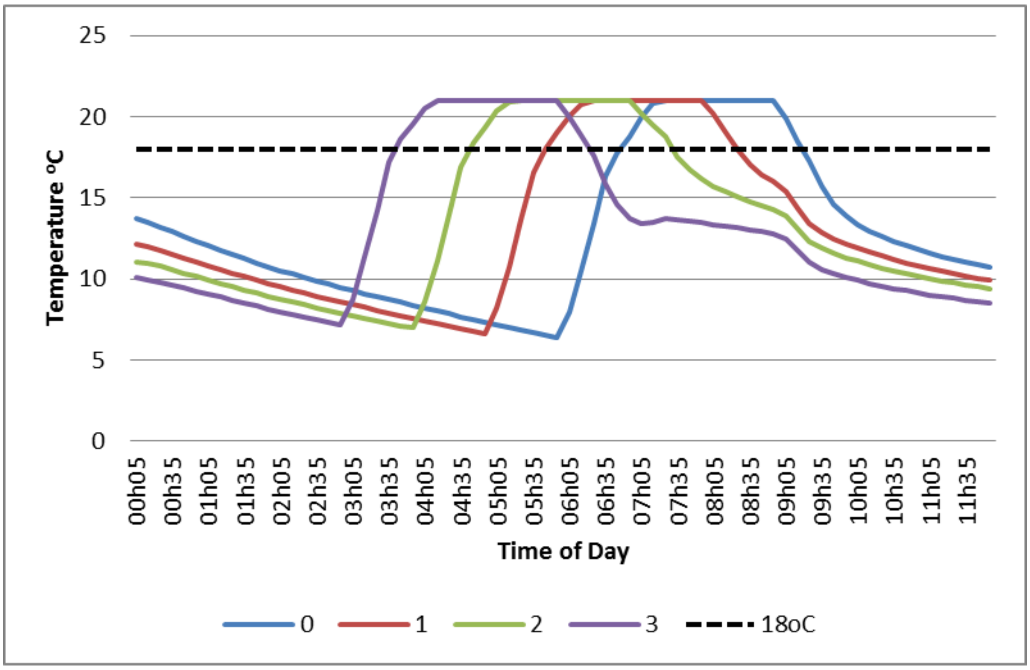

Figure 11: Effect of back-shifting the heat input for first half of the day

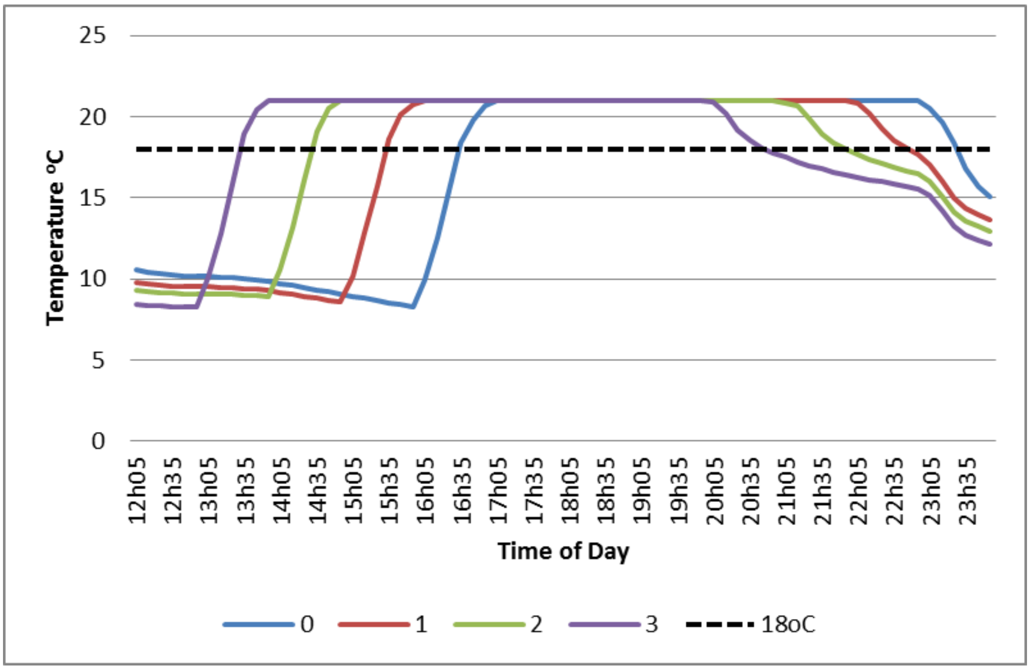

Figure 12: Effect of back-shifting the heat input for second half of the day

The periods of active occupation (7am-9am and 5pm-11pm) are the periods of time that are of most interest for carrying out the analysis. The minimum acceptable temperature defined by Ole Fanger, is said to be 18^{o}C. [44] This temperature is at the lower end of the thermal scale and does not mean that the occupants would be comfortable. Comfort level is dependent on other factors such as activity and clothing levels. However, this temperature will be used to compare the percentage of time below this value. The two graphs displaying the back-shift above clearly show that a back-shift of 3 hours would clearly be below this value at certain points during the occupied period. That's why it was important to carry out analysis in half hourly back-shifts to find out the maximum possible time, before internal conditions begin to deteriorate.

It was expected that the model with average standards wouldn't allow much flexibility in the ability to back-shift the on/off times of the heating system, but as the fabric was improved, there would be more of an allowance. The degree of flexibility would solely be dependent on the occupant, as everyone would have a different opinion on what is really an acceptable percentage of time below 18^{o}C. For the purpose of the analysis, it was assumed that anything below 9% of the time would be acceptable. Going on that basis, only 1 hour was possible with average standards. After this time there was significant deterioration of the environmental conditions. The results for the model with 2010 standards showed that only a further half hour was possible. Table 4 below summaries the results obtained for the first 3 hours for both models. Tables showing the results for the full 6 hours can be found in Appendix B.

	Average Standards							2010 Standards						
Back-Shift	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**
Mean Space Temperature	20.97	20.87	20.53	20.12	19.75	19.28	18.87	20.98	20.91	20.65	20.35	20.07	19.62	19.34
Maximum Temperature	21.05	21.15	21.24	21.06	20.98	21.18	21.42	21.26	21.27	21.38	21.32	21.42	21.2	21.16
Minimum Temperature	19.62	17.63	14.46	13.33	12.68	11.99	11.45	19.98	18.46	15.97	14.95	14.3	12.8	12.12
% Hours Below 18°C	0	0.2	6.4	15.2	22.4	31.0	36.7	0	0	3.1	8.8	15.0	23.6	26.0

Table 4: Summary of results for winter period

Improving the building fabric reduces the decay of the indoor temperature. Although only a minimal additional offer of flexibility was shown by improving the standards to represent the 2010 standards. The results obtained from the model with PassivHaus standards showed a significant increase. The graph in figure 13 below again show the effect of back-shifting the on/off times of the heating system, but this time for the PassivHaus model.

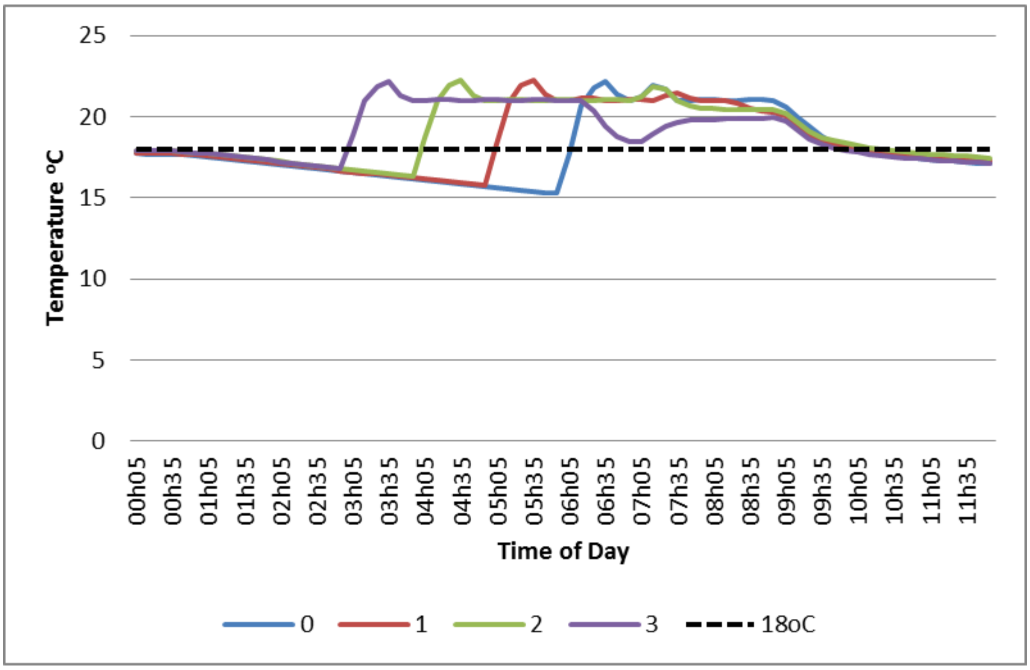

Figure 13: Effect of back-shifting the heat input for first half of the day (Passiv)

The results for the PassivHaus model really stood out. As can be seen in figure 13 above, this clearly shows that temperature never drops below 18°C during any point in the morning, so it is already showing the promise of a greater flexibility. Table 5 below shows the results for the full 6 hours. It can be seen that the temperature doesn't drop below 18°C until a back-shift of 3.5 hours. In addition, even after 6 hours, the temperature is only below 18°C for 0.9% of the time. This clearly shows the advantages that increasing the building fabric could have in the ability to offer flexibility of the operation of the heating system.

PassivHaus Standards													
Back-Shift	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
Mean Space Temperature	21.88	21.94	21.97	22.03	22.05	22.01	21.99	21.99	21.97	21.97	21.96	21.96	21.95
Maximum Temperature	24.69	24.76	24.82	24.88	24.92	24.96	24.99	25.03	25.04	25.07	25.08	25.09	25.10
Minimum Temperature	21.00	20.34	20.18	20.23	20.24	18.82	18.14	17.78	17.51	17.3	17.12	16.96	16.81
% Hours Below 18°C	0	0	0	0	0	0	0	0.1	0.2	0.4	0.5	0.7	0.9

Table 5: Results from the PassivHaus Model for Winter Period

The heating system was then changed to replicate that of an underfloor heating system. As mentioned earlier, the major drawbacks associated with underfloor heating are it is difficult to control and the fact that the heating isn't as instantaneous as from wall hung radiators, which results in the house taking longer to heat up. These characteristics are clearly shown below in figure 14. However, there is also less of temperature decay as the house takes equally as much time too cool down.

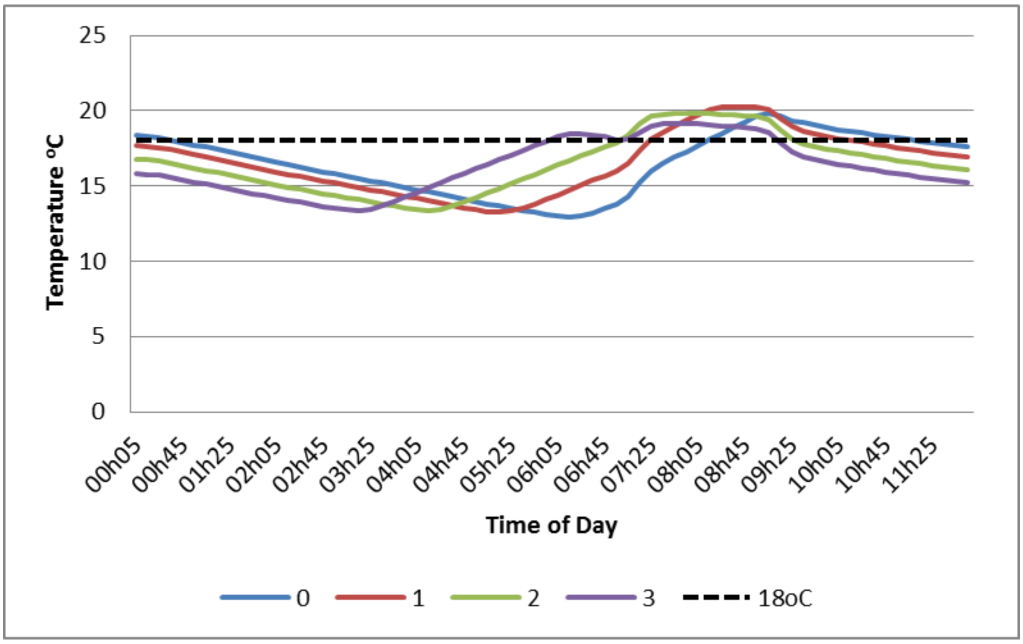

Figure 14: Effect of back-shifting underfloor heating

The results obtained are very interesting and back up these characteristics. For the Average standards model, before a back-shift in operation is applied, the results for the week indicate that the temperature is below 18^{o}C for 8.1% of the occupied period. There is then the potential for a back-shift up to 4.5 hours before deterioration of the environmental conditions. The results for the 2010 standards model show a similar pattern. Before a back-shift is applied, the space temperature is below 18^{o}C for 5.2% of the time. The conditions then begin to improve and the results show that a back-shift of the full 6 hours was possible. As expected the same was found for the PassivHaus standard model, with a full 6 hours of back-shift possible. Tables displaying the full results can be found in Appendix B.

1.2 Spring and Autumn Analysis

The previous analysis carried out was then repeated for a week in March and November to represent a typical spring and autumn week respectively. The results for the PassivHaus model were very similar to that obtained from the winter period, again showing the potential increased building fabric can have. However, the results during the spring analysis showed the draw backs of a tight building in the form of overheating. In reality mechanical ventilation would be installed to remove the heat and reduce the risk of overheating, or the occupants would open windows to cool the place down. For this reason, the results from the 2010 and average models will only be covered in this section.

Figure 15 below shows once again the effect of a time-shift in the morning but this time during the spring week. Comparing this to the one obtained for winter shown in figure 11, it can be seen that temperatures are significantly higher; this should mean there would be good potential in the flexibility of operation during the spring season.

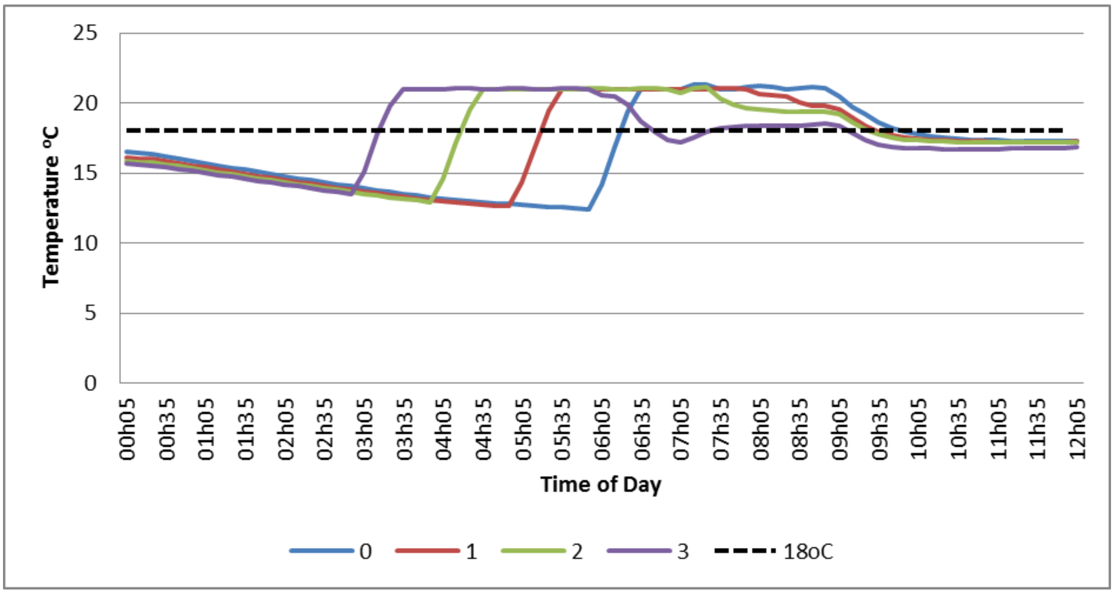

Figure 15: Effect of back-shift during spring week

The results for the Average and 2010 standards model in the winter period showed that a back-shift of only 1 and 1.5 hours was possible. This time around, both models showed flexibility of 2 and 3 hours respectively. Table 6 below shows a summary of the results for both models for a back shift from 0.5-3.5 hours. Once again, tables showing the results for the full 6 hour back-shifts can be found in Appendix B. For the 2010 model, the results show that a back-shift of up to 2.5 hours was possible before the occupied period temperature dropped below 18^{o}C. Even then it was only below this temperature for 2.1% of the time. A 2 hour back-shift was found to be possible for the Average model. Any time after that and there was significant deterioration of the environmental conditions.

	Average Standards								2010 Standards							
Back-Shift	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**
Mean Space Temperature	21	20.95	20.8	20.6	20.41	20.15	19.95	19.8	21.16	21.13	21.05	20.93	20.82	20.6	20.45	20.33
Maximum Temperature	21.54	21.51	21.57	21.73	21.5	21.56	21.62	21.73	22.96	23.07	23.16	23.24	23.31	23.37	23.42	23.46
Minimum Temperature	20.95	19.68	18.57	18.08	17.74	17.04	15.33	14.51	20.95	19.78	19.04	18.79	18.55	17.44	15.96	15.22
% Hours Below 18^{o}C	0	0	0	0	1.7	9.3	13.3	15.7	0	0	0	0	0	2.1	6.1	11.4

Table 6: Summary of results for spring period

The same simulations were also repeated for a typical autumn week. A week in November was chosen, as November over the last few years has seen the month experience a mix of both mild and cold conditions and was seen as a good choice for an autumn-winter transition period. Table 7 below once again shows a summary of the results obtained for the Average and 2010 standards model. Results for the full 6 hours of back-shift can again be found in Appendix B. The results for the autumn week analysed show that only a 1 hour back-shift was once again possible with the average standards model, while the results for the 2010 model showed that a 2 hour back-shift was possible without significant deterioration of the environmental conditions.

	Average Standards							2010 Standards						
Back-Shift	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**
Mean Space Temperature	20.98	20.91	20.65	20.34	20.06	19.72	19.41	20.99	20.94	20.76	20.54	20.34	20.03	19.77
Maximum Temperature	21.14	21.24	21.45	21.51	21.01	21.30	21.41	21.31	21.28	21.67	21.76	21.14	21.36	21.56
Minimum Temperature	20.95	18.82	16.71	15.98	15.63	15.12	14.42	20.96	19.53	18.30	17.10	16.76	16.14	15.41
% Hours Below 18°C	0	0	3.10	10.20	15.70	25.70	31.20	0	0	0	1.90	4.00	11.20	20.00

Table 7: Summary of results for autumn period

2. Hot Water Tank Results

Once the model was developed and verified, different draw profiles which represented the activities of a typical family of four with intermittent occupancy were used to test the system. Figure 16 below shows an example of the temperature profile within the tank, taking into account, the heat input into the system, the energy losses to the environment and due to the water draw off.

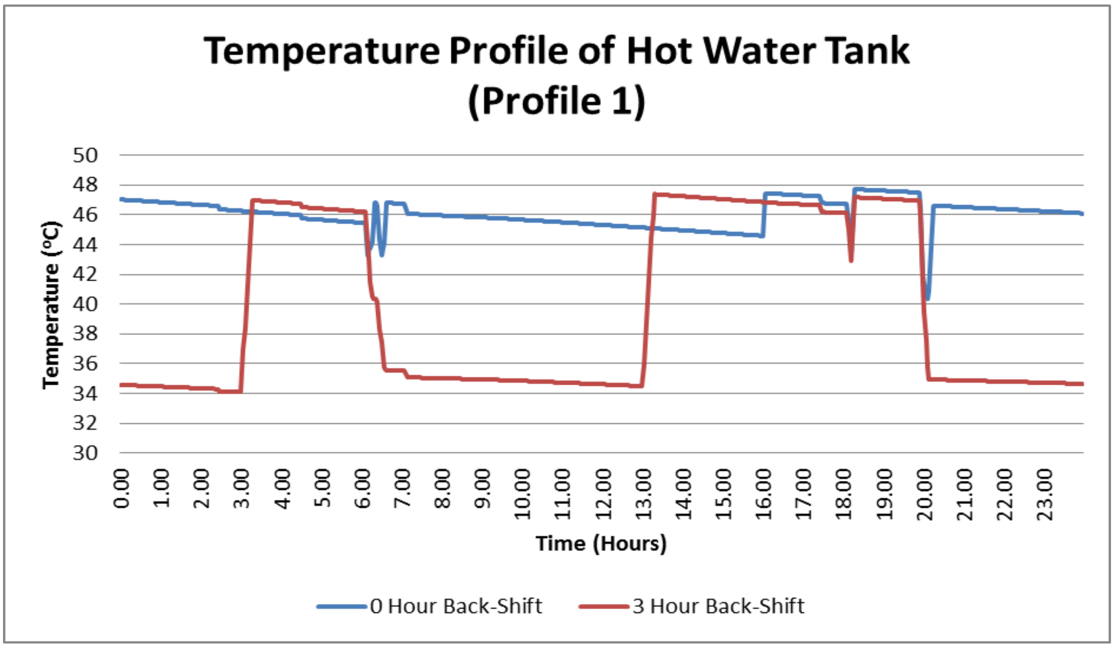

Figure 16: Temperature profile within hot water tank

The blue plot shows the profile before any back-shift in the heat input was applied. Looking at the graph there is a rather big draw occurring around 8pm, most likely representing an occupant filling a bath. The temperature drops to just above 40°C at this point, before an input of heat brings the temperature of the water back up to above 46°C. As a time-shift is applied there will be no heat input to recover the heat lost during this time. This is shown by the red plot on the graph after a 3 hour back-shift was applied. The same is happening in the morning between 7am and 9am. In this case only 2.5 hours of back-shift was possible before the temperature of the water became unacceptable. A temperature below 40°C was taken as the minimum acceptable temperature, as the water would begin to feel lukewarm to the occupant below this temperature. The graph clearly shows that between the occupied hours of

7am-9am and 8pm-10pm, the temperature of the water delivered during this period would be below 40°C.

The next draw profile was used because it had different draw off lengths and flow rates and would test the system in a different way. This one was derived from Roman Spur [45] who developed three profiles based on low, medium and high hot water usage. His medium usage profile based on time varying hot water draws totalling 180 litres, was used in this case. This time a back-shift of 1.5 hours was possible before the temperature during the occupied periods dropped below 40°C. Figure 17 below shows the temperature profile of the water inside the tank based on this profile before a time-shift was applied and after a 2 hour time-shift. The results show that during the occupied period in the morning of between 7am and 9am, the temperature delivered would have been below 40°C.

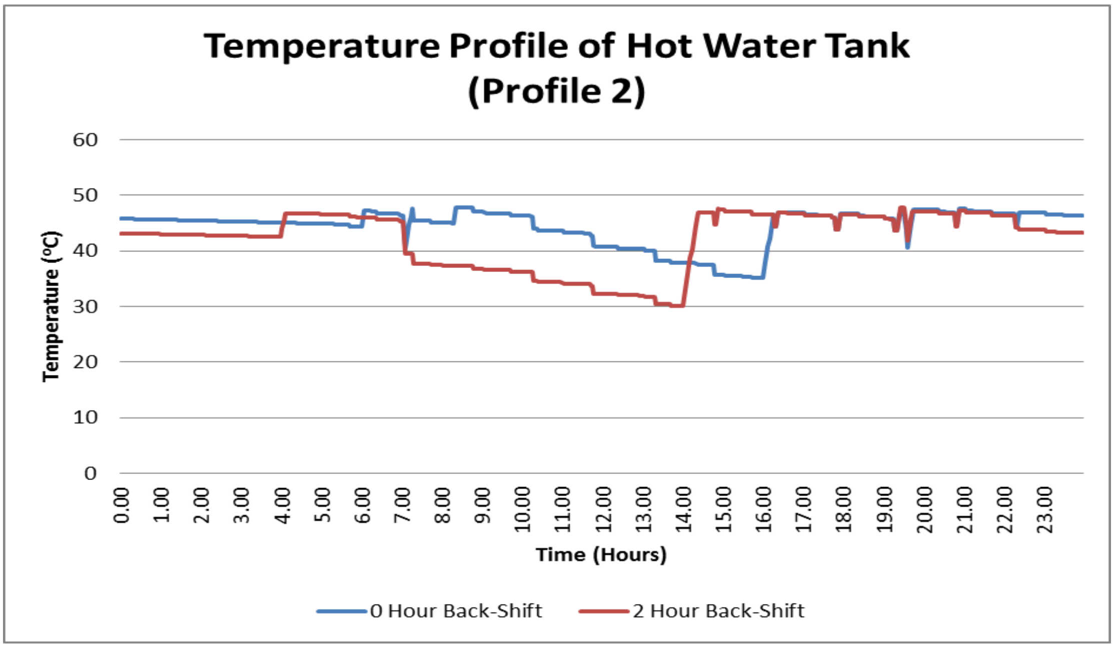

Figure 17: Temperature profile within hot water tank (profile 2)

The next domestic hot water profile used was generated using a software tool called DHW-calc developed by U.Jordan and K.Vajen. [46] The software generates random event schedules based on the desired total mean daily draw-off volume for different time-step durations. The user sets the probability distributions for weekdays and weekends and the flow rates. The temperature profile for the generated hot water profile can be seen in figure 18 below. In this case a time-shift of only 1.5 hours was possible before there was significant deterioration of the temperature delivered during occupied periods. Once again it's the morning period which suffers the most after the 2 hour time-shift, with its temperatures being delivered to occupants below 40^{o}C for a good portion of this period.

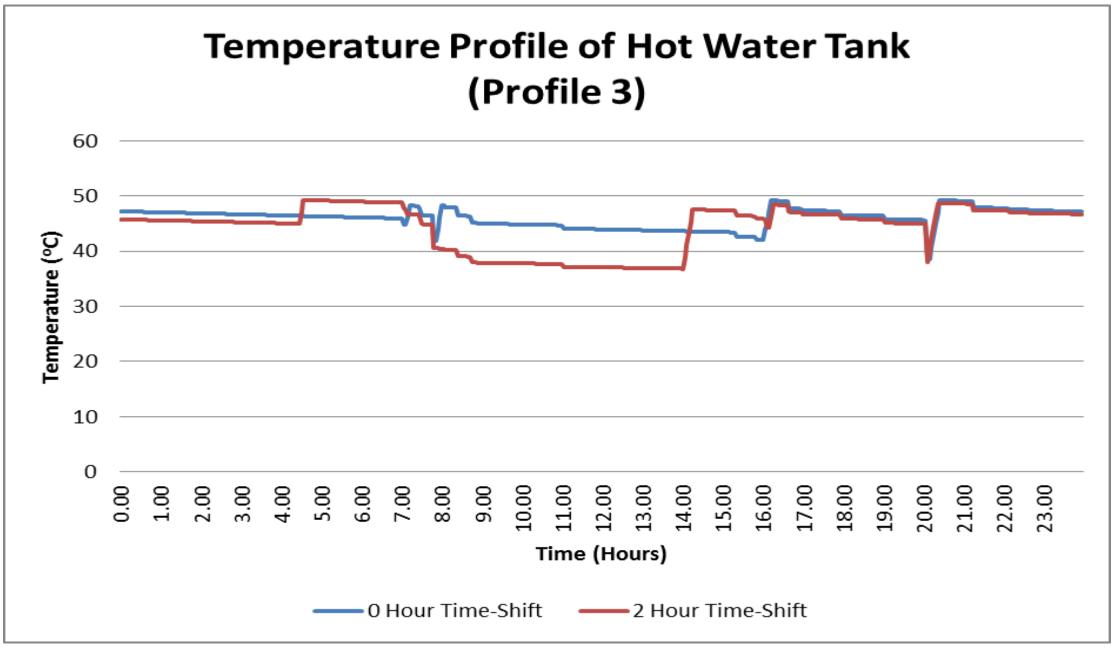

Figure 18: Temperature profile within hot water tank (profile 3)

The results obtained from both models are very interesting. While the average and 2010 standards model only offered a limited possibility of a time-shift, the PassivHaus standards model offered full flexibility with a full 6 hour time-shift being possible. Based on these results, if a heat pump was being used to provide space heating, its operation could be fully flexible, which would be an attractive option in regards to demand shifting and moving the peak load to off-peak times. That's fine if it was just providing space heating. However, in reality it would also be used for water heating. The results for the effect of time-shifting on the water delivered during occupied periods showed that the allowance was dependent on the draw profile used, but only around 2 hours was possible. Therefore the hot water tank is the limiting factor in this investigation. Increasing the storage capacity of the tank is therefore the next step in this investigation to improve the allowance of a time-shift.

There are different options to increase the thermal capacity of the tank. One method is by increasing the volume of water stored within the tank. This was tested by increasing the size of the tank to 400 and 500 litres. In both cases this significantly improved the allowance of a time-shift, so much that in the case of the second and third draw profiles, there was no sign of the temperature dropping below 40^{o}C during occupied periods. However, the limiting factor here would be the space in the dwelling to allow increasing the size of the hot water tank. Therefore the next investigation will look at the addition of latent storage materials in order to increase the storage capacity of the tank, without increasing its physical size. This should release heat to the water in the tank when the material is changing phase and allow for an improvement in the time-shifting allowance.

The next section will give some information about latent storage materials and look at situations where they have been implemented. Developing a sound understanding of the different types of latent storage materials, how they operate and the ways they could be potentially used in this investigation was important.

F. Investigation: Latent Thermal Storage

1. Background Information

Latent heat storage involves the use of materials which change phase within the operating temperature. They are quite fittingly called Phase Change Materials (PCMs) and they are substances with a high heat of fusion. When the material is melting and solidifying at a certain temperature, it is capable of storing and releasing large amounts of energy. PCM latent heat storage is achieved through either: solid-solid, solid-liquid, solid-gas and liquid-phase change. However, solid-liquid phase change is the only change used for PCM applications, because unlike the others it has a higher level of heat transformation and does not require as high a pressure to store the materials. [47]

Initially the solid-liquid PCM behaves like sensible heat storage materials and their temperature rises as they absorb heat. However, unlike conventional sensible heat storage materials, when the PCMs have reached the temperature at which there is a phase change (their melting temperature), they absorb large amounts of heat at an almost constant temperature. The heat absorption continues without a significant rise in temperature until all the material has been transformed into the liquid phase. Then, once the ambient temperature around the liquid material drops, the PCM solidifies and releases its stored latent heat, and thus increases the temperature of its surroundings. The phase change process is shown below in figure 19. Because their storage capacity during the phase change is much higher than the specific heat capacity of the material, it is estimated that PCM materials can store between 5-14 times more energy per unit volume than sensible heat storage materials such as masonry, rock or water. [48]

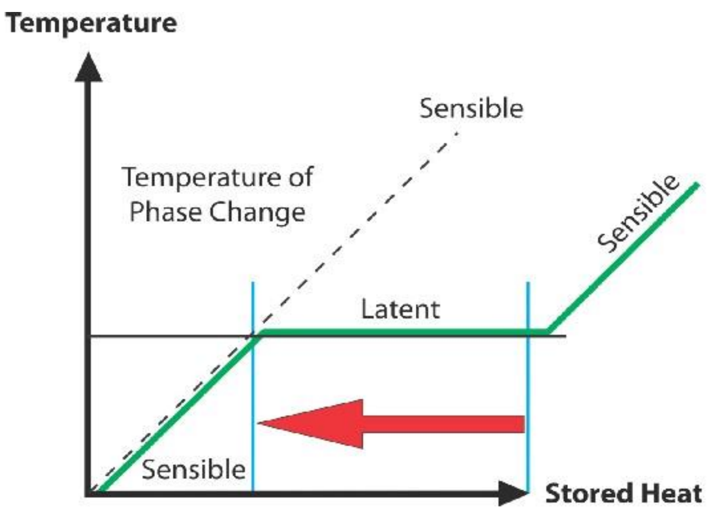

Figure 19: Phase change process [49]

1.1 Phase Change Material Types

A large number of phase change materials are readily available in any desired temperature range. The three main categories of solid-liquid PCMs are: organic compounds, inorganic compounds and eutectics (which can be of an organic and/or inorganic nature. The flow diagram in figure 20 below shows the classification and the different types of PCMs within these categories.

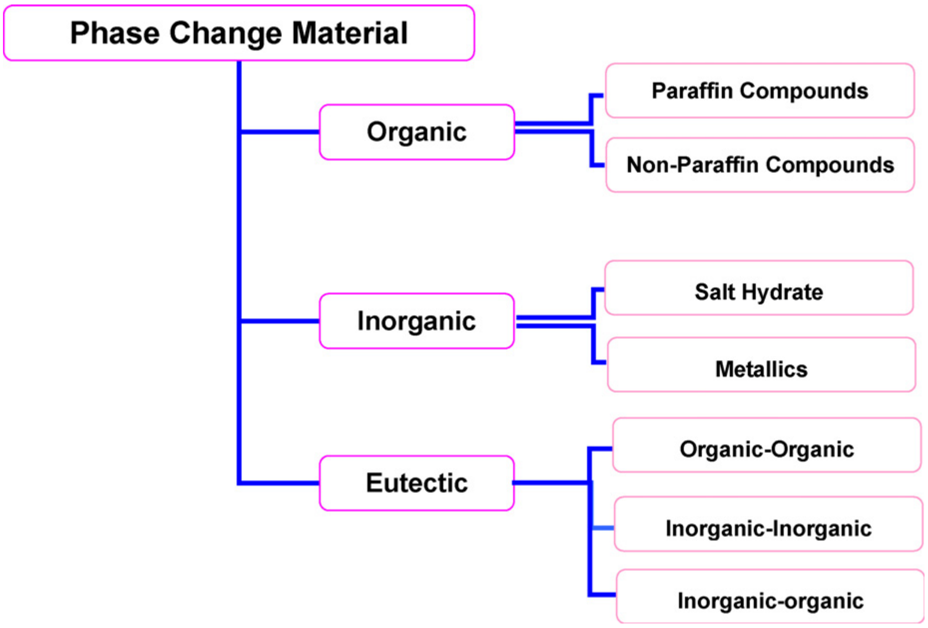

Figure 20: Classification of PCMs [48]

Organic compounds include Paraffin Compounds and Non-Paraffin compounds (fatty acids). Paraffin compounds were of particular interest to me as this was the type of PCM that I would eventually use as part of one of my investigations. Paraffins (C_nH_{2n+2}) have a high latent heat of fusion (around 200kJ/kg), negligible sub cooling, low vapour pressure in the melt and technical grade paraffins are commercially available and also relatively inexpensive to purchase. They are also safe, reliable and non-corrosive. However, paraffins do have some undesirable characteristics. They have low values of thermal conductivity (around 0.2W/mK) which limits their applications, their volumetric latent heat storage capacity is low and they are also moderately flammable, so extra care has to be taken. Their characteristics can be modified to make them more desirable by modifying the wax and storage unit. [51]

Organic Non-Paraffins make up the largest category of the materials for phase change materials. Unlike the paraffins which all have similar properties, the properties of these types are very varied. Included in this category are: esters, fatty acids, alcohols, and glycols. These organic materials have comparable desirable characteristics to that of paraffins and have high heat of fusion values (Caprylone has a value of 259kJ/kg). However, they still have low values of thermal conductivity; some are toxic and are instable at high temperatures. On top of this, their major drawback is their cost. This is around 2-2.5times more than that of paraffins. [48]

Inorganic materials are further classified as salt hydrates, salts, metals and alloys. Salt hydrates (M_nH_2O) are made up of salt and water which combine to form a typical crystalline solid. They are the most important group of PCMs and have been extensively studied for their use in thermal energy storage systems. Their main advantages include: a high volumetric latent heat storage capacity value, are readily available and at a low cost, have a sharp melting point, are non-corrosive and unlike the aforementioned organic materials, they have a high thermal conductivity value (almost double that of paraffins) and are non-flammable. The major disadvantages associated with Inorganic materials are: problems with subcooling and phase segregation which have limited their use and nucleating agents are often needed as there has been a reported decrease in their latent heat of fusion after repeated cycling. [48, 50-51]

Metallics include the low melting metals and metal eutectics. These types of metallics have not yet been seriously considered for PCM applications because of their weight penalties. However, they do have a high heat of fusion per unit volume and high thermal conductivity values. Although this quality also causes engineering problems in their use as a PCM.

Eutectics are mixtures of two or more salts which have definite melting/freezing points. This means they nearly always melt and freeze without segregation, because they freeze to an intimate mixture of crystals, leaving little opportunity for the liquid components to separate. When they melt, both components liquefy simultaneously due to their sharp melting point, meaning separation is again unlikely. Their behaviour is similar to that of salt hydrates and they have great potential for thermal energy storage applications. Another advantage they pose is the fact that their volumetric storage density is slightly above organic compounds. The major disadvantage is that there is limited available data on the thermo-physical properties of eutectics, as they are relatively new to thermal storage applications. [47-48]

1.2 PCM Selection Summary

From the research carried out, any latent heat thermal energy storage material, will ideally possess the following properties: [47-51]

- A high latent heat of fusion per unit volume value
- Melting temperature will be within the operated temperature range
- A relatively high thermal conductivity value so that the temperature gradients required for charging and discharging the material are small
- A high specific heat capacity value to provide a high level of sensible storage
- A high density, so that a smaller container volume holds the material
- Readily available and inexpensive to purchase
- Non-Toxic
- Non-Corrosive
- Non-Flammable or explosive

- Show no degradation after a large number of repeated freezing and melting cycles
- Chemical Stability
- Little or no subcooling occurs during freezing

1.3 Applications of PCM

This section will look at different situations were PCMs have been implemented to improve the thermal storage capabilities of the application studied. Extensive work has been done by different people investigating the addition of PCM modules to a domestic hot water tank. Other applications include their integration into the walls and floors of buildings, but for the purpose of this thesis and the investigation at hand, their integration into hot water tanks will only be considered.

The first article that was studied was by E.Talmatsky and was titled: "*PCM storage for solar DHW: An unfulfilled promise?"* [52] In this report a comparison of the performance of a storage tank with the addition of PCM modules to a standard tank without them was carried out. Different PCM volumes and different kinds of PCMs were used for their analysis and what they discovered surprised them. They discovered that the use of the PCM tank under investigation did not bring any significant benefit to the user. The reason they found for this was because of the heat losses at night due to the PCM reheating the water. The results calculated were produced using a: "*simplified model,"* and in order for this conclusion to be verified more detailed modelling should be carried out, to fully analyse the performance. They did state that the PCM addition to a tank shouldn't be ruled out and their performance could be better in a different design or a different geometry of tank. This statement was also similar to the conclusions derived in another report.

M.Esen and A.Durmus, [53] compiled a report titled: "*Geometric design of a solar-aided latent heat store depending on various parameters and phase change materials*." In their investigation they developed a theoretical model using numerical methods, to predict the effect of various thermal and geometric parameters on the whole PCM melting time, for various materials and tank configurations. From their results they could conclude that the PCM melting time depends also on the thermophysical properties of the material as well as the thermal and geometric parameters. Based on this, they concluded that the choice of PCM and geometry of the tank should be considered together when designing a thermal store. If Talmatsky had considered this beforehand, the results might have been different..

The location of the PCM module within the tank also appears to be important. L.F.Cabeza and others [54] carried out an experiment with an encapsulated PCM at the top of the water tank. In their experiment they used a granular PCM-graphite compound and added the encapsulated PCM model to the top of a hot water storage tank with stratification. It was hoped that the PCM module would give a higher density in the top layer and make better use of the waste heat. They experimented with different configurations involving the number of modules and also the volume they occupied within the tank. The results they achieved showed the improvements that the addition of PCM modules to a domestic hot water tank could provide. The results indicated that the addition of PCM modules could allow the user to have hot-water for longer, or even allow the possibility of the user using smaller tanks for the same purpose. This would be particularly important if space was an issue and there wasn't room for a big tank.

In a similar experiment, but this time using an encapsulated paraffin PCM, [55] they once again added a PCM module to the top of the hot water tank and hoped this would give the system a higher storage and compensate for the heat loss in the top layer. The results again showed that the addition of a PCM module at the top of the water tank does give the system a higher storage density and the PCM addition caused the time to delay the heat loss up to 200%.

Rubitherm is an innovative partner for PCM-technology and are at the forefront in developing PCMs for various applications. They have carried out significant research and analysis and produced two graphs that show that the greater the paraffin content, the heat storage capacity in the module is increased. They also state that using a latent heat storage unit is only really fully effective when a minimum of 50% of the storage unit's volume is filled with latent heat storage material. [56]

From the research carried out the opinion on PCM addition to domestic hot water tanks appears to be inconclusive. More promising results have been reported when the PCM module has been placed in the top of the tank. Other factors that affect performance include: the composition of the PCM module, the number of modules used relative to the size and also the draw off profiles used. These were all considerations that were taken into account during the final investigation. The next section will describe how the Excel model used in the previous investigation, was then expanded to include the addition of PCM modules.

2. PCM Hot Water Tank Modelling

2.1 Introduction

The final investigation carried out was to expand the model developed for the previous hot water tank investigation and add phase change materials to add latent heat storage to the tank. Encapsulated paraffin modules were added to investigate the advantages and possibilities they could have to improve the hot water tanks back-shifting capabilities. It was hypothesised that the addition of the phase change module, would increase the storage density and should eliminate the large drops in water temperature that were evident in the previous investigation, when there was no input of heat. This should allow for an improved potential of back-shift without changing the size of the tank.

Paraffin was chosen as the PCM material for the following reasons; it is relatively inexpensive to purchase, non-toxic and non-corrosive, 100% recyclable so environmentally friendly, does not exhibit degradation which would make modelling simpler and has a high latent heat of fusion. [57] The paraffin is encapsulated in stiff plastic containers. These containers are normally cylindrical in shape and have ridges around their edges to ensure a good heat exchange with the water, allowing the water to pass between the containers freely.

2.2 The Model

The same size of tank that was used in the previous investigation was also used in this one. Because PCM modules were being added into the tank, this meant that the mass of water within the tank would be reduced. Three additional columns were added to the spreadsheet model, so that the inclusion of the PCM modules could be taken into account. These columns give information about the heat transfer between the PCM and the water in the tank, the vapour fraction at a given time of the module and also the temperature of the module.

2.3 Heat Transfer between the PCM and the Water

There will be a constant transfer of heat between the water and the PCM module. When $\dot{Q}_{pc}$ is positive, this means energy is being transferred from the water to the PCM, and the opposite is happening when $\dot{Q}_{pc}$ is negative. The heat transfer between the PCM and the water was calculated by using equation (6) below.

$$\dot{Q}_{pc} = U_m . A_m \left(T_{tank} - T_{pc}\right) \quad (6)$$

In this case U_m is the overall heat transfer coefficient of the PCM module and was calculated using equation (7) below. The convective heat transfer through the PCM was ignored in this instance. This was allowed because as the PCM was going to be solid at certain points during the procedure. Because the tubes are extremely narrow, convection was not likely to be the main method of heat transfer through the PCM, so for this reason again, it could be ignored. A_m and T_{pc} were the area and temperature of the module respectively.

$$\frac{1}{U_m} = \frac{x_h}{k_m} + \frac{1}{h_w} \quad (7)$$

2.4 Water Temperature Calculation

Taking into consideration the heat transfer between the PCM and the module, the temperature of the water in the tank was calculated similarly to the way it was in the previous investigation and is shown below in equation (8).

$$M_w . C_{p(w)} \frac{d\theta_{Tank}}{dt} = \dot{Q}_{in} - \dot{Q}_{draw} - \dot{Q}_{loss} - \dot{Q}_{pc} \quad (8)$$

Then like described earlier, the temperature at every time step was calculated using the forward difference method.

2.5 PCM Temperature and State

The PCM is defined by both its temperature and its state. This means by how much of the material is solid and how much is liquid. Its state is defined by its mass fraction; X. Thermal expansion has been ignored to not over complicate things, so a constant density of 880kg.m^{-3} has been assumed. As the PCM module melts there would be an expected decrease in matter due to the decrease in density, but this has also been ignored to keep things simple.

- When $T_{pc} < T_{melt}$ and X=0

X remains at 0 or 1 and the temperature of the PCM varied according to equation (9) below:

$$M_{pc}.C_{p(pc)(s)}\frac{dT_{pc}}{dt} = \dot{Q}_{pc} \quad (9)$$

- When $T_{pc} \geq T_{melt}$ and X=1

Again, X remains at 0 or 1 and the temperature of the PCM varied according to equation (10) below:

$$M_{pc}.C_{p(pc)(l)}\frac{dT_{pc}}{dt} = \dot{Q}_{pc} \quad (10)$$

- When $T_{pc} < T_{melt}$ and X $1 \geq X > 0$

In this case X is below 1 but above 0 and the material is undergoing a phase change. The rate of change of the mass fraction varied according to equation (11) below.

$$M_{pc}.hfg.\frac{dX}{dt} = \dot{Q}_{pc} \quad (11)$$

In each case, for T_{pc} and X respectively, these values were found out using the forward difference method, which is shown below in equation (12).

$$\frac{dT_{pc}}{dt} = \frac{T_{pc} - T_{pc}'}{\Delta t} \quad , \quad \frac{dX}{dt} = \frac{X - X'}{\Delta t} \quad (12)$$

2.6 Model Validation

With the addition of the parameters to take into account the PCM modules, it was even more important to make sure the model was working properly and produced the expected results. Some of the cells contained complicated embedded 'IF' statements, so time was spent testing the model to ensure it wasn't producing inaccurate results. As a lot of the constraints were dependent on the relationship with the temperature of the water in the tank and the melting point of the PCM, varying the melting temperature was an effective way of testing for errors within the statements. In addition, a similar model had been developed by my supervisor, so the models could be cross-referenced to ensure the equations used were correct.

G. Results: Latent Thermal Storage

In order for the PCM to make a difference, the temperature of the melting point of the module is the most important characteristic to consider. The melting point of the PCM module must be exceeded by the temperature of the PCM so that charging can occur. It must also drop below this temperature so that the module can discharge and solidify. Therefore a melting temperature of 55^{o}C would not be a sensible value to use as none of the temperature profiles displayed earlier in section G reaches this temperature. A melting point temperature of between 42^{o}C and 47^{o}C was a more suitable value. Each temperature within this range was tested to see which temperature gave the most effective result. Starting with 42^{o}C improvements in the amount of time in the week the temperature was delivered below 40^{o}C were already evident. The percentage of water delivered below 40^{o}C significantly reduced, up until a temperature of 46^{o}C, after which there was no significant improvements to the system. So the melting point temperature range in this case was found to be between 42 and 46^{o}C. The specific heat capacity of the module was 2130 kJ/kg K when in liquid phase and 2900 kJ/kg K when in the solid phase. Notice this is less than that of water, meaning that it will only be effective in increasing the storage density when it undergoing phase change.

The amount of PCM used also played an important part in improving the systems effectiveness. The number of PCM modules used was varied to observe what improvements, if any they made on the systems performance. When too little were used, this made no difference to the results when comparing them too the results achieved without the PCM addition. When too many were used, this had an adverse effect on the system and resulted in large temperature differences. Sometimes, it would even force the temperature of the water to way below the minimum allowable temperature during occupied periods. The size of the PCM modules is the other factor that could affect system performance, so different sizes of PCMs were also tested to see what effect they had on results.

The draw profiles used in the earlier investigation were used in this investigation to see if the addition of PCM modules could improve on the performance of the hot water tank and therefore improve on the allowable time-shift. The results for each profile will be compared to the results from before and are displayed in the section below.

1. Draw Profile 1

The results from the earlier investigation showed that for this particular draw a back-shift of 2.5 hours was achievable before the temperature of hot water delivered to the occupants was below 40^{o}C. Various combinations of different module number, sizes and temperatures were investigated. 60 modules, with a height of 1m and an outer diameter of 0.05 metres and a melting point temperature of 44^{o}C gave the best results. This was the optimum number of modules for this particular case, with the addition of more not making any difference to the storage density and causing larger temperature drops to occur at the draw off points. The interesting observation here was that 60 modules have a volume of 0.118m^3, with 0.082m^3 being water. This reinforces the aforementioned findings that Rubitherm discovered, stating that at least 50% of a mixed storage system should be latent storage to make a significant improvement.

Looking at what is happening throughout the day to the water inside the tank after the inclusions of the PCM modules; the graph in figure 21 below clearly shows the characteristics of the water and the modules, after a back-shift of 3 hours was applied. The heat input was occurring between the hours of 2am-5am and 1pm-8pm.

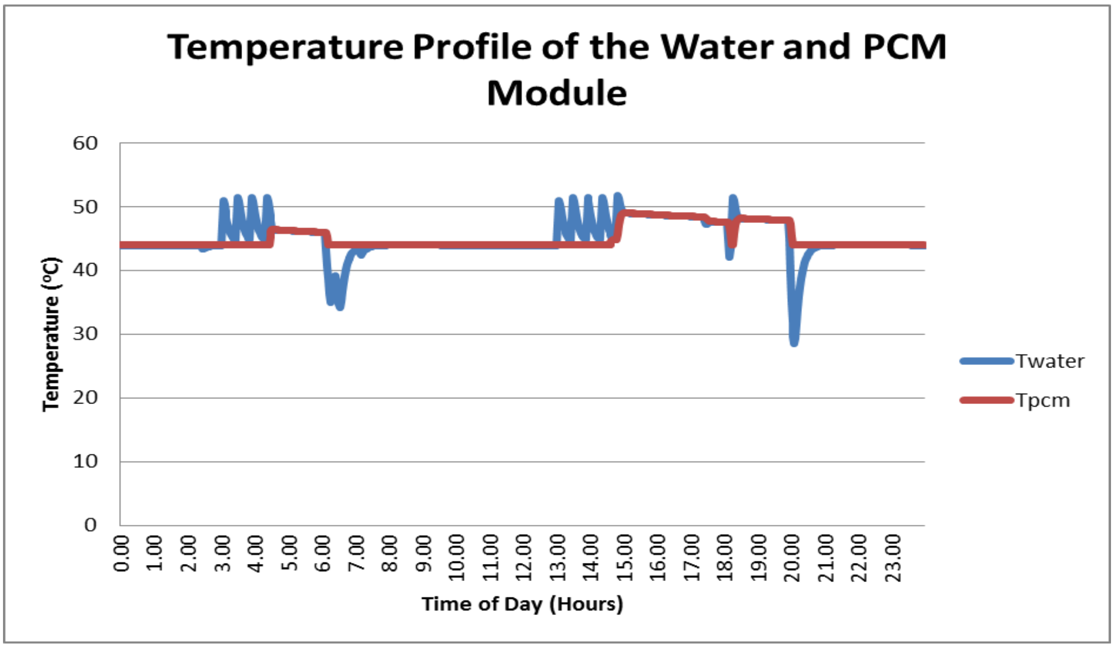

Figure 21: Temperature profile of the water and PCM module

Looking at the large draws that occur in the morning and evening, after which times the heating system has been switched off. As discovered in the earlier investigation, there was no heat input to recover the temperature of the water and the temperature remains below 40^{o}C for long periods in the day. However in this case, the heat transferred from the modules brings the temperatures of the water back up to an acceptable temperature. This clearly shows the benefits of latent heat storage over traditional sensible storage.

The liquid fraction profile of the module displayed in figure 22 below helps to illustrate the behaviour of the PCM module throughout the day. The module is initially in a solid/liquid state before it begins to charge as the temperature in the tank begins to rise, due to the heat input. It then undergoes a phase change as it melts (shown by the horizontal line on the profile when the liquid fraction is at 1). The module then begins to discharge and transfers heat to the water to raise the temperature of the water in the tank. This process is then repeated in the afternoon.

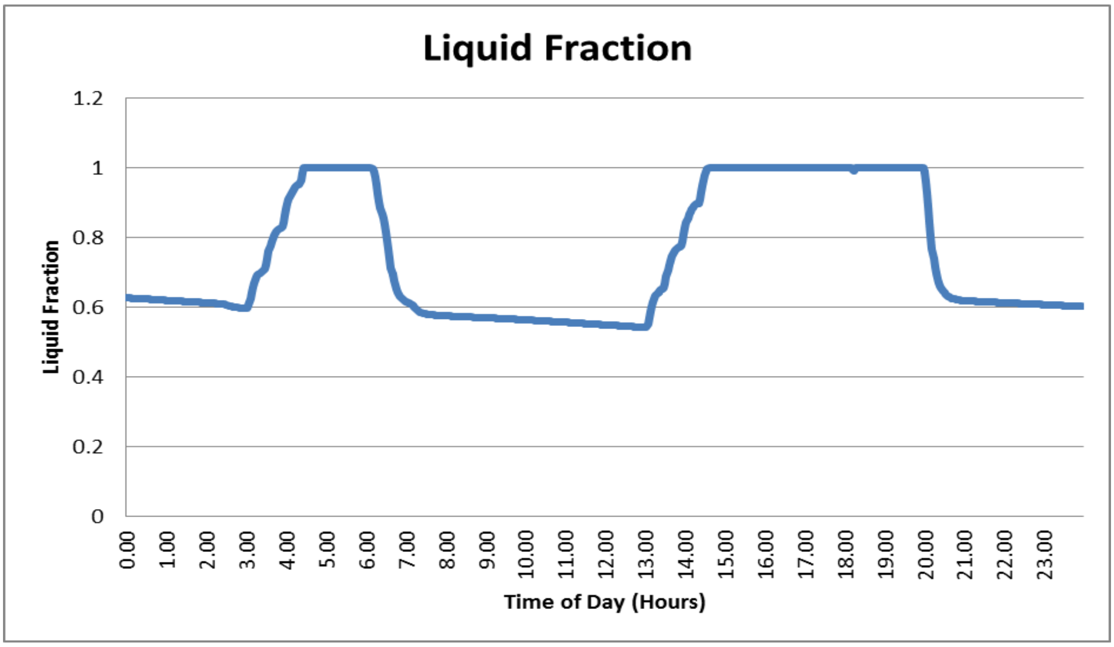

Figure 22: Liquid fraction profile for draw profile 1

To fully appreciate the benefits of the addition of PCM modules in this case, table 8 below summarises the conditions of water delivered during occupied hours, with and without the PCM addition, over the investigated week as the back-shift was applied.

	No PCM							With PCM						
Time-Shift (Hours)	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
Mean Temperature (°C)	39.79	39.74	39.64	39.59	37.61	37.51	37.49	44.76	44.73	44.47	44.57	43.71	43.65	43.59
Maximum Temperature (°C)	47.65	47.58	47.43	47.35	46.88	46.78	46.69	52.42	52.35	52.19	51.90	51.77	48.31	48.20
Minimum Temperature (°C)	34.68	34.66	34.63	34.59	31.74	31.70	31.65	28.45	28.39	27.98	27.98	27.53	27.53	27.53
% of Hours Below 40oC	60.96	60.96	60.96	60.96	61.78	61.78	61.78	4.91	4.91	4.91	4.91	5.20	5.32	5.49

Table 8: Summary of results for draw profile 1

Considering that after a time-shift of 3 hours was applied, the addition of PCM modules reduced the percentage of water below 40°C from the massive 60.96% to a significantly smaller 4.91%, this clearly shows the advantages that using latent thermal storage could offer. The addition never fully eliminated the occurrence of the temperature falling below 40°C, but it did reduce it significantly. The results obtained for the second draw profile will be discussed next.

2. Draw Profile 2

The results from the earlier investigation showed that for the second draw profile analysed that a back-shift of 1.5 hours was achievable before the temperature of hot water delivered to the occupants was below 40°C. Once again a melting temperature of 44°C was identified as being the optimum, melt temperature. This time the number of PCM modules which gave the best result was 55. Similarly to before, the heat transferred from the modules raises the temperature of the water back to an acceptable temperature at periods it wouldn't have before. This temperature profile of the water and the PCM module after a back-shift of 3 hours was applied is shown below in figure 23. The graph displays the results for a back-shift of 3 hours in order to clearly see the effect the PCM modules have in both the morning and evening periods. Water draws were more frequent in this draw profile and this is evident by the peaks and troughs in the graph. However, the PCM module is effective at recovering the temperature lost even after multiple draws that occur close together.

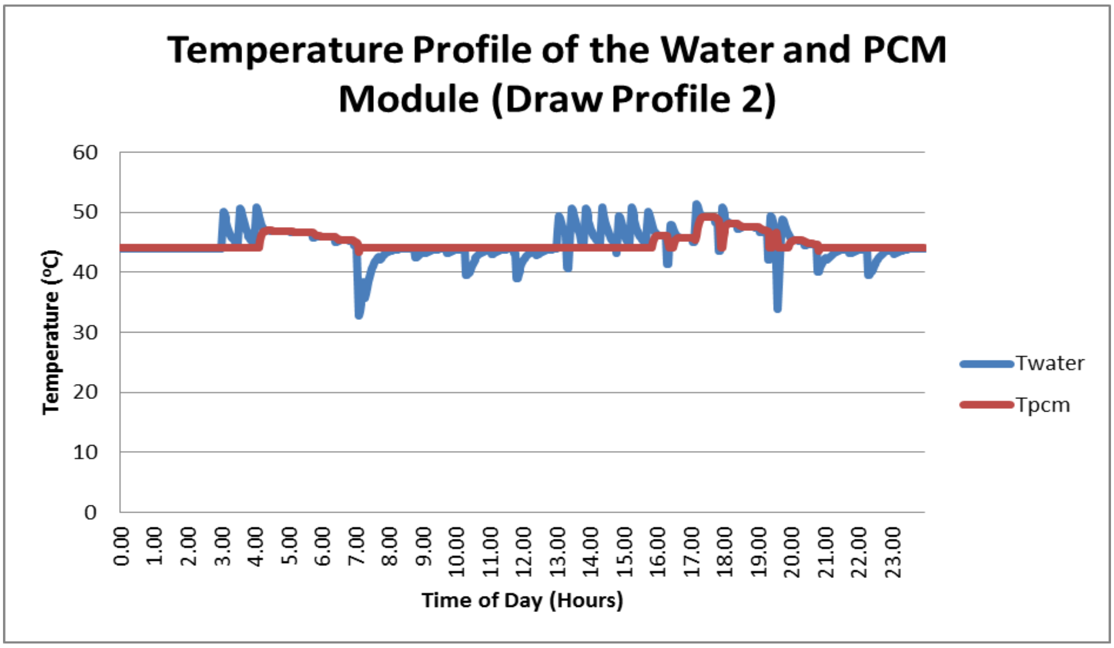

Figure 23: Temperature profile of the water and PCM module (Profile 2)

Once again a comparison of the results with and without the addition of the PCM module can be found in the table 9 below. Again the problem of the water temperatures falling below 40^{o}C during occupied periods could not be fully eliminated. However, the percentage that this occurs again had been significantly reduced.

No PCM										With PCM								
Time-Shift (Hours)	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
Mean Temperature (°C)	44.14	43.39	43.19	41.03	39.89	40.06	39.99	38.30	38.05	44.93	44.15	44.07	43.22	42.73	42.93	42.82	42.09	42.11
Maximum Temperature (°C)	47.85	47.83	47.58	47.80	47.41	47.84	47.56	47.41	47.42	50.05	49.84	49.79	49.44	48.95	49.80	49.04	48.68	48.00
Minimum Temperature (°C)	36.65	36.58	36.51	35.45	33.36	33.70	33.47	31.18	31.19	35.19	35.82	34.63	34.57	34.02	34.29	34.11	33.62	33.62
% of Hours Below 40oC	22.78	22.67	23.38	51.58	65.85	65.85	65.85	66.27	66.27	5.32	6.78	7.36	10.23	11.51	11.51	11.57	13.09	13.09

Table 9: Summary of results for draw profile 2

3. Draw Profile 3

The results from the earlier investigation showed once again, that a back-shift of only1.5 hours was achievable before the temperature of hot water delivered to the occupants was below 40^{o}C. Again various combinations of different module numbers and sizes for a range of melting temperatures were tested to see what the optimum combination was. This time around a melting temperature of 45^{o}C gave the best results and the number of modules was 57. This once again reinforced Rubitherm's findings that at mixed storage system should be made up of at least 50% latent storage material, as 57 modules rook up a volume of 0.112m^{3}.

The temperature profile with the addition of the PCM module can be seen in figure 24 below. Similarly to the results shown for draw profile 2, the graph displays the results for a back-shift of 3 hours. This is to clearly show the effect the PCM modules have when larger draws occur and there is no heat input from the heating system to recover the lost temperatures. Once again the PCM modules prove to be effective in providing heat to the water to recover lost temperatures due to the draw offs.

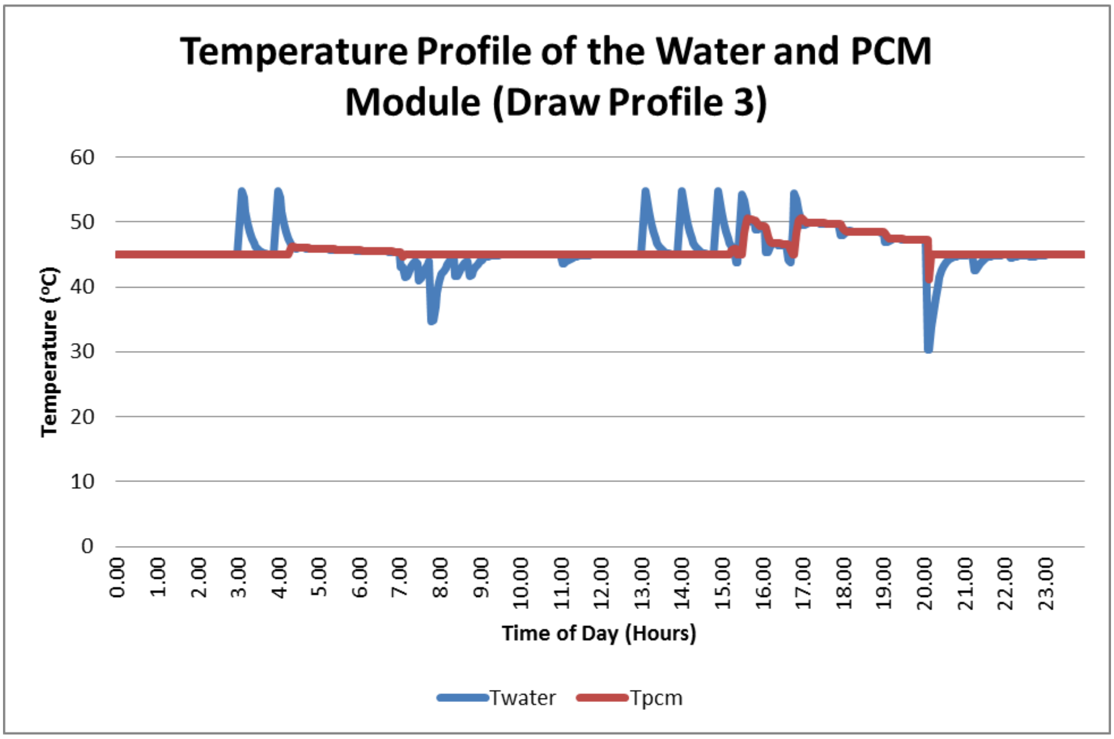

Figure 24: Temperature profile of the water and PCM module (Profile 3)

Once again a comparison of the results obtained, with and without the addition of the PCM modules can be found in table 10 below. The problem of the temperatures of the water delivered falling below 40°C could not be fully eliminated, but the percentage of time that it was below this value, has again been significantly reduced.

	No PCM									With PCM								
Time-Shift (Hours)	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
Mean Temperature (°C)	45.04	45.02	42.09	42.03	41.37	41.32	41.27	40.86	40.81	45.50	45.62	45.19	45.35	45.11	45.11	44.49	44.47	44.46
Maximum Temperature (°C)	49.28	49.29	49.22	49.19	48.59	48.59	48.59	48.59	48.59	56.11	56.11	55.17	55.16	54.91	54.94	50.06	50.03	50.02
Minimum Temperature (°C)	35.52	35.50	36.39	36.33	36.27	36.22	36.16	35.73	35.68	29.51	29.51	30.28	30.27	29.07	29.35	29.07	29.07	29.07
% of Hours Below 40oC	7.84	12.57	12.30	46.52	46.52	50.18	50.18	50.18	50.18	3.84	4.37	5.35	5.53	5.62	5.71	5.62	5.62	5.62

Table 10: Summary of results for draw profile 3

The results from this investigation are very interesting. They clearly show that the addition of PCM modules significantly improve the thermal storage capacity of the tank and helps to maintain the temperature of water in the tank, even after a time-shift in the operation of the heat input. The results were very much dependent on the nature of the hot water being drawn from it, but results show the improvement of potential load shifting. The earlier investigation identified the hot water tank as being the limiting factor in defining the maximum possible time-shift allowance, due to the large percentage of time water was being delivered below 40°C. Although this occurrence was not fully eliminated, the percentage of time it was delivered below this value has been significantly reduced.

H. Conclusion

This thesis has looked at the use of thermal storage to investigate the possibility of time-shifting the operation of heating systems. Time-shifting is going to be important in the future, especially with current policy encouraging the large-scale use of low-carbon heating systems which require being connected to the electrical distribution network. Time-shifting their operation would remove the electrical loads they would use at times when demand is high. The investigations were carried out through the use of an intensive modelling-based approach.

A typical UK detached dwelling was modelled with three different levels of building fabric (UK Average, 2010 and PassivHaus standards). For the winter week when the investigation was carried out, the maximum possible time-shift with the UK Average standards model was found to be 1 hour. Using the 2010 standards, only improved the allowance by a half hour. With these results, it might seem underwhelming as it wouldn't allow sufficient flexibility to reduce the demand peaks that occurs in the electricity distribution network in the morning and evening periods. However, if they were installed on a district level, their operation could be staggered by a local network operator. This would prevent all the devices being switched on at the same time and having a massive demand on the network all at once. The results in spring and autumn showed more of an allowance, so this idea to stagger the operation of devices like heat pumps, would have more flexibility in warmer seasons.

Projecting to the future and the modelling was repeated with the models fabric representing that of PassivHaus standards. The allowance here was significantly improved, so much that a full 6 hours time-shift was found to be achievable without significant deterioration of the environmental conditions during occupied periods. This is very interesting to know, because there is effectively maximum flexibility to shift the demand to any point at the day and by using less energy to heat to the house. Therefore it can be concluded that improving the quality of building fabric, offers a greater degree of flexibility in regards to load shifting.

Increasing the buildings effective thermal mass was also investigated by modelling the effect of an underfloor heating system. This showed significant improvements in the allowance of time-shifting. The results showed that the heating system actually benefitted from the time-shift as initial conditions showed that the temperatures were below the minimum allowable temperature. Due to the characteristics of radiant heating ensuring the building takes equally as long to cool down as it does to heat up, therefore it was found that there was more of an allowance here than with wall hung radiators. However underfloor heating would be easy to install in a new build building, to install this in an existing building would be both difficult and costly.

The effects of time-shifting were then applied to a domestic hot water tank. Results here showed that they were very much dependent on the nature of the draw off profile used, but an allowance of around 2 hours was only found to be possible. Therefore it can be said that the hot water tank and the temperature of water delivered to occupants, is the limiting factor in regards to defining the overall time-shift allowance.

Phase change heat storage was then investigated to improve the thermal storage capacity of the tank. This never fully eliminated the occurrence of the temperature of water being delivered at low temperatures during occupied periods. It did however offer significant improvements. A small allowance was only possible when just using sensible storage because there was no heat input to recover the temperature when the draws occurred during periods of high usage; meaning the temperature of the water remained low for long periods in the day. The addition of the phase change material modules was able to recover the lost heat during these periods and significantly reduce the amount of time the water was delivered at low temperatures.

Domestic phase change heat storage is not widely available and still requires further research before being implemented at a domestic level. The results from the investigation show the potential it can offer. The hot water system in reality will be judged on how successfully it delivers water at the desired temperature.

I. Further Work

Due to the tight time scale allocated to carry out this thesis and how long it initially took to develop both the ESP-r and Excel models, the number of investigations carried out was restricted. However, during the course of the thesis additional areas for potential further investigations became evident.

Firstly, the model on ESP-r developed only had one zone. A more detailed model including living and non-living zones would give more detailed results as there would be more heat interactions between the walls and ceiling in the house. Therefore more detailed modelling should be carried out, as it would be interesting to compare the results in both cases. The idea of expanding the investigation onto different dwelling types such as; semi-detached housing, terraced, bungalows or flats would also be interesting. This would enable the results to be compared to see which type of building offers the greatest potential for time-shifting.

The Excel model of the hot water tank gave a good indication of the conditions that would be expected inside the tank. However, modelling the tank as a plant component using ESP-r may be a more appropriate tool. This would then take into consideration common configurations for UK heating systems, such as, if the tank temperature dropped below its setpoint, heat would be diverted to it instead of the radiators or underfloor heating system. This would add more realism to the results. Improvements could also be made to the model by improving on some of the assumptions that were made. One of these could be to model the effects of stratification on the water in the tank.

The draws off profiles used were generated using software or from data other people had taken. Modelling the hot water tank based on own recorded monitored data would be an interesting addition. Using calibrated heat pump data would also be an interesting addition, as once again this would add realism by using real heat input data, rather than just assuming that 10,000 W of energy would be used if the temperature dropped below the set point temperature.

Finally, including different levels of thermal buffering could be investigated with the PCM tank to see if this offers a greater temporal shift on demand, by eliminating the occurrence of the water being delivered below $40^{o}C$.

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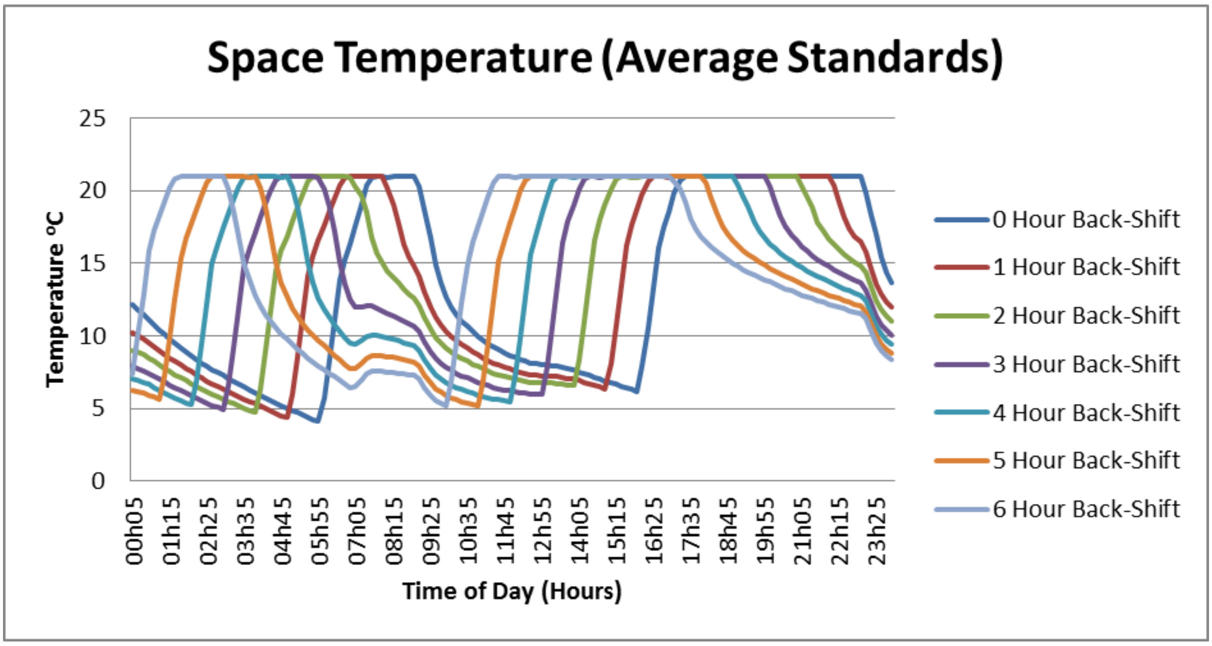
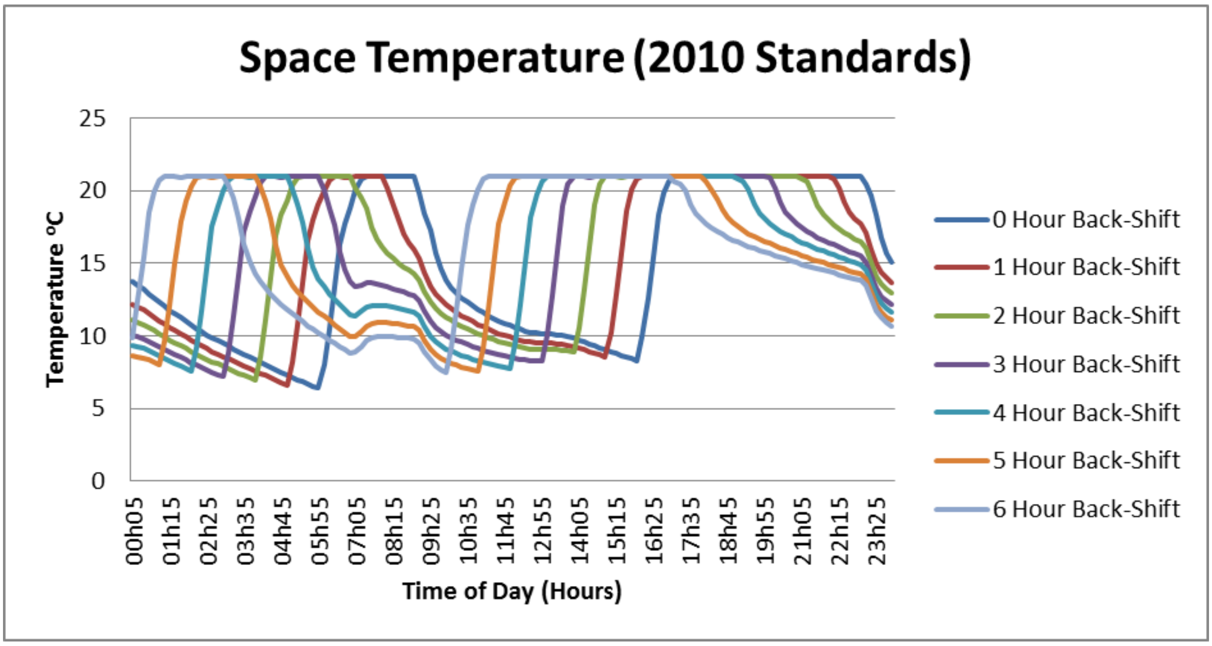
K. Appendix A

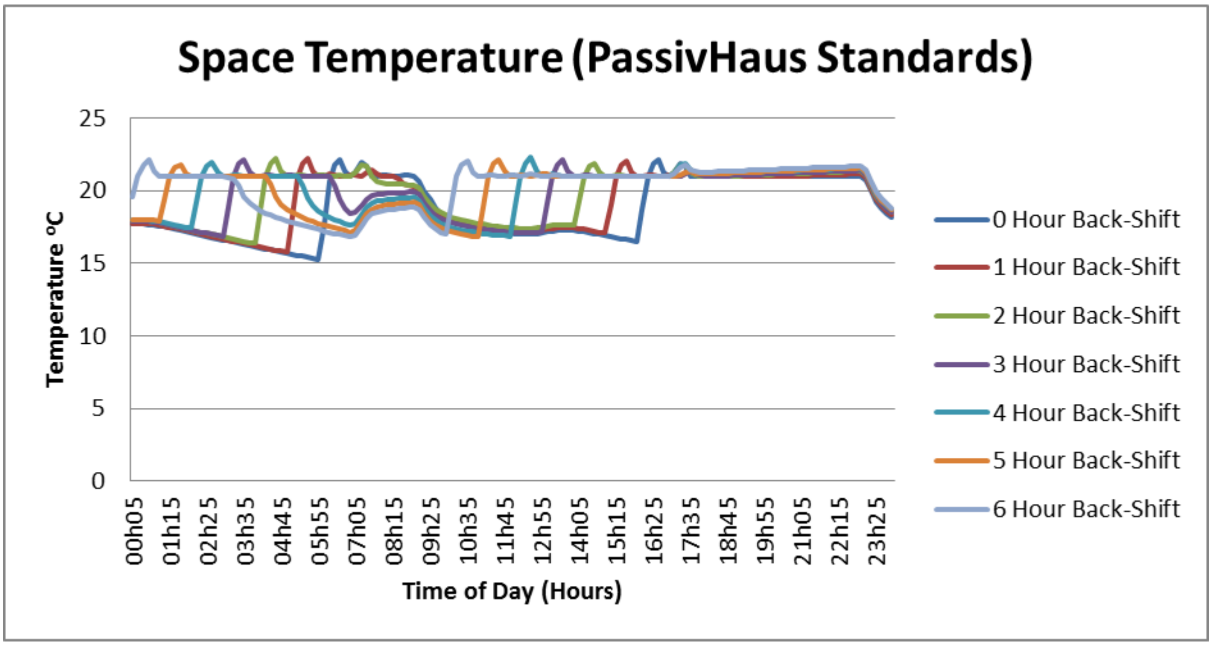
1. Graphs From Winter Simulations



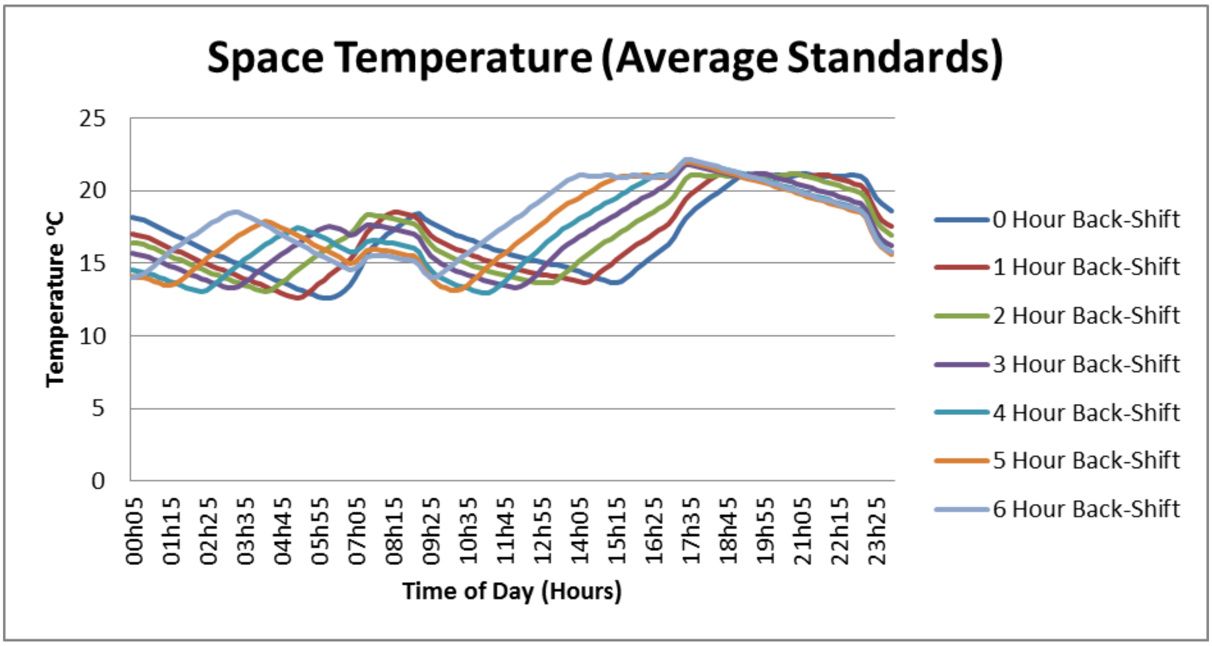
Wall hung radiators (average standards model)



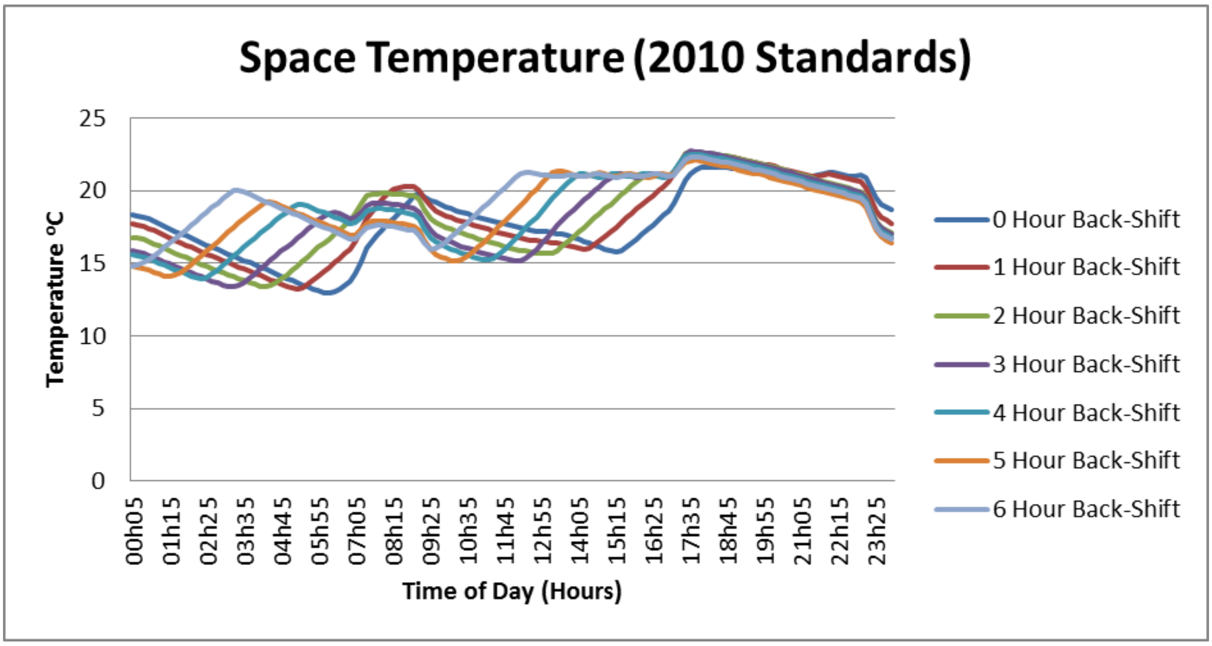
Wall hung radiators (2010 standards model)



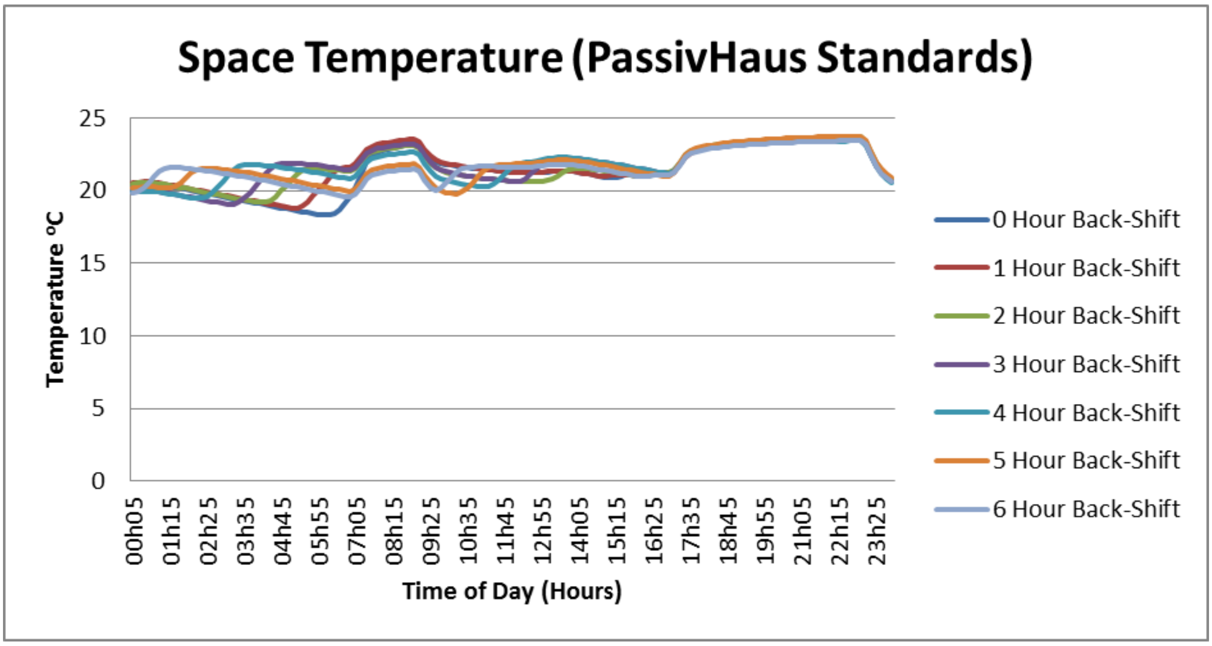
Wall Hung Radiators (PassivHaus Standards Model)



Underfloor heating (average standards model)

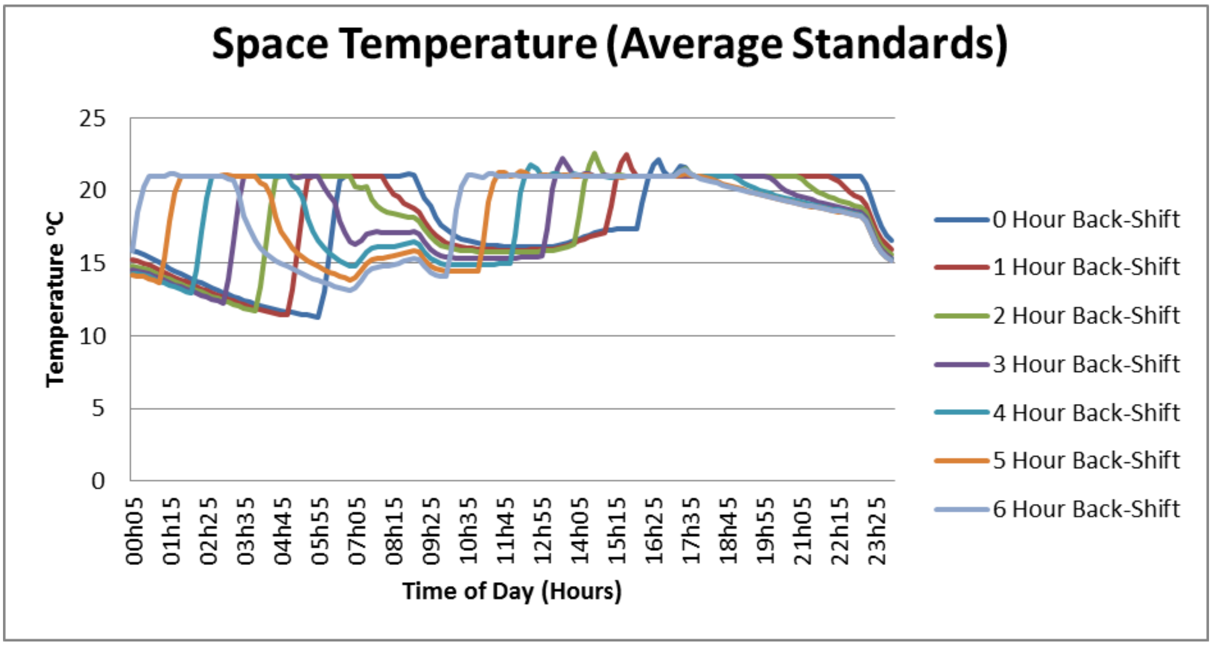


Underfloor heating (2010 standards model)

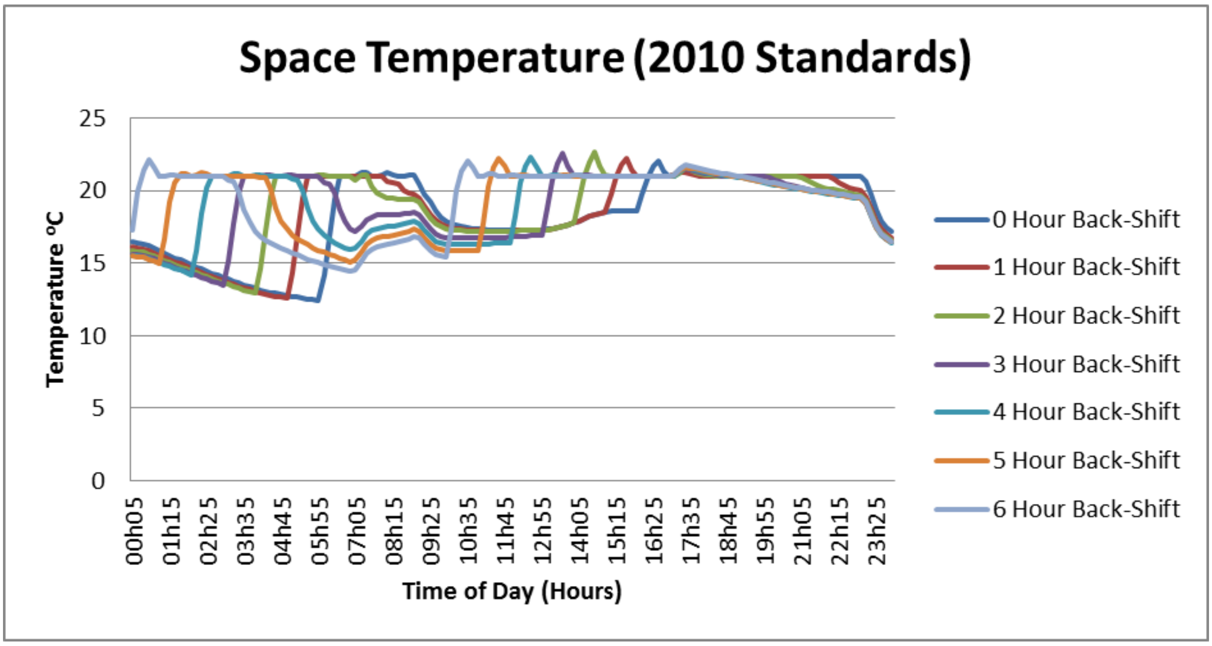


Underfloor heating (PassivHaus standards model)

2. Graphs From Spring Simulations

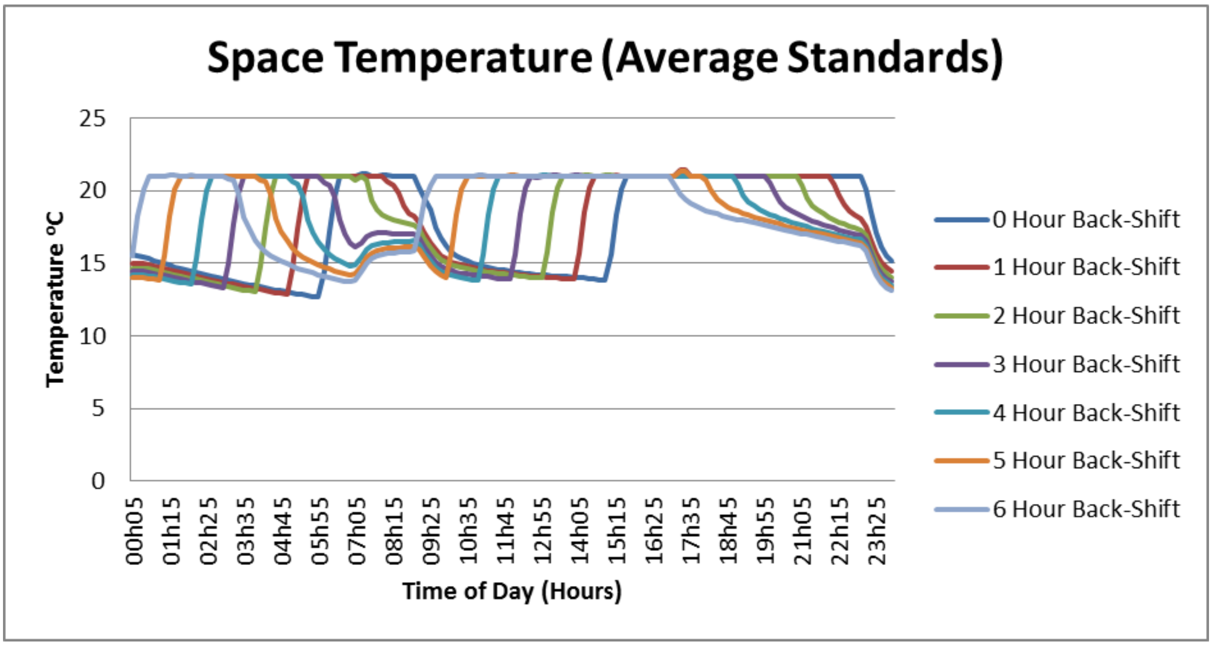


Wall hung Radiators (Average Standards Model)

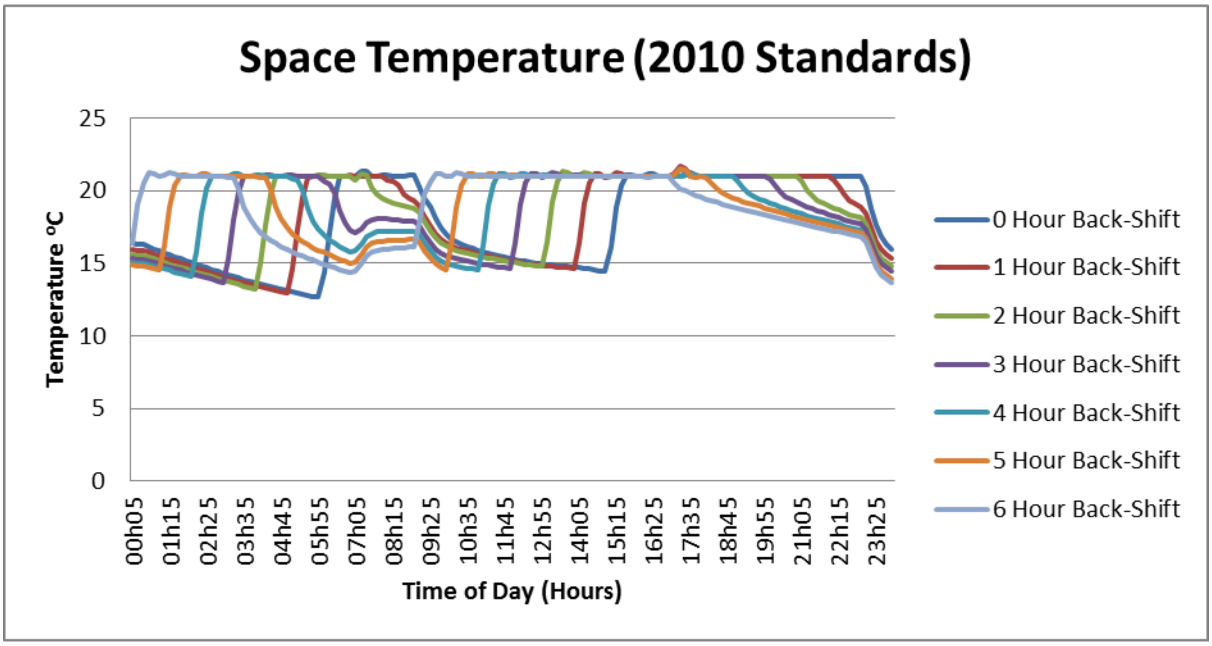


Wall hung radiators (2010 standards model)

3. Graphs From Autumn Simulations



Wall-hung radiators (average standards model)



Wall-hung radiators (2010 standards model)

L. Appendix B

1. Tables From Winter Simulations

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	20.97	20.87	20.53	20.12	19.75	19.28	18.87
Maximum Temperature	21.05	21.15	21.24	21.06	20.98	21.18	21.42
Minimum Temperature	19.62	17.63	14.46	13.33	12.68	11.99	11.45
% Hours Below 18^{o}C	0	0.2	6.4	15.2	22.4	31	36.7

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	18.53	18.26	17.95	17.62	17.29	17.04
Maximum Temperature	21.17	21.14	21.2	21.33	21.09	21.09
Minimum Temperature	10.6	9.85	9.27	8.79	8.4	8.06
% Hours Below 18^{o}C	41.2	44.8	49.5	53.8	58.3	61.9

Results from the Average Model for wall-hung radiators

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	20.98	20.91	20.65	20.35	20.07	19.62	19.34
Maximum Temperature	21.26	21.27	21.38	21.32	21.42	21.2	21.16
Minimum Temperature	19.98	18.46	15.97	14.95	14.3	12.8	12.12
% Hours Below 18^{o}C	0	0	3.1	8.8	15	23.6	26

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	19.13	18.91	18.68	18.48	18.19	17.92
Maximum Temperature	21.2	21.23	21.18	21.12	21.19	21.16
Minimum Temperature	11.51	10.95	10.36	9.81	9.3	8.82
% Hours Below 18^{o}C	28.7	31.3	34	36.4	41.1	46.9

Results from the 2010 Model for wall-hung radiators

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	20.45	20.7	20.8	20.89	20.85	20.79	20.69
Maximum Temperature	21.9	22.14	22.27	22.3	22.06	22.17	22.36
Minimum Temperature	13.98	14.85	15.69	16.49	17.4	17.21	17.01
% Hours Below 18°C	8.1	4	1.9	1.2	1.4	2.9	3.6

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	20.57	20.45	20.45	20.46	20.41	20.33
Maximum Temperature	22.27	22.12	22.27	22.27	22.34	22.24
Minimum Temperature	16.39	15.79	15.43	15.06	14.71	14.6
% Hours Below 18°C	4.8	5.2	6	9	15.8	16.9

Results from the Average Model for underfloor heating

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	20.93	21.19	21.36	21.35	21.37	21.35	21.32
Maximum Temperature	22.57	22.54	22.63	22.78	22.71	22.49	22.72
Minimum Temperature	14.31	15.52	16.49	17.67	18.4	18.79	18.45
% Hours Below 18°C	5.2	2.1	0.7	0.2	0	0	0

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	21.19	21.2	21.15	21.09	21.07	20.91
Maximum Temperature	22.57	22.63	22.78	22.77	22.73	22.73
Minimum Temperature	18.14	17.8	17.45	16.97	16.12	16.68
% Hours Below 18°C	0	0.2	0.5	2.9	3.5	4.2

Results from the 2010 Model for underfloor heating

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	23.45	23.72	23.83	23.74	23.63	23.5	23.49
Maximum Temperature	25.86	26.2	26.46	26.31	26.22	26.09	26.06
Minimum Temperature	20.23	21.28	21.23	21.25	21.2	21.2	21.17
% Hours Below 18°C	0	0	0	0	0	0	0

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	23.42	23.37	23.39	23.31	23.26	23.24
Maximum Temperature	25.98	26.08	25.95	25.81	25.75	25.78
Minimum Temperature	20.95	20.74	20.56	20.09	19.85	19.72
% Hours Below 18°C	0	0	0	0	0	0

Results from the PassivHaus Model for underfloor heating

2. Tables From Spring Simulations

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	21	20.95	20.8	20.6	20.41	20.15	19.95
Maximum Temperature	21.54	21.51	21.57	21.73	21.5	21.56	21.62
Minimum Temperature	20.95	19.68	18.57	18.08	17.74	17.04	15.33
% Hours Below 18°C	0	0	0	0	1.7	9.3	13.3

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	19.8	19.65	19.56	19.49	19.41	19.3
Maximum Temperature	21.73	21.52	21.52	21.62	21.73	21.55
Minimum Temperature	14.51	14.02	13.68	13.41	12.93	12.44
% Hours Below 18°C	15.7	16.1	16.7	16.9	17.1	17.6

Results from the average model for wall-hung radiators

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	21.16	21.13	21.05	20.93	20.82	20.6	20.45
Maximum Temperature	22.96	23.07	23.16	23.24	23.31	23.37	23.42
Minimum Temperature	20.95	19.78	19.04	18.79	18.55	17.44	15.96
% Hours Below 18°C	0	0	0	0	0	2.1	6.1

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	20.33	20.24	20.17	20.11	20.08	20.04
Maximum Temperature	23.46	23.49	23.53	23.56	23.6	23.63
Minimum Temperature	15.22	14.64	14.12	13.71	13.17	12.71
% Hours Below 18°C	11.4	12.9	13.6	14	14.3	14.3

Results from the 2010 model for wall-hung radiators

3. Tables From Autumn Simulations

Back-Shift	0	0.5	1	1.5	2	2.5	3
Mean Space Temperature	20.98	20.91	20.65	20.34	20.06	19.72	19.41
Maximum Temperature	21.14	21.24	21.45	21.51	21.01	21.3	21.41
Minimum Temperature	20.95	18.82	16.71	15.98	15.63	15.12	14.42
% Hours Below 18°C	0	0	3.1	10.2	15.7	25.7	31.2

Back-Shift	3.5	4	4.5	5	5.5	6
Mean Space Temperature	19.12	18.88	18.68	18.46	18.19	17.98
Maximum Temperature	21.46	21.02	21.24	21.93	21.46	21.01
Minimum Temperature	13.52	12.97	12.54	12.2	11.68	11.09
% Hours Below 18°C	36.2	40	42.6	47.1	51.7	54.8

Results from the average model for wall-hung radiators

Back-Shift	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**
Mean Space Temperature	20.99	20.94	20.76	20.54	20.34	20.03	19.77
Maximum Temperature	21.31	21.28	21.67	21.76	21.14	21.36	21.56
Minimum Temperature	20.96	19.53	18.3	17.1	16.76	16.14	15.41
% Hours Below 18°C	0	0	0	1.9	4	11.2	20

Back-Shift	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**
Mean Space Temperature	19.52	19.3	19.1	18.9	18.67	18.47
Maximum Temperature	21.69	21.11	21.4	21.55	21.65	21.11
Minimum Temperature	14.59	13.94	13.4	12.93	12.3	11.53
% Hours Below 18°C	25	28.1	31	33.3	36.4	39.3

Results from the 2010 model for wall-hung radiators