Department of Mechanical and Aerospace Engineering

Analysis of Potential Building Retrofits to Accommodate the Shift to Low Temperature Heating

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Abstract

The built environment is estimated to consume over 30% of global energy. Consequently, there has been a rise in the focus and uptake of energy efficient and sustainable technology in the building sector. Space heating in a significant energy usage so energy reduction methods here are particularly important. One such technology is using low temperatures for space heating.

With improvements in low temperature supply and distribution technology, there is increased focus on these types of system. With a large portion of existing buildings still expected to be in use for many decades, the challenge is to find a way to effectively implement low temperature heating systems into current buildings. This report focuses on low temperature heating technology and its place in current and future of space heating systems. Particular focus has been on the current housing stock and what systems can be realistically retrofitted into existing buildings. The aim of this project is to find and propose a suitable route for retrofitting current housing to allow for use of low temperature heating systems. The dynamic simulation tool ESP-r was used to test a range of systems and control schemes for a base construction.

Results showed that if installed correctly LTH systems with fabric upgrades and better control can effectively replace conventional high temperature space heating systems, with varying success. However, some systems provide greater challenges when retrofitting. The underfloor heating system gave very consistent temperature throughout the day, therefore would be suitable for zones with variable occupancy periods. The very low temperature here gives the best COP of all the systems in this study, however from the literature underfloor heating systems can be challenging and expensive to retrofit. Ceiling heating panels are easier to retrofit than underfloor heating systems, and have better reaction times and thermal comfort. Although the energy efficiency is reduced. The wall panel gives a good balance between the other two systems, giving similar thermal comfort to the ceiling panel without sacrificing energy efficiency. Wall heating panels are possibly the easiest to install of all three in an existing building. The results were promising, they showed that low temperature heating systems can be implemented into existing buildings with significant energy saving and improved thermal comfort.

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Firstly, I would to like to extend my thanks and gratitude to my supervisor, Dr Daniel Costola, for his encouragement and continued support throughout this project. The weekly meeting greatly helped me to stay on track and move forward with my project at a suitable pace.

I would also like to thank my lecturers over the past year, who have helped to provide the knowledge required to complete this dissertation and more.

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Contents

List of Figures

List of Tables

Acronyms

EU - European Union

EPBD - Energy Performance of Buildings Directive

EED - Energy Efficiency Directive

LTH - Low Temperature Heating

LT - Low Temperature

EPC - Energy Performance Certificate

DH - District heating

CHP - Combined Heat and Power

RHI - Renewable Heat Incentives

IAQ - Indoor Air Quality

OECD - Organisation for Economic Co-operation and Development

UFH - Underfloor Heating

BIM - Building Information Modelling

COP- Coefficient of Performance

DHW - Domestic Hot Water

ASHP - Air Source Heat Pump

GSHP - Ground Source Heat Pump

HVAC - Heating ventilation and air conditioning

1 Introduction

1.1 Problem Definition

It is widely accepted that the built environment is responsible for the largest energy consumption in the market (IEA, 2013). It is estimated to consume over 30% of global energy and half of global electricity usage. Consequently, buildings are responsible for over one-third of global greenhouse gas emissions (Gourlis & Kovacic, 2017). With population expected to increase further the energy usage in the building field is projected to increase accordingly. Therefore, implementation of energy efficient and sustainable technology in the building sector will be crucial to limiting worldwide energy consumption and carbon emissions (Khaddaj & Srour, 2016). These problems have promoted the development of more policies to better energy efficiency in buildings. In the European Union (EU) the central policies are the 2010 Energy Performance of Buildings Directive (EPBD) and the 2012 Energy Efficiency Directive (EED). The EPBD has recently been amended and revisions will came into force on 9th July 2018 (Europa, 2018a). There are numerous approaches taken to improve building energy efficiency, one that has seen an increase in the last few decades is employing lower temperatures for space heating (Wang, Ploskić, & Holmberg, 2015).

With technological improvements in building construction and energy supply, there are many exciting developments in this field that can be studied. One promising change is the increase in low temperature heating (LTH) systems (Schmidt et al., 2017), with advancements in more efficient heating systems and a greater uptake of district heating (DH) systems that use sustainable sources of energy (Biomass, waste heat, CHP). One reason for increased application of LTH systems is the progression of district heating systems to Lower 4th generation temperatures (<50-60˚C) (Lund et al., 2014). Another factor that has contributed to this shift is the continuous improvement of insulation in our homes (IEA, 2013). Heat pumps have also seen a rise in popularity, and similarly to DH there are currently renewable heat incentives (RHI) for these systems to encourage interest. Heat pumps are suitable in this field as they are generally more efficient at lower temperatures.

Using LTH for central heating would reduce distribution temperatures from 75-85˚C to 35-55˚C. This has benefits to the occupiers for example, heating in a more constant and even manner compared to conventional high temperature central heating improves thermal comfort (Vasco, 2015). The energy required is also decreased so greenhouse gas emissions are reduced and therefore lessens the impact on the environment. Likewise, the operational costs are reduced. One notable drawback is that LTH systems are not suitable for spaces which are required to heat up quickly or intermittently (BRE, 2014). LTH systems can also be challenging to implement in existing buildings.

The major barriers currently standing in the way of operating heating systems at lower temperatures is that it requires specialist heating systems and a certain standard of insulation. This is where the challenges become evident. Much of the UK housing stock employs standard high temperature heating systems that would require extensive upgrades to be effective operating at low temperatures (Department of Energy and Climate Change, 2012). The same applies to the insulation in many buildings. These upgrades would include a new heat source (e.g. condensing boiler, heat pump) (Carbon Trust, 2012) and a new distribution network with a large area (e.g. underfloor heaters, wall heaters, air-air heat pump).

This project will focus predominantly on hydronic heat distribution units. There are a range of different systems that can be used for LTH heat distribution, such as specialised LT radiators with large surface areas, LT convectors and wall, ceiling or underfloor heating. There are also some situations where two of these systems can be combined. All of these systems if used with low temperatures should reduce heating bills, though aside from this these systems each have their advantages and disadvantages. Underfloor heating (UFH) systems are completely hidden so improve the aesthetics and also improve the indoor air quality (IAQ). However, it can be difficult to retrofit in existing homes and is more suited to new buildings, and UFH can take longer to heat up. LT radiators or radiant panels are more suited for retrofitting to current buildings and radiant panels have a quick response compared to other heating technology, because individual panels can be controlled for each room. (Energy.gov, 2017)

So, the problem to be solved is finding an effective way to have a mass transition to LTH systems by retrofitting current homes with suitable systems. BRE discovered in the preparation of their guide to designing LTH systems that there is no generally accepted and understood design method for many LT heating systems. (Young, Shiret, Hayton, & Griffiths, 2013).

1.2 Aims

The aim of this project is to find and propose a suitable route for retrofitting current housing to allow for use of LTH systems, and to investigate current and emerging technologies to identify which system configurations have potential to be most effective. A dynamic simulation tool will be used to test a range of LTH systems and control schemes for a base building. This should provide an accurate projection of the energy consumption compared to national calculation methods often used in industry, which can be too simplistic for detailed analysis. By the end of the project it is hoped that a suitable LTH system configuration that is effective when applied to a current generic domestic UK house can be identified. This will be a system that can realistically be mass retrofitted to adapt the UK housing stock to low temperature distribution.

1.3 Objectives

The objectives below have been identified to achieve the aims stated previously:

- Investigate current and future LTH technologies to understand the trends of this sector, and identify appropriate components to use in this project, by reviewing current literature
- Perform an analysis the UK housing stock to identify what building retrofits are required to allow for LTH implementation
- Use suitable software to model and test a range of possible LTH system configurations and building upgrades
- Collect and analyse data from modelling to evaluate the model's accuracy and recommend appropriate retrofits for current buildings, and designs for new built housing
- Discuss areas for future work and research, to improve the project

1.4 Overview of Methodology

The methodology of this project should allow for the objectives to be successfully achieved. More detailed information can be found on the methods in the corresponding segments. Figure 1 shows a diagram of the overall methodology of the project.

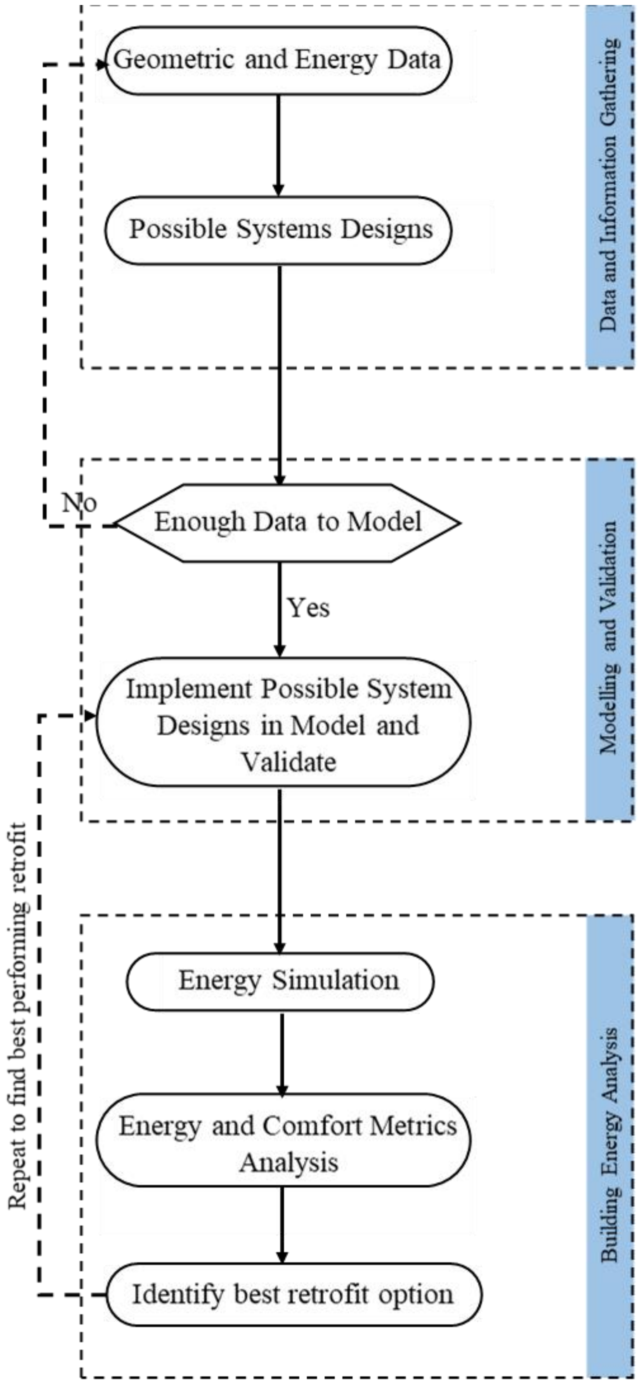

Figure 1: Overview of Methodology

This project will include both research carried out quantitatively and qualitatively. The first stage will be carrying out an in-depth literature review. Data will be collected from a range of sources. Firstly, the university library can provide access to online public access catalogues, valuable databases and relevant scientific journals found on sources such as Science Direct. This section will be focused on developing knowledge of LTH systems, retrofit possibilities and current state of housing stock relating to insulation and heating systems.

Once an in-depth knowledge of the topic is gained, critical analysis can be carried out. The focus here will be to devise possible retrofit options to convert to LTH systems. Next using a building energy simulation program, different solutions will be tested and a conclusion will be drawn as to the best route of action. A quick look at software that is typically used in similar cases gave three possibilities, ESP-r, EnergyPlus and the IDA Indoor Climate and Energy (ICE) tool. The ICE tool seemed to be used in many scientific journal (Georges, Håheim, & Alonso, 2017), however as it is a commercial program it could prove difficult to gain access to. ESP-r and EnergyPlus are both free and open source so they seem to be most suitable, additionally in house support is also available for ESP-r.

Finally, the data collected will be analysed with reference to similar studies allowing comparison to develop an understanding of how realistic the data is. An in depth of discussion of the results will be completed to allow for a conclusion to be drawn from the project, and any future recommendations.

1.5 Structure of Dissertation

The first part of this project outlines the motivation to investigate this subject area, why it will be beneficial and a brief section on the background of LTH systems their importance. The first chapter includes the aims and objectives of the project, these will be executed by carrying out the methodology included in this section. The second chapter will give the reader an in-depth look into LTH systems through a literature review. It also includes previous related work and challenges that may be confronted. A range of other related topics are also explored here including LTDH, Retrofit techniques and investigation of current building stock.

Chapter 3 describes in detail the methodology involved to achieve the aims stated at the beginning. Next the results of the analysis will be presented to show the outcome of the investigation. These results are then discussed in section 4 to draw suitable conclusions, which are presented in section 5. The final sections will discuss future work that could be undertaken and drawbacks of the project as a whole.

2 Literature Review

2.1 Synopsis of Literature Review

In this section the reasons for undertaking the project are established, and relevant and important literature is studied. The review starts in section 2.2 looking at the overall issues in global energy use in buildings, with a particular focus on the state of affairs in the EU and the UK, relevant policies and energy efficiency.

With the motive for the study established, the next sections (2.3, 2.4) review the main focus of study low temperature space heating systems. This includes heat production and supply systems, such as district heating and heat pumps. Suitable LT heat emitters are also investigated through a range of technical and research papers. Finally, sections 2.5 and 2.6 give a brief look in to retrofitting and building information modelling (BIM) respectively.

2.2 Energy use in Buildings

2.2.1 Introduction to Energy Use in Buildings

The search for secure and comfortable living conditions applies to all life forms well before human existence. Early humans succeeded by finding caves and other simple solutions, and over time we have developed the built environment to what we see today. We now have complex building structures that require equally complex systems to maintain at desirable conditions. People now spend the majority of their time in indoor environments, and this has had an effect on the fraction of energy that is devoted to the building sector. Over the last 50 years the energy consumed in the building sector has seen a steady increase, and in 2010 it was estimated to consume 35% of final global energy use. Figure 2 shows the where global energy is used and the building sector mix (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016)(IEA, 2013).

This increased energy use has a detrimental effect. It has resulted in buildings contributing 17% of the direct energy related Carbon Dioxide (CO_2) emissions, and if secondary emissions from other sources are included this percentage rises to 40% (Gourlis & Kovacic, 2017). These emissions are having a damaging effect on our environment and health. With global population expected to continue to rise and undergo demographic transition increasing the population shift from rural to urban environments, this will only lead to more energy use and is expected to lead to a 33% rise globally by 2050 (Sandberg et al., 2016). This will only increase the strain on the planets resources and escalate climate change. Therefore, it is crucial that we take action to improve energy efficiency to achieve any sustainable development policies that have been put in place.

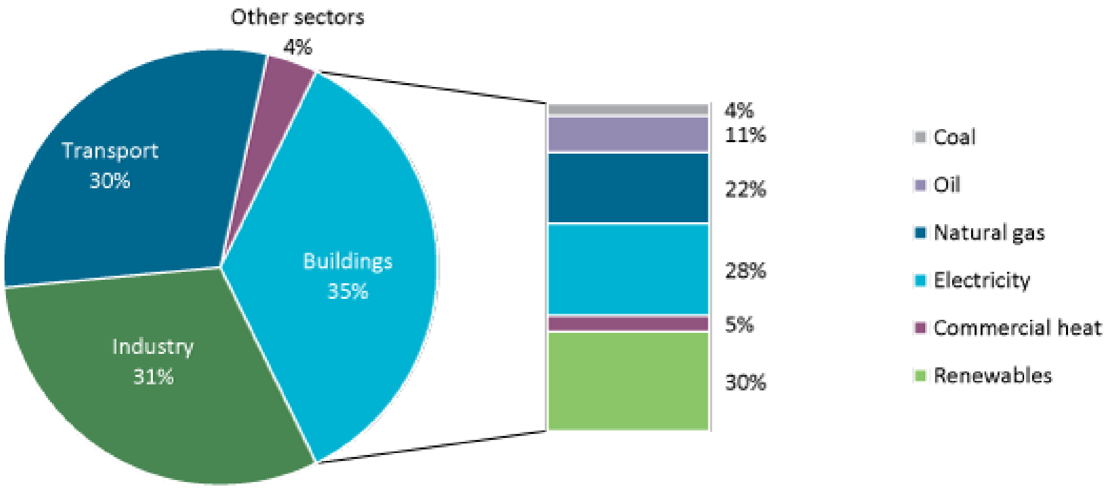

Figure 2: Final energy consumption by sector and buildings energy mix for 2010

There is a huge range of technology available that could be implemented in improving building envelopes in space heating, water heating, cooling, lighting, appliances, etc. One way to narrow down options is to separate residential and commercial buildings. The energy used in these two sectors is 12.8EJ and 6.5EJ for residential and commercial respectively. The final energy use differs as shown in Figures 3 and 4 (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016). It is clear that residential buildings use significantly more energy in space and water heating, and commercial building require more energy for lighting.

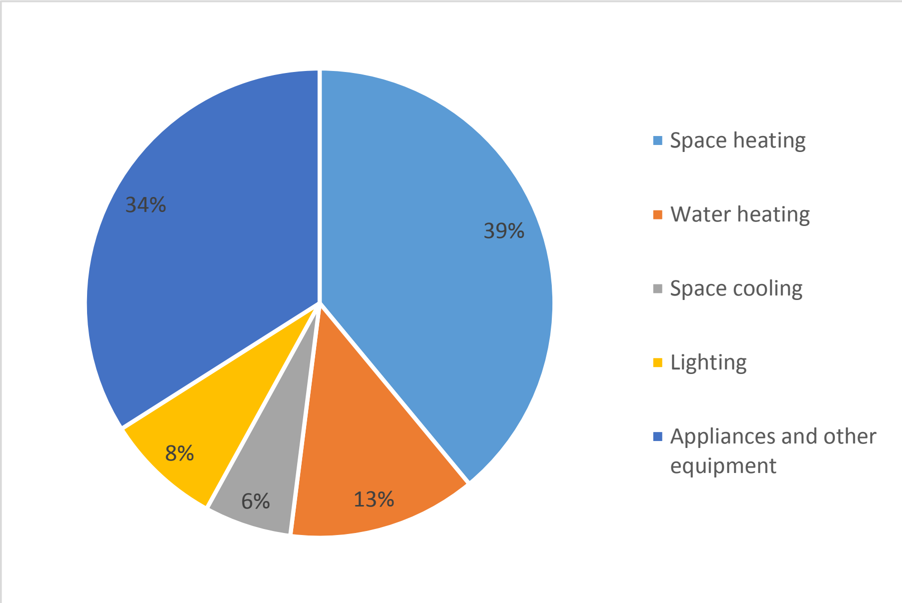

Figure 3: Commercial building energy use

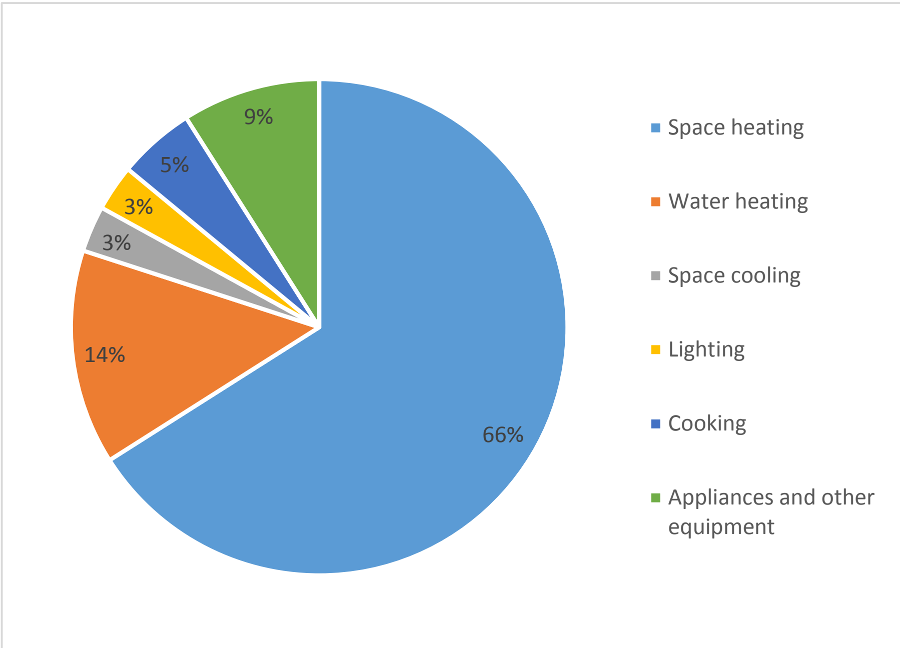

Figure 4: Residential building energy use

In this project the focus will mainly be on residential buildings and space and water heating, where the majority of energy is used, so there is higher potential for significant savings. In the residential sector in 2010 there was an estimated 474 million households for countries in the Organisation for Economic Co-operation and Development (OECD) and 1,412 million households in non-OECD countries. Transitioning to more efficient energy use in buildings will require considerable financial investment. This is estimated to be 19 trillion US dollars over the next 40 years to achieve the 2050 target of 80% decrease in carbon emissions since 1990 (IEA, 2013). It is evident that buildings are a crucial part of reducing global energy use, and action must be taken to improve their energy efficiency to reduce carbon emission and combat climate change.

2.2.2 EU and UK Overview

The EU is one of the biggest energy markets and energy importers globally. Therefore, the trends in the EU building sector will be significant for the whole world. Energy consumption in buildings has increased over the past two decades. However, coal and oil use has decreased and been replaced by a greater uptake in natural gas and renewable energy sources, and in 2010 10% of energy usage in buildings was provided by renewables (Azari & Abbasabadi, 2018). Although this is positive, and there are further plans to improve these numbers energy use in buildings is expected to rise further in the near future. Building stock in the EU is considered to have a high number of outdated and inefficient buildings in areas with substantial space heating needs. So, there is huge potential for large energy reductions by updating building fabric and heating systems. This should be encouraged through policy changes and revised equipment standards (Europa, 2018a).

In 2015 the residential sector in the UK accounted for around 29% of the total final energy consumption, and 23% of CO_2 emissions (Department for Business Energy and Industrial, 2017a)(Department for Business Energy and Industrial, 2017b). Accordingly, the UK government has recognised the need to renovate residential buildings and reduce energy demand if they are to meet their decarbonisation aims. Meeting these targets will require extensive energy

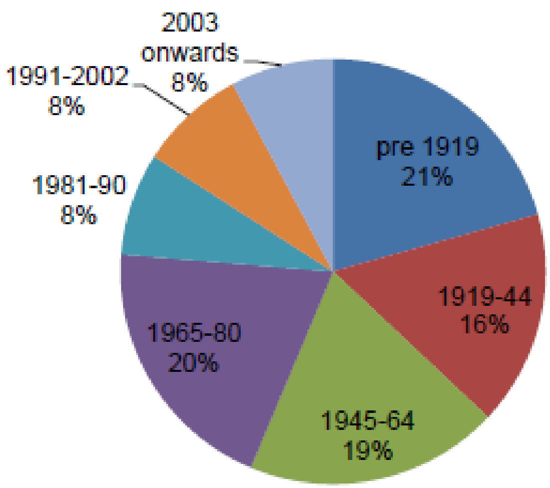

Figure 5: Age profile of domestic housing in England (2015)

performance upgrades as the UK residential housing stock is one of the oldest and least efficient in the EU (Trotta, 2018). There has been a 9% fall in final building energy use in the UK since 2005 but more work is required (DECC, 2014). The UK has about 28 million homes across a wide range of housing types, with a significant portion of older buildings, as shown is Figure 5 (DECC, 2017).This ageing housing stock can also be seen in the Energy Efficiency rating of English housing stock, as shown in Figure 6, also shown is an example of an Energy Performance Certificate (EPC) which all domestic and commercial buildings in the UK available to buy or rent must have (DECC, 2014).

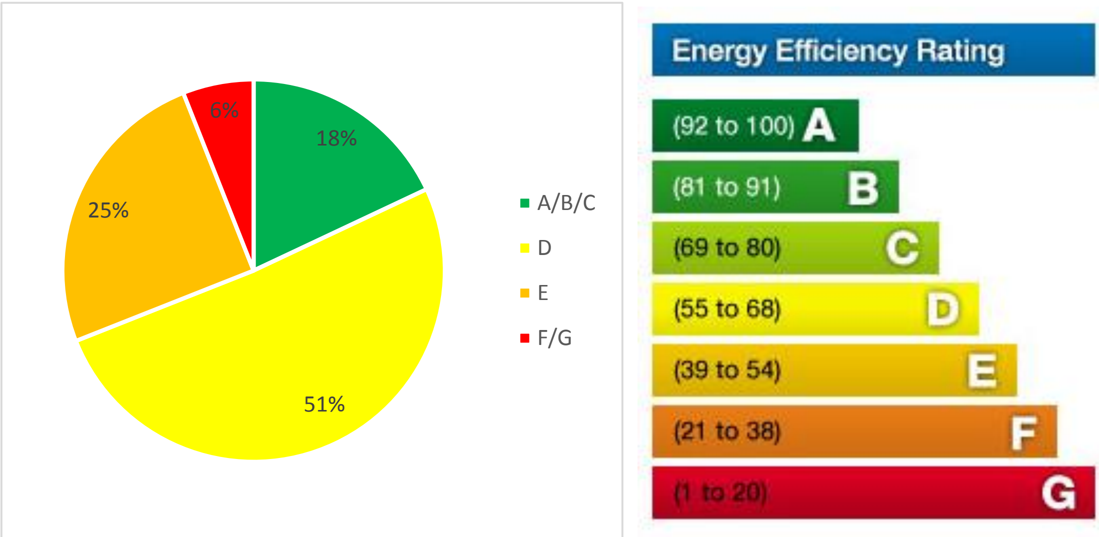

Figure 6: Energy Efficiency rating of English housing stock (2012) and an example energy performance certificate.

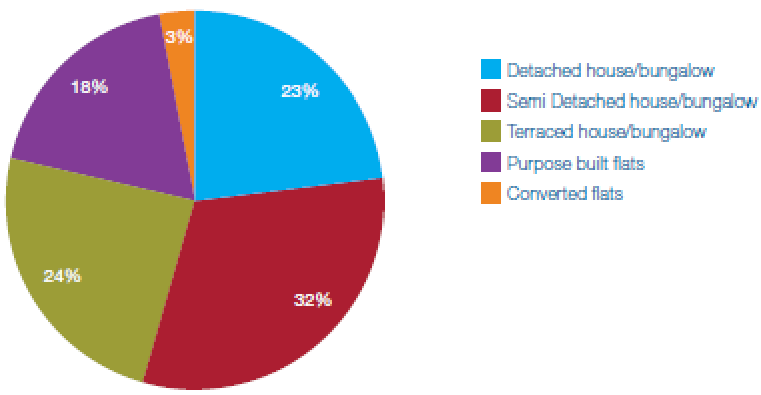

Figure 7: Domestic building categories within UK (2011)

There are a range of different housing types in the UK. Predominantly, these are houses of some form, as seen in Figure 7. However, this can vary across the nation, for example tenement blocks are common in Scotland's cities (DECC, 2014). The UK has taken measure to improve insolation levels in homes, but space heating still consumes 70% of end use energy in domestic homes. So, there is certainly scope to reduce energy used in space heating. In Scotland there are around 2.3 million dwellings, the majority of which are houses (62%) or flats (38%). A 2002 survey identified 94% of dwellings have whole house or partial central heating. Although this is an improvement, and 90% of homes now have loft insulation, only 27% of these meet the 1991 building standards. Therefore for Scotland, the UK and Europe the need to improve housing stock to meet any carbon emission targets is evident (Clarke, Johnstone, Kim, & Tuohy, 2009).

Of the 28 million houses in the UK 19.6 million have cavity wall, 8.5 million have solid walls, and 24.3 million have a loft. Only 69% of properties with cavity wall have insulation, 66% of properties with a loft have loft insulation, and only 9% of solid wall properties have insulation (DBEIS, 2018).

2.2.3 Policies Involving Energy Use in Buildings and Heating

With the need to heavily improve energy efficiency across Europe there has been a rise in international policies targeted at improving building energy performance standards. In 2002 the EU introduced the EPBD to improve energy efficiency in the building sector. The EPBD required all EU members to improve building standards through minimum energy performance requirements, develop a calculation method for energy performance and define EPC rating criteria. The EPBD was updated in 2010 with more stringent building requirements, one of which was to ensure that all new buildings will be nearly zero-energy buildings (ZEB) by the end of 2020. The most recent revision to the EPBD was in June 2018. EU countries must now establish strong long-term renovation strategies, aiming to decarbonise the national building stocks, with a solid financial component by 2050. Smart technology and health and well-being of building users will be promoted, plus EU states must be able to provide their national energy performance requirements and allow for cross-national comparisons (Europa, 2018a)(IEA, 2013).

Another major EU legislative instrument promoting better building energy performance is the 2012 Energy Efficiency directive. This establishes a set of binding measures with reaching the 20% reduction in greenhouse gas emissions from 1990 levels by 2020 target in mind. An update in 2016 included a new 30% energy efficiency target for 2030 (Europa, 2018b). The European Commission have also published An EU Strategy on Heating and Cooling. The main goal is to decarbonise buildings, through renovations in energy efficiency, renewable energy, district heating and use of automation with better control systems.

The UK is fully committed to meeting the 20/20/20 and 2050 sustainability targets set by the EU and the Government has a range of polices to help in achieve this(DBEIS, 2016). The main approaches to energy efficient renovation are:

- making buildings more thermally efficient through better insulation and improved airtightness
- improving the efficiency of heating systems through the use of more efficient boilers, and supporting the transition to lower carbon and renewable energy fuels and technologies
- reducing electricity use through improved energy management systems and technologies, enabled by the introduction of smart meters and more efficient energy services within buildings (DECC, 2014)

One specific example the Government has put in place is licence conditions requiring energy suppliers to take practical steps to roll out smart meters to all domestic homes in the UK by the end of 2020. The smart meters will help consumers manage their energy consumption more effectively. The roll-out is making good progress. At the end of December 2016, there were more than 5.87 million smart meters operational across homes in the UK (DECC, 2017). Developing new policy can be very challenging, with variations in countries or regional political culture, but the outlooks appears to be promising.

2.2.4 Energy Efficiency in Buildings

Improving energy efficiency in building will be vital if any carbon emission targets are to be met. This is a very relevant topic and there are many easily accessible current technologies, along with plenty of accredited research assessing potential routes to sustainable energy use. An energy efficient building should provide the required internal environment and services with minimum energy use in a cost effective and environmentally sensitive manner, without conflicting with thermal comfort (Jones, 2004).

The UK Government has several schemes to encourage energy efficiency improvements. Two popular ones are The Energy Company Obligation (ECO) and Green Deal (GD). Their aim is to encourage the uptake of energy efficiency measures so that the efficiency of the building stock is improved. Between 2013 and 2017 almost 2 million energy efficiency measures have been installed in properties under these schemes (DBEIS, 2018).

Having an energy efficient building requires careful design of both the fabric and systems used. It is also important to have an operation and upgrading plan to ensure the building remains effective. Figure 8 shows an example of a low energy, efficient house. There are a huge range of possible options to improve energy efficiency, this project is focusing on HVAC systems and associated fabric upgrades (e.g. insulation).

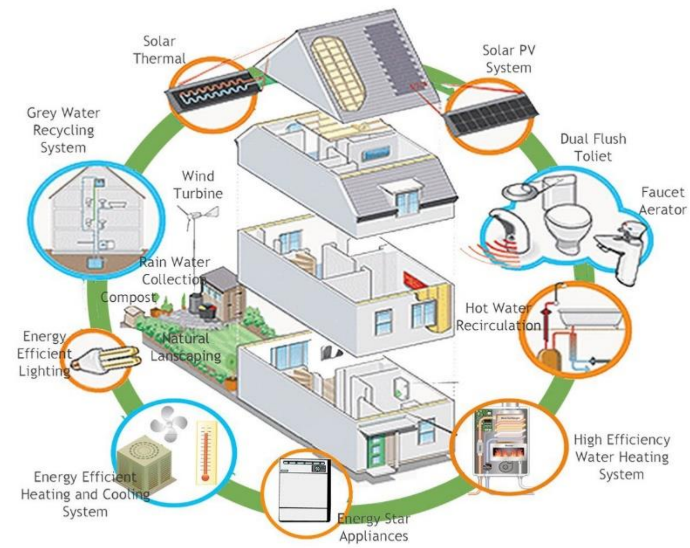

Figure 8: Energy efficient house

2.3 HVAC Systems

2.3.1 HVAC Background

Heating, ventilation and air conditioning (HVAC) is a huge field and covers many systems inside buildings. People have used fire for heating for thousands of years and initially the air flow from the fire provided adequate ventilation. However, with the introduction of central heating systems came the need for separate ventilation, and by the late 1880s general ventilator designs had been developed. Refrigeration also started to become available by the 1880s, but mainly for freezing foods and making ice. It was not till the early 1900s that this technology was used to cool buildings. Modern day HVAC systems can be very advanced and can be found in almost every area of human activity. Currently the main topics of research are indoor air quality, greenhouse gas emissions and energy efficiency/conservation. (McDowell, 2007)

There are seven main processes involved in achieving fill air conditioning: heating, cooling, humidifying, dehumidifying, cleaning, ventilation and air movement. These processes change depending on the conditions of the environment. The comfort of a space can be determined by thermal conditions, air quality, acoustics, lighting, physical and the psychosocial environment (McDowell, 2007). This project is mainly focused on heating systems, with thermal comfort, air quality and energy consumption as indicators of efficiency and comfort.

2.3.2 District Heating

DH has roots that trace back to the Roman Empire, but the first commercial DH system was in 1877 in New York (Bloomquist, 2002). District energy has had a greater uptake in recent years, mainly due to increased awareness in the government's energy strategy plans. For many it is seen as the solution for large scale renewable heating and reducing CO_2 emissions from heating. Looking into the four generations of DH, it is clear that as DH technology has advanced the supply temperature has decreased, as seen in Figure 9 (Lund et al., 2014). With increasing numbers of energy efficient buildings that can manage lower temperatures, lower temperatures are an essential to reduce heat losses in the DH network and remain economically viable (Gudmundsson, Thorsen, & Brand, 2016).

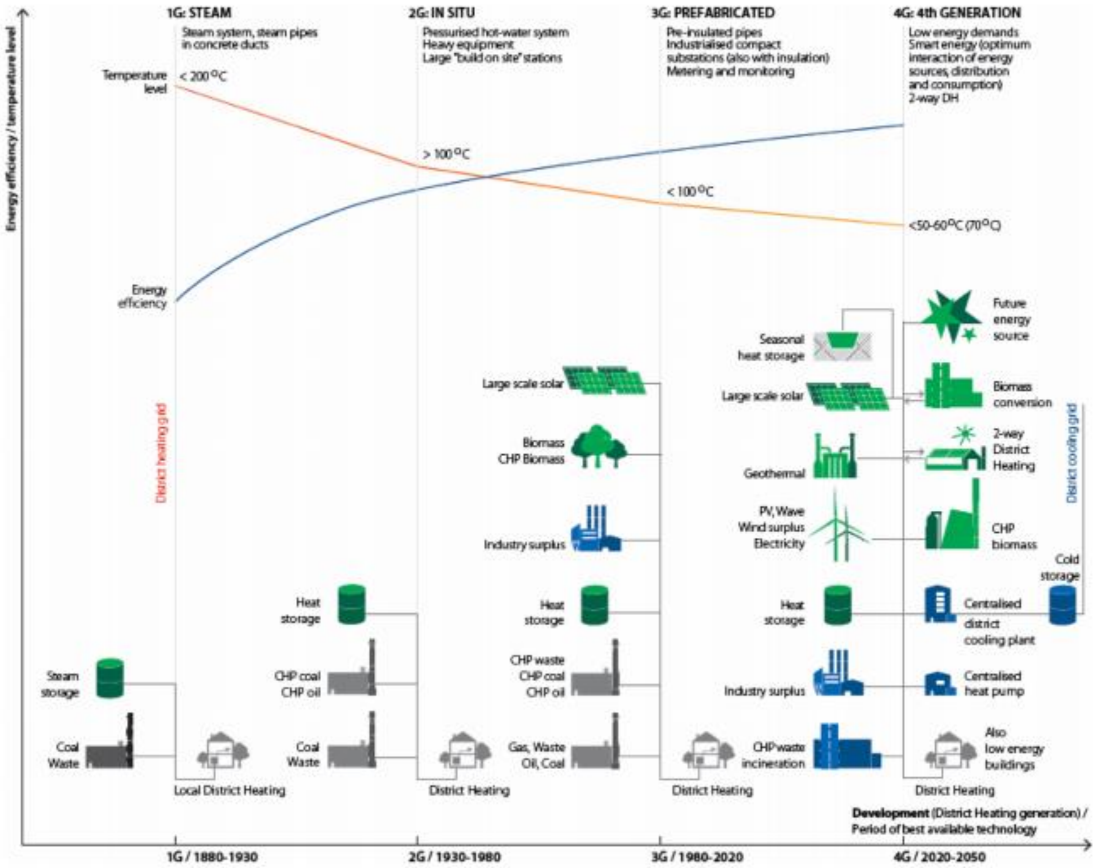

Figure 9: The four generations of district heating

DH comprises of a network of pipes that connect buildings in small community, town or entire city, allowing them all to be provided with heat from a centralised unit or a number of distributed units, as shown in Figure 10 (Schmidt et al., 2017). This allows heat to come from an extensive range of sources (typically low carbon) including:

- waste heat from industrial processes
- renewable sources e.g. heat pumps, biomass, solar, hydrogen
- CHP using conventional fossil fuels
- Energy from waste and anaerobic digestion (DHS, 2018a)

Some of these heat sources do require installation of new generation systems, however others use excess heat that is otherwise going to waste. For example, waste heat and cooling will continue to be produced in industrial processes, and much of this could be reused in nearby buildings. Although the heating and cooling sector is improving by using more clean low carbon energy sources, 75% of fuel used is still fossil fuels (mainly gas) so there is still a need to invest in more clean technology (European commission, 2016). DH systems also often include a thermal store to hold hot water until there is demand.

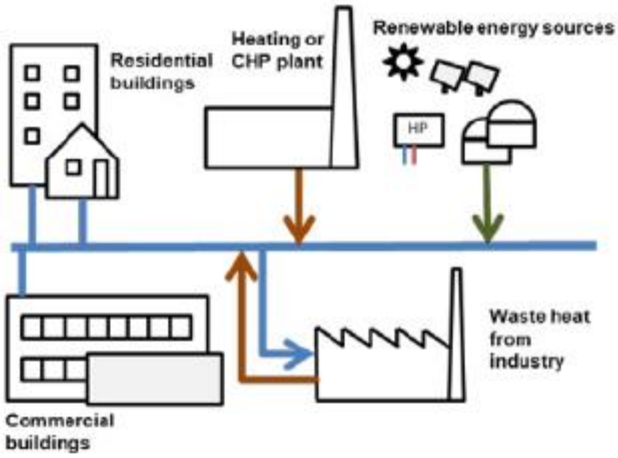

Figure 10: Schematic DH network with multiple supply options

In Scotland, the government provides a range of funding for DH projects with low carbon emissions and renewable technology that can also benefit local communities. A target has been set to provide 40,000 homes with affordable low carbon heating from DH. This is part of an overall plan to provide both domestic and non-domestic buildings with 1.5 TWh of heat through DH by 2020 (DHS, 2018b). Other countries have also seen an

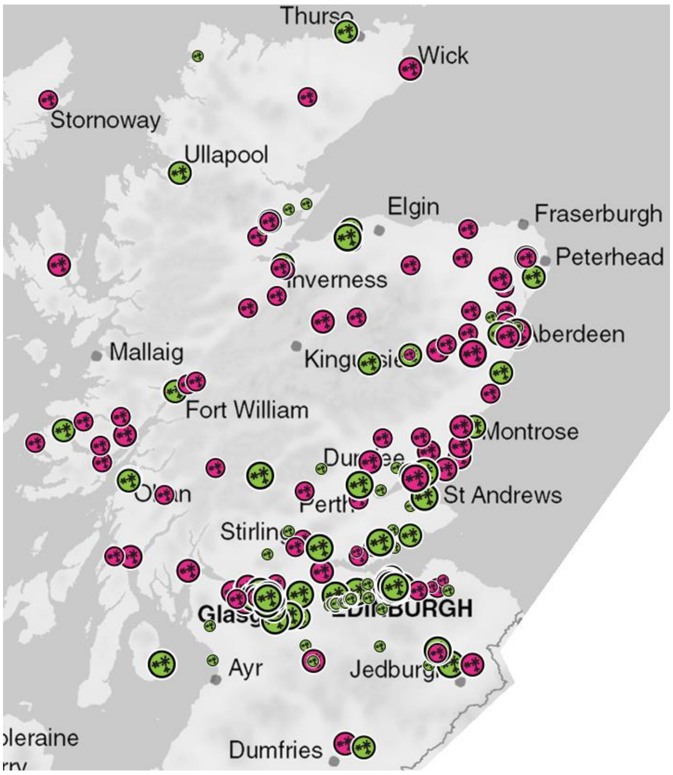

Figure 11: DH networks in Scotland

increase in DH use. In 2012 the penetration of DH into the heating market was around 50% in Scandinavian countries, 15% in Germany and 1-2% in the UK (Xing, Bagdanavicius, Lannon, Pirouti, & Bassett, 2012). DH is gaining traction in Scotland with more projects in planning as shown in Figure 11, where green represents a project in development and red is in operation (gov.scot, 2017).

Future DH infrastructure should be designed to integrate with the electricity and transport sector. This would be referred to as a smart energy system where thermal, electricity and gas grids are combined. A number of recent studies conclude that DH will play an important role in implementation of future sustainable energy systems. But they emphasise that current systems must transition to low temperature systems to interact with low energy buildings (Lund et al., 2014). Low temperatures are used in district heating as supply losses can be reduced considerably. Improving energy performance of buildings makes low temperature DH supply possible (Kaarup Olsen, 2014). Lower supply and return temperatures also gives higher power to heat ratios in steam CHP plants, higher coefficient of performance (COP) for heat pumps, improved utilization of geothermal and industrial low temperature heat sources, and higher heat recovery from flue gas. In order for DH to be part of future energy systems it must be able to:

- Supply heat for space heating and domestic hot water (DHW) to existing buildings, energy renovated buildings and new low energy buildings
- Supply heat with low distribution losses
- Recycle heat from low temperature sources and use renewable heat sources (Lund et al., 2014)

When using low temperature DH for DHW it is important to consider bacteria which can grow in lower temperatures. Temperatures of 50°C and above should be sufficient to eliminate the risk form the legionella bacteria. If temperatures are below 50°C then DHW must be processed before use, for example through an instantaneous heat exchanger (Schmidt et al., 2017).

DH systems in use are increasing across the EU and they now provide approximately 13% of the heat demand in the EU. This has resulted in substantial energy saving. In addition, if supply and return temperatures are reduced from 80°C/40°C to 60°C/30°C an estimated 30% could be saved in heat losses. DH temperature can be lowered further to between 35°C-45°C, this is known as ultra-low temperature district heating (ULTDH). This requires DHW to be heated through a combination of DH and electricity, micro heat pumps or instantaneous electric heaters can be used to raise the temperature further after DH is used (D. Østergaard & Svendsen, 2017).

Scandinavian countries are leading in the DH sector and have many systems in use. One example is a set of seven low energy buildings in Denmark that have been connected to LTDH to reduce distribution losses. They have reduced the distribution temperature to 55°C, reduced pipe dimensions, used twin pipes, installed storage tanks and high heat output heat exchangers. This has resulted in a 75% reduction in energy use compared to a conventional DH system. Another similar project was carried out on 1544 refurbished 1960's houses in Denmark. The energy expected to be saved in this case is 62%. The project has an extra cost of 3.1 million USD and will result in a profit of 4.85 million dollar over the 50 year project lifetime (Nord, Løve Nielsen, Kauko, & Tereshchenko, 2018).

An example of a district heating system in Scotland is biomass boiler that provides heat to 6 high-rise flats and 5 terraces at West Whitlawburn housing cooperative. In a recent group project, it was determined that realistically the distribution temperature could be reduced from the current 85°C to 70°C without any major housing upgrades, and save up to 24% in heat losses. If temperatures were reduced further to 4th generation temperatures of 50°C, heat losses would be reduced by around 50%, however this would require extensive building and system upgrades.

2.3.3 Heat Pumps

Another technology that has gained more traction in the last decade is heat pumps. Heat pumps are also effective for providing low temperature heat, and are sometimes used in DH systems. Heat pumps are devices that provide heat by transferring or 'pumping' heat from a source of heat to another area or heat sink. Heat pumps move heat by absorbing heat from a cold area and moving it to a warm area (against the natural flow of heat from hot to cold). They are often used for space heating through radiators or panel heating, but are also used for DHW and DH. Heat pumps can also be used in reverse to provide space cooling (Renewable Energy Hub, 2018)(Sayegh et al., 2018).

Heat pumps can use air, water or the ground as a heat source. They are energy efficient and use electricity to pump the heat, so don't directly create any emissions. Heat pumps are also part of the UK government's RHI so there is potential for income. Air source heat pumps (ASHP) work in the same way as a fridge, but an ASHP extracts heat from the outside air rather than the inside. Ground source heat pumps (GSHP) circulate water and antifreeze around a loop of pipe. Heat is absorbed by the fluid in the pipe, this heat is then transferred through a heat exchanger to the desired area. The working fluid is converted from liquid to gas in an evaporator and absorbs heat, this gas is then compressed to increase the temperature. When this gas is condensed it releases heat, the liquid is then cooled by expansion so that it can go through the cycle again. This process is shown in Figure 12 (European Commission, 2016) (McDowell, 2007).

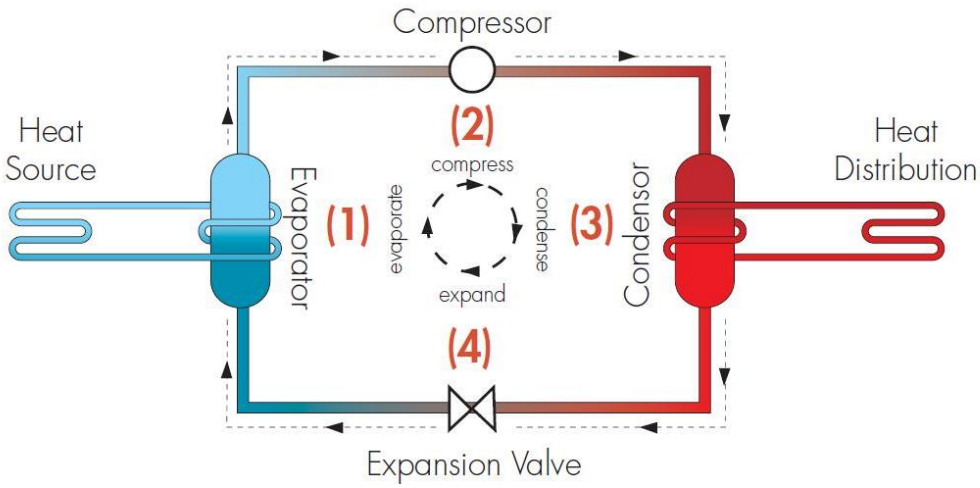

Figure 12: Heat pump cycle

The COP of a heat pump is a ratio of the power used in the compressor to heat that is delivered to the heat sink. To be economically feasible the COP should be greater than 3. The COP decreases as the temperature difference between the heat source and heat sink increases. This is why they are suitable for providing low temperature heat (Sayegh et al., 2018).

2.3.4 Low Temperature Boilers

In connection to a district heating source that is unavailable or undesired, an alternative to heat pumps for in house low temperature heat production is a low temperature boiler. This is most often a condensing boiler. Biomass boilers are also used, though they are typically installed in DH systems to serve larger loads. In traditional boilers the hot gases produced from combustion are passed through a heat exchanger to heat the water and then vented out via a flue. Condensing boilers exploit the latent heat of water by passing the hot gases over a second heat exchanger to condense water vapour in the flue gases. This heat in transferred back into the boiler through the returning water flow, as shown in Figure 13 (IEA, 2013). The gas is then ejected through a flue, which is often fan assisted due to the lack of buoyancy in the cooled combustion gases (CIBSE, 2016) (Brown, 2011).

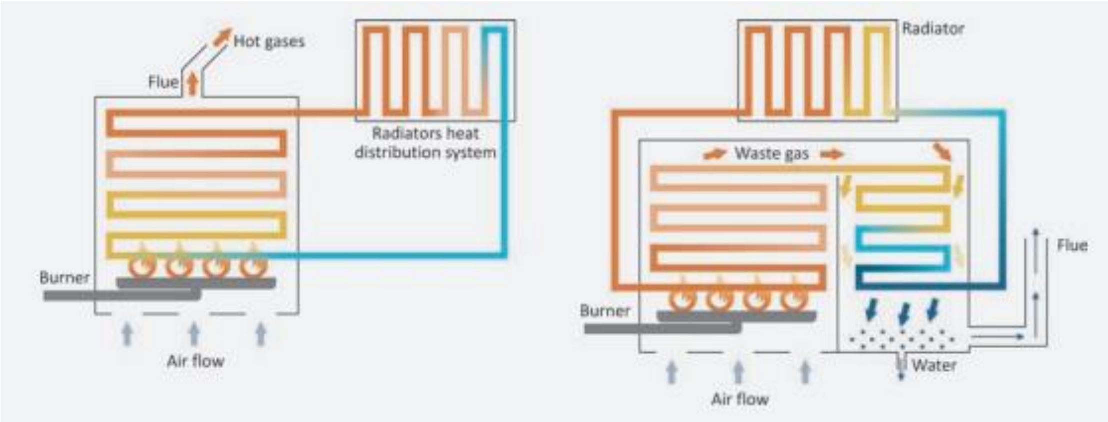

Figure 13: Traditional (left) and condensing boiler (right) flow system

Condensing boilers are suitable for LT systems as lower return temperatures result in greater condensation, and therefore better efficiency. Typical boilers are about 70-84% efficient, compared to condensing boilers which can operate at efficiencies up to 85-95%. Condensing boilers are most often gas fired. This improved efficiency does come at price, as typically condensing boilers are 20-50% more expensive, but their price is expected to lower as popularity increases. The energy saving can also reach 10-20% meaning a payback time of only 2-5 years (Jones, 2004). However, some research has concluded that payback period for the transition from traditional to condensing boilers is similar or longer than the standard lifespan of the boiler. This means that economically it is unappealing without financial support, such as subsidies (Bălănescu & Homutescu, 2018).

2.4 LTH Systems

With space heating loads decreasing in new buildings, due to improved building standard e.g. lower U-values and heat recovery, there has been a greater uptake of low temperate heating systems. Although this is a positive development in space heating and new buildings, it creates an issue for existing building stock that will need to be upgraded (Hasan, Kurnitski, & Jokiranta, 2009).

In traditional central heating systems across Europe the typical supply and return temperatures are 90°C/70°C. LTH improves energy efficiency by lowering supply and return temperatures of heating systems. The lower the temperature the better the efficiency. Recent research has found benefits of operating at supply and return temperatures as low as 35°C/20°C. Typically LTH systems are supplied by LTDH, a heat pump or a LT boiler. There are a range of distribution systems that can be used including specialised LT radiators with large surface areas, LT convectors and wall, ceiling or underfloor heating (D. S. Østergaard & Svendsen, 2016)(Sarbu & Sebarchievici, 2015). Table 1 shows a range of hydronic heating systems and at what temperatures they typically used (Ovchinnikov, Borodiņecs, & Strelets, 2017).

Table 1: Types of hydronic heating systems

System	Supply flow (°C)	Return Flow (°C)	Type of heating
High temperature	Up to 95	Up to 75	Conventional hydronic or baseboard radiator
Medium temperature	55	35-40	LT radiator
Low temperate	45	25-35	Ventilation radiator
Very low temperature	35	25	UF/wall/ceiling heating

LTH has a number of benefits over normal heating systems:

- In a well-insulated home, it is claimed that LTH could reduce energy consumption in homes by 30% (Vasco, 2015)
- LTH provides more evenly distributed heat, so there are less drafts and cold corners
- IAQ is also improved, producing less airborne dust due to weaker air currents
- The radiators are also cooler so are safe to touch and scorch marks from descending dust are avoided (LowEx, 2002)

However, LTH inevitably has some specific requirements and drawbacks. To have an effective LTH system a property must have a good standard of insulation to maintain an even temperature. A suitable heat source must be available, for example DH or another centralised heat source, or a heat source for each building can be installed e.g. a LT (condensing) boiler or a heat pump. Also, the heat must be distributed through a heating element with a large surface area or forced convection. Due to the nature of LTH systems they will take considerably longer to heat a space than conventional high temperate heating. Therefore, LTH requires effective control. These systems can often be more expensive than traditional systems, but with reduced energy bills they should pay for themselves. Finally, although LTH system are simple to integrate into the design of new buildings, it can be challenging and expensive to replace heating systems in existing homes (Young et al., 2013).

There are some studies that suggest existing houses in colder climates have radiators that are designed to accommodate very cold temperatures and are typically oversized. Therefore, they would be able to operate at lower temperatures for large parts of the year with little system and building upgrades (Hasan et al., 2009)(Gudmundsson et al., 2016). In modern and renovated houses, LTH is found to provide good thermal comfort and reduce energy consumption significantly compared to traditional systems in a number of studies (Ovchinnikov et al., 2017).

A radiators heat output P (W) can be calculated using the following equations:

$$(1)\ P = k.A.\Delta\theta_{lmtd}^{n},$$

$$(2)\ \Delta\theta_{lmtd} = \frac{\theta_{water,in} - \theta_{water,out}}{\ln(\frac{\theta_{water,in} - \theta_{air}}{\theta_{water,out} - \theta_{air}})},$$

$$(3)\ \frac{1}{k} = \frac{1}{\alpha_{ins}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_{out}},$$

Where, A=surface area of the radiator (m^2), k=total heat transfer coefficient (W/m^2K), n=radiator exponent, usually set to 1.3, α_{ins}=heat transfer coefficient between internal water and radiator (W/m^2K), α_{out}=heat transfer coefficient between radiator and air that contains radiative and convective parts (W/m^2K), λ=conductivity (W/mK), δ=radiator wall thickness (m), $\Delta\theta_{lmtd}$=logarithmic mean temperature difference between heated surface and ambient air (°C), θ_{air}=mean room air temperature (°C), $\theta_{water, in}$=water inlet temperature (°C), $\theta_{water, out}$=out water outlet temperature (°C) (Ovchinnikov et al., 2017).

2.4.1 Floor Heating

The floor of a space can be used for space heating or cooling. A floor that uses the floor surface for heating is known as a radiant floor, these are most commonly heated by small diameter plastic pipes. The pipes snake back and forth at even spacing to cover the entire floor area and provide even heating. Insulation beneath the heating elements is very important to avoid heat loss. Heat output from the floor is roughly 50% radiant and 50% convective. Typically, the water is introduced at the perimeter of the room to produce higher temperatures where the greatest heat losses are. According to the ASHRAE Standard 55, the acceptable floor surface temperature for occupant's feet ranges from 19-29°C (Oubenmoh et al., 2018). Higher temperatures are permitted in bathrooms and beneath windows or external walls, where there is higher heat loss. This limits the amount of heat that can be provided to the floor. Therefore, flow temperatures in LTH systems are typically no more than 40°C. This makes LTH ideal for LTDH, heat pumps and condensing boilers. For a room temperature of 20°C in general the maximum heat output is 100 W/m^2 and 175 W/m^2 around the edges (CIBSE, 2016). However, generally 35-75 W/m^2 is sufficient to maintain 20°C internal temperature (WAVIN, 2006).

Although these systems are often more expensive to install, they are economical to run and improve thermal comfort and IAQ. Savings of 30-50% on running costs are often quoted (Brown, 2011). The control is usually through outdoor reset of water temperature and thermostats for each zone. Similar systems are often used outdoors, with antifreeze instead of water, under pavements or driveways in areas that are susceptible to snow and ice (McDowell, 2007).

Floor heating has different heat emission traits compared to radiators. The heat output from the floor is nearly directly proportional to the temperature difference. This leads to a degree of self-regulation, however due to the high thermal mass of the floor the reaction time between changing the heat input to a change in the floor temperature can be slow. Also, underfloor heating doesn't handle cold drafts well. Since the heat output of floor heating is often limited, this may mean that it cannot provide enough heat to balance out a cold draft. Therefore, sometimes floor heating used to provide a base heating load, with the addition of a fast response emitter on colder days. Normally room temperature with floor heating is controlled by modulating the water temperature using a three-port valve connected to a thermostat. During cold weather periods, it is sometimes preferable to operate underfloor heating continuously (CIBSE, 2016).

The heat output from a floor heating system can be calculated using the following equation:

$$(4)\ \emptyset = 8.92\ (\theta_{fm} - \theta_i)^{1.1}$$

Where, $\emptyset$=heat output per unit area of floor (W/m^2), θ_{fm}=average floor temperature (˚C) and θ_i=room operative temperature (˚C) (CIBSE, 2016).

Floors must be well insulated to reduce downward heat loss for floor heating. The level of insulation required will depend on the floor finish material and if pipes are installed in a screed layer, and how thick this layer is. In general, for the ground floor the resistance value of the insulation should be at least 10 times that of the floor finish. Intermediate floors are normally not required to be insulated by building regulations, but insulation would be required if a UFH systems is used to unsure upward heat flow (Brown, 2011)(Trenell, 2017).

UFH pipes may be embedded within the screed of a solid floor or laid out beneath timber or floating floors. When UFH is installed over a solid floor the insulation is laid over this layer, then the pipework is arranged on top of this. The pipes are then embedded in a layer of screed, to fix them in place. The floor covering can then be laid over this, as seen in Figure 15. In timber floors UFH is installed between floor joists in two possible configurations. Firstly, and most commonly, pipes can be inserted within a preformed metal diffuser plate that is in contact with floor finish to ensure even heat transfer (Figure 14). Secondly, the pipes could be embedded in a lightweight layer of screed on top of insulation between joists (Figure 17). Floating floor UFH is attained by using a rigid layer of insulation that has pre-moulded tracks for the pipes. The floor finish is then laid on top as shown in Figure 16. This configuration benefits from faster response times (Bleicher & Vatal, 2016) (Brown, 2011).

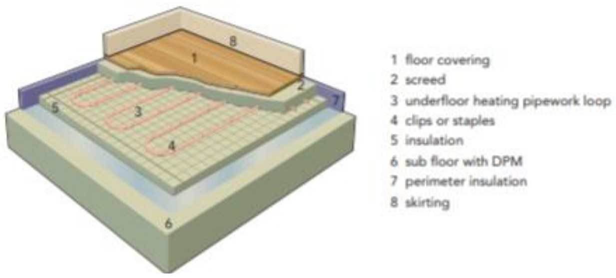

Figure 15: Concrete floor UFH design

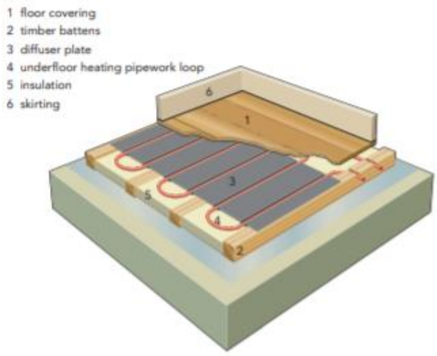

Figure 14: Timber floor UFH design with diffuser plate

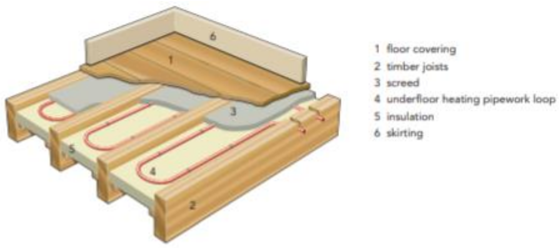

Figure 17: Timber floor UFH design with lightweight screed

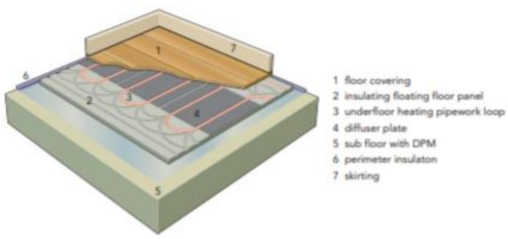

Figure 16: Floating floor UFH design

The pipes can also be laid out in a range of different patterns, as shown in Figure 18 (Bleicher & Vatal, 2016).

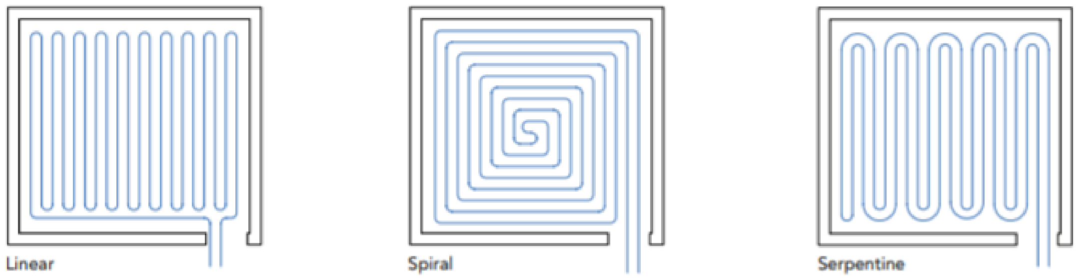

Figure 18: Typical UFH pipework layout patterns

Night set back is a control that is used in UFH. It is an automatic adjustment of the temperature set point at night to reduce the heat input. It is used as an alternative to switching off the heating completely. Optimum start/stop is a function that turns the heating on or off at a set point in time, so that the set temperature is maintained during scheduled operating periods, but no longer than necessary (Brown, 2011).

There has been research into improving UFH systems, specifically into using capillary mats and phase change materials (PCM) as the thermal mass (Thalfeldt & Simson, 2016). One paper investigated the performance of LTUFH with sand and PCM as the heat storage material, and used poly-ethylene (PE) coils and a capillary mat. Results showed that with a capillary mat the vertical temperature profile is more uniform and heats up faster compared to PE coils. PCM were also found to release heat for about 2 times longer than sand when used as the thermal mass (Zhou & He, 2015). Another alternative design that is suitable for retrofit projects is the over floor design. The piping in this design is embedded in a separate wooden flooring placed above the structural slab (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016). In general UFH outperforms regular radiators, but only with extensive fabric retrofits in existing buildings. Extra information on UFH can be found in Appendix C.

2.4.2 Radiant Panel Heating

Radiant heating panels can also be used as heat emitters where there is a low temperature supply. They are often used in ceilings or on walls, and have a lot in common with underfloor heating systems. Radiant panels are typically used for heating and cooling, unlike underfloor heating which is best suited to heating. However, ceiling and wall panels are used for heating, occasionally as stand-alone units but more in conjunction with an air-water system (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016).

Low temperature radiant panels provide heating mainly through radiation (70%), but also through convection (30%). They have a faster response time than floor heating systems, so are more suited to rooms with changing loads. Simple radiant panels can be mounted to the ceiling of a room, similarly to UFH, hot water is distributed through pipes in a serpentine or parallel arrangement. However, pipes are typically copper, and are thermally bonded to a sheet of metal. This is then topped with a layer of insulation to reduced upward heat loss. The panel usually only covers a portion of the ceiling and can also be deployed as a suspended panel, this increases the natural convection. This makes ceiling heating panels a suitable retrofit or renovation option. Ceiling radiant panels are less effective the higher the ceiling, so wall radiant panels can be more suitable for rooms with high ceilings. Compared to UFH systems these radiant panels can utilise higher flow temperatures, up to 69˚C, as there is no direct contact with the occupants. The heating panel temperature should not exceed 46˚C. Although this has benefits mentioned previously, it may result in reduced energy efficiency (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016).

Similarly, to UFH systems control of radiant panels can be challenging because of their large time constant. These systems can suffer from both overheating and under heating, and if there is a rapid change in outdoor temperature these systems struggle to respond quickly. However, with the emergence of smart controls the operation of these systems should improve.

An alternative to traditional radiant panels is to use heating sails. The sails are similar to radiant panels but without the insulation. Pipes are thermally bonded to slats, and are typically suspended from the ceiling or can also be installed along a wall. The air is allowed to flow between gaps in the sail which increases the capacity of the system. This is because he sail generates natural convective flow to supplement the radiative heat transfer (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016).

The radiant heat output per unit area (heat flux) $\dot{q}_{rad}$ for radiant panels can be represented by the Stefan-Boltzmann equation:

$$(5)\ \dot{q}_{rad} = \varepsilon_{eff}.F_{rp-uhs}.\sigma[(T_{rp}+460)^4 - (T_{uhs}+460)^4]$$

Where, T_{rp}=Panel surface temperature (˚F), T_{uhs}=area weighted unheated surface temperature (AUST) (˚F), ε_{eff}= $(1/\varepsilon_{rp}+1/\ \varepsilon_{uhs}-1)^{-1}$= effective emittance of space, where rp in the heated panel and uhs in the unheated surface, ε_{eff} is typically 0.87, F_{rp-uhs}=view factor between the heated and unheated surfaces=1.0, σ=the Stefan-Boltzmann constant=$5.67x10^{-8}$ W/m^2K^4. This equation can be simplified for low temperature heating systems to give:

$$(6)\ \dot{q}_{rad} = 0.15 \times 10^{-8}[(T_{rp}+460)^4 - (AUST+460)^4]$$

For indoor spaces AUST can be taken as the indoor air dry-bulb temperature. This equation can be plotted graphically as shown in Figure 19. For example if AUST=70˚F (21.1˚C) and T_{rp}=110˚F (43.3˚C) then the radiative heat flux in about 40 $Btu/h.ft^2$ ($126W/m^2$) (ASHRAE, 2016)(T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016).

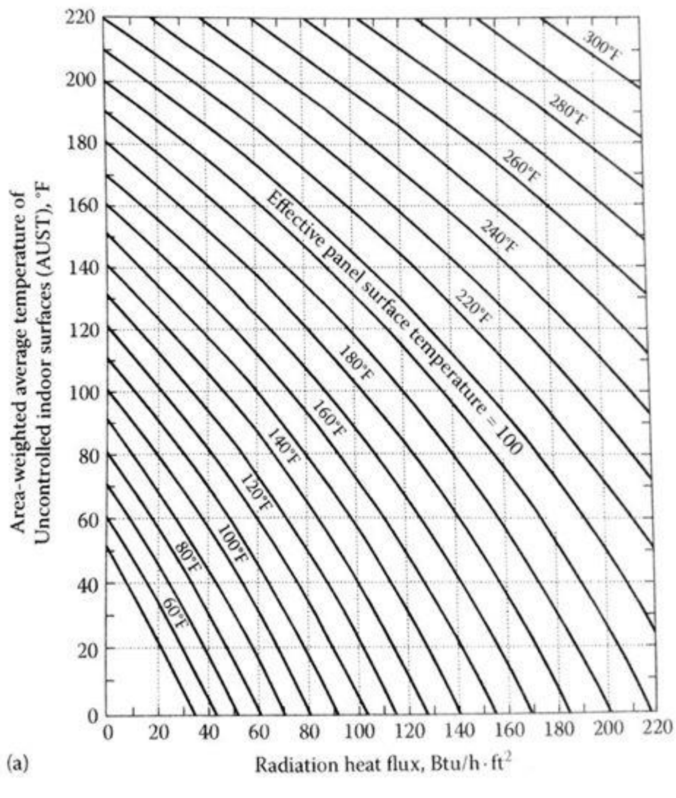

Figure 19: Radiation heat flux plots for ceiling, wall or floor heated panels

The convective heat transfer can be calculated using the equations in Table 2. These equations can then be plotted graphically as shown in Figure 20 (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016)(ASHRAE, 2016).

Table 2: Natural Convection heat flux equations for radiant panels

Type of panel	**Equation (IP units)**	**Equation number**
All-heated ceiling	$\dot{q}_{con} = 0.02.\left(T_{rp} - T\right)^{0.25}(T_{rp} - T)$	(18.5)
Heated ceiling with cold unheated strips	$\dot{q}_{con} = 0.13.\left(T_{rp} - T\right)^{0.25}(T_{rp} - T)$	(18.6)
Floor	$\dot{q}_{con} = 0.31.\left(T_{rp} - T\right)^{0.31}(T_{rp} - T)$	(18.7)
Wall	$\dot{q}_{con} = 0.26.\left(T_{rp} - T\right)^{0.32}(T_{rp} - T)$	(18.8)

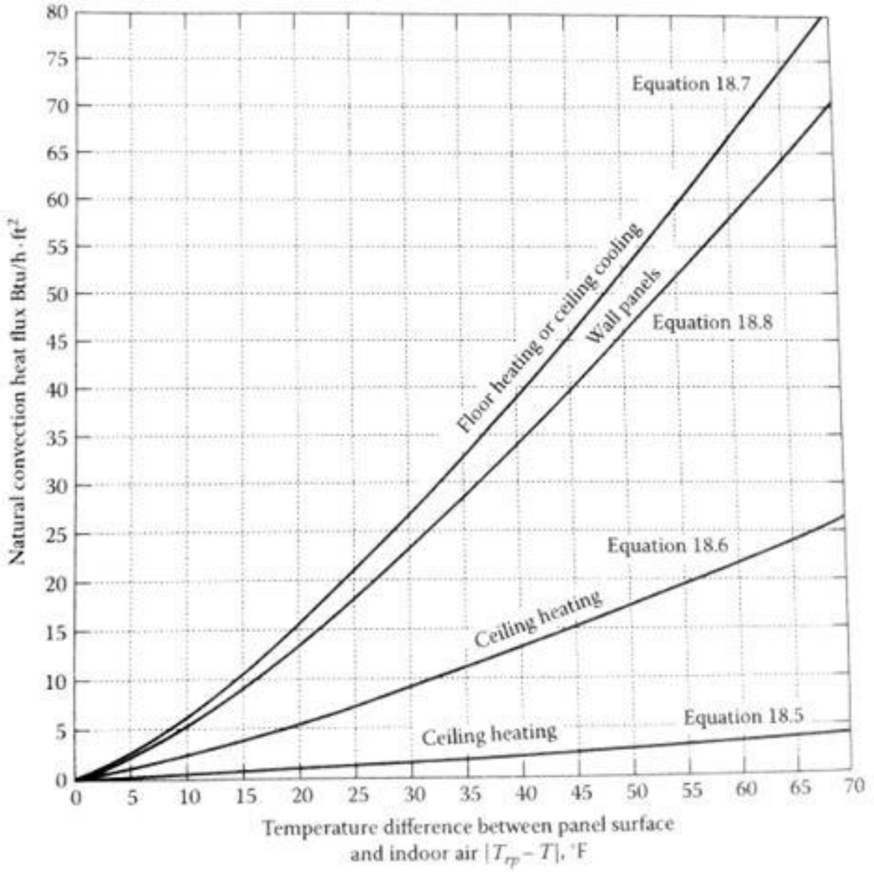

Figure 20: Natural convective heat transfer for floor, ceiling and wall panels

An example of a wall or ceiling heating panel is shown in Figure 21 (Ovchinnikov et al., 2017). Some research that suggests that wall and ceiling heating are better than underfloor heating. It reports that wall heating will result in considerable energy use reduction and better thermal comfort. A study found that stronger air circulation occurs in a room with underfloor heating compared to wall heating, which has a detrimental effect on the comfort. The conclusion was that wall heating should be considered over floor heating as it has better thermal performance and comfort without any limitations (Karabay, Arıcı, & Sandık, 2013).

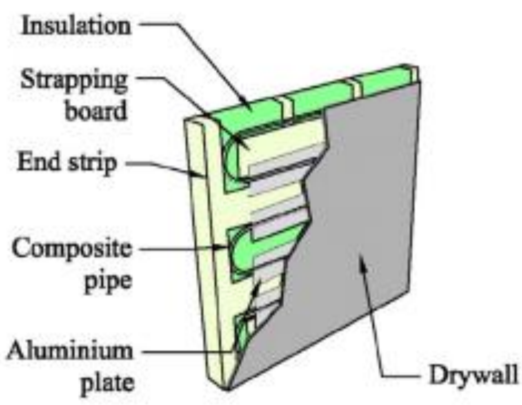

Figure 21: Wall or ceiling heating panel

2.4.3 LT Radiators

The issue with low temperature heating is that the temperature difference is reduced, and although this saves energy in distribution it means that heat transfer is slowed down. Typically, LT emitters either address this by increasing the area or using a forced air flow over the heated surface. This will result in greater radiative or convective heat transfer. LT radiators are no different and generally either have a larger surface area or employ forced convection (CIBSE, 2016). There is evidence of natural convection radiators working effectively at lower temperature but only down to around 55-60˚C minimum. This would also require extensive building upgrades and floor, wall and ceiling heating would likely be a better investment. Therefore, forced convection ventilation radiator are more common (Ovchinnikov et al., 2017).

Ventilation radiators use cold air passed through an inlet in the wall, behind which it is then passed through a channel and over fins and panels where it is heated to a comfortable air temperature. Air movement is accomplished through indoor-outdoor pressure difference and buoyancy forces, or the use of an electric fan. Both radiators work by enhancing convection. This also means that during cold days when the air inlet temperature is low, ventilation radiators will see an increase in heat output at the same supply temperature (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016). Studies have shown that a ventilation radiator operating with supply temperature of 35˚C has the same output as a traditional radiator with supply of 55˚C. For add on fan radiators, fans are placed below or inside the radiator, and they often include a filter. It has been proven that five fans below a radiator can double the heat output compared to conventional radiators. This is a result of the increased convective heat transfer. However, the fans also reduce the radiator surface temperature so the radiative heat transfer is reduced. The fans also only consume a small amount of electricity compared to the resultant increase in heat output. However, the fans can cause a noise problem, so shouldn't be installed in bedrooms. Figure 22 shows an example of both a ventilation and add on fan radiator (Elmegaard, Ommen, Markussen, & Iversen, 2016).

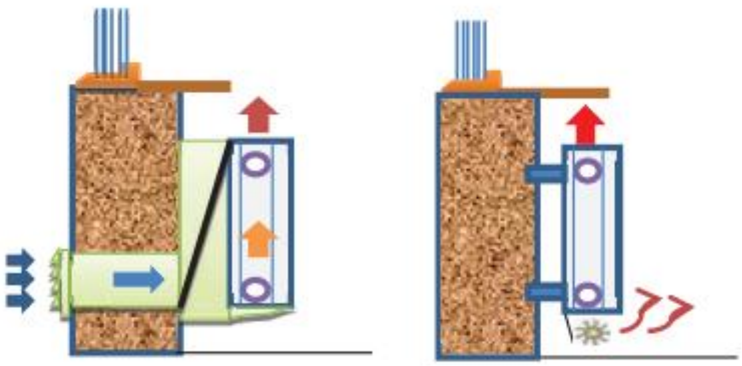

Figure 22: Ventilation radiator (left) and add on fan radiator (right)

Tests have shown that forced convection radiators have the potential to raise the air temperature by up to 30˚C on a cold day. It was also revealed that to ensure energy efficient operation, it is key to have an airtight building. High infiltration will lead to an increase in non-preheated air, this is especially relevant when retrofitting an existing building. These radiators can also be improved significantly through simple solutions, such as high emissivity surfaces on the wall behind the radiator. Forced convection heaters have a faster response time than other LTH emitters and can handle cold drafts better. So, questioners have also shown the occupants felt more comfortable in rooms with ventilation radiators than UFH. However, in terms of environmental impact and energy consumption other LTH systems clearly outperform LT radiators. LT radiators are sometime used in combination with UFH. An example of this could be where UFH provides a base load on the first floor of a house, and LT radiators are used on upper floor to supplement this load when required (Hesaraki & Holmberg, 2013).

2.5 Retrofitting

With buildings currently contributing to large portion of global energy use, and with about 75% of these building expected to still be in service for the next 40 years, upgrading and retrofitting the existing building stock to reduce energy usage will be crucial if we are to meet greenhouse gas emission targets. There have been improvements in successful progressive policies, but there is a need for deep energy renovation to have a meaningful reduction on heating and cooling loads. Many of these policies are a good step forward, however an all-inclusive multi policy approach to ensure building retrofitting must be carried out effectively in the long term and in a suitable manner (IEA, 2013)(Ma, Cooper, Daly, & Ledo, 2012).

The UK Government has taken measures to promote building renovations, and the last 20 years has seen a significant reduction in average domestic energy usage. However, there is still much to do. For example, almost 20 million houses still do not have double glazed windows. Another challenge is that many upgrades are not effective when implemented as a single measure. Heat pumps, for example were identified as having a high energy saving potential, but they only operate efficiently and economically in buildings with high levels of insulation and are airtight. Insulation is one area with potential for improvement. About 30% of properties in the UK with cavity walls have the potential to be insulated, and for solid wall properties the number is about 90%. If 2050 goals are to be reached package measures are required across the UK to bring them up to current new build EPC rating ‘B’. Some suggested measures are shown in Appendix D (DECC, 2014).

The Government has a long-term strategy for improving energy efficiency of the UK’s housing stock. The strategy refers to policies and analysis that have an influence, the main objectives are to make buildings more thermally efficient, improve the efficiency of heating systems and reduce electricity use. The National Planning Policy Framework published in 2012 also supports the transition to a low carbon future. The framework requires local authorities to actively encourage existing building energy retrofits. Figure 23 shows how these policies and incentives work to promote the refurbishment cycle (DECC, 2014). In Scotland, the Scottish Sustainable Housing Strategy sets out the plan for housing renovations. It sets the following targets for 2020:

- Where feasible every home will have loft and cavity wall insulation
- Every home with gas central heating will have an efficient boiler and suitable control
- A minimum of 100,000 houses will be connected to some type of individual or community renewable heat source for space and water heating

The Scottish Government has also invested £79 million in the Home Energy Efficiency Programmes for Scotland (HEEPS), which is a part of the Scottish Sustainable Housing Strategy.

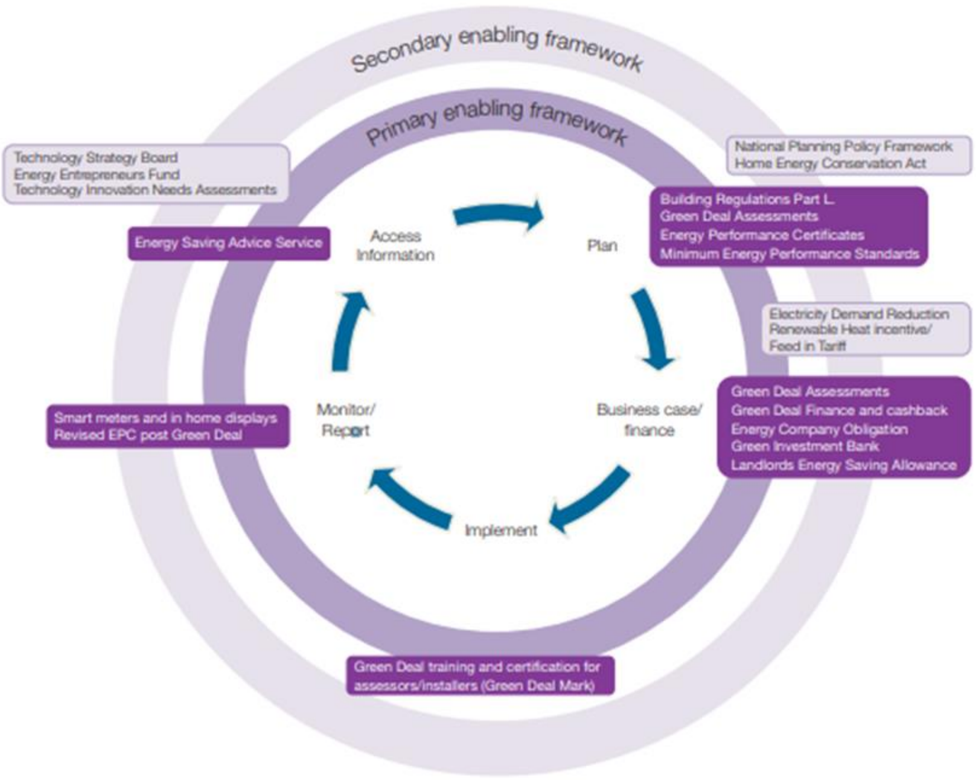

Figure 23: Domestic refurbishment cycle

One country which has realised energy saving through housing renovation is Sweden, with an estimated 17% final energy saving through retrofits in the past decades. However, these often require multiple visits, long installation times and significant impacts to occupants. With aims of carrying out more energy efficient retrofits it is crucial to make this process more efficient. Despite the urgent need for solutions there is a lack of investigation into this technology.

Many studies carried out on LTH systems are based on newly constructed energy efficient buildings. It was found in many cases that if LTH systems are installed in existing homes they can struggle to maintain thermal comfort, and should be installed in conjunction with fabric upgrades (Wang et al., 2015). A study found that when a LTH system was combined with ventilation and air-tightness retrofits, the energy heating demand could be reduced by 41% (Wang & Holmberg, 2015). Another study of a small house from the 1970 showed that a small renovation such as changing to windows with better U-values would allow for DH supply temperature to be lowered from 78 to 67°C, and could be lowered further to 60°C for 98% of the year (Brand & Svendsen, 2013).

A large portion of the UK Housing stock was built before climate change was understood and its links to energy use became apparent. This means that roughly 10.3 million (40%) of homes in the UK are classed as ‘hard to treat’. These are homes with solid walls, no loft to insulate, are high rise or are not connected to the gas network. There has also been an emergence of housing built to low energy performance standards, further complicating the retrofit challenge. It has been estimated that in 2050 four out of five homes that will be occupied have at present been built. Therefore, one house will have to be retrofitted per minute to meet the 80% reduction in greenhouse gas emission by 2050. There has also been a significant decrease in the installation rate of energy efficient retrofits in the English residential sector in recent years. This has made evident the need to reinforce policy that funds households in investments to improve energy efficiency. It is suggested that policies should target household groups that on average have a low renovation uptake (Trotta, 2018).

2.6 Building Information Modelling (BIM)

With global objectives to reduce energy use and carbon emissions, there has been a significant increase activity in the building sector with regards to energy efficiency. Due to ageing housing stocks in many countries much of the focus lies in building modifications and retrofitting on existing buildings. This has stimulated a shift in the use and research in BIM from early life cycle stages (design and construction) to maintenance and refurbishment of buildings in later stages.

BIM is defined as a ‘digital representation of physical and functional characteristics of any built objects which forms a reliable basis for decisions’. Despite this shift, energy retrofitting in existing buildings is still a small topic in BIM, although it is emerging and should only gain more focus in future. The major challenges it faces include automatic data acquisition and model creation, updating and maintaining information, treatment of uncertainty in data and objects in existing buildings, and the multi-disciplinary nature of the topic (Volk, Stengel, & Schultmann, 2014)(Khaddaj & Srour, 2016).

Building energy modelling (BEM) has also gained further attention due to energy reduction in existing buildings. Existing building energy models for short term daily operation modelling can be labelled as white, black or grey box models. White box modelling uses detailed physics based calculations to replicate building constructions, subsystems and systems to predict a buildings behaviour, energy use and indoor comfort. Due to the detailed dynamic equations there is potential to accurately model buildings using white box models, however this can result in length development and simulation periods. Black box models are purely data driven. They use statistical models to depict the relationship between energy use and operation data. These models require on site period data to predict building operation in varying conditions. Black box models are often used to determine building control strategies in existing studies. They are efficient and easy to build, but require long training periods. Grey box models are a hybrid of white and black box models. They use similar, but simplified physics use in white box models. This reduces the training data sets required, but also reduces calculation time (Li & Wen, 2014).

BIM and BEM have a solid place in our future and applications in existing building energy retrofits. Developments in the near future in this field are expected to come in automation of geometric 3D model generation, improvements in model quality verification, development of energy analysis software and advances in data interoperability (Sanhudo et al., 2018).

3 Methods

3.1 Modelling

To evaluate the performance of a range LTH system configurations and their suitability in retrofitting to transfer the current housing stock to energy efficient LT systems, a modelling process was established. The characteristics and all relevant information on the model used can be found in the following section. The main results that are focused upon are thermal comfort, energy delivered and COP. More Information on thermal comfort and COP can be found in Appendix A and B. These results will be compared in various iterations of the model to determine what system is most suitable for application in retrofit in existing homes. The aim of using LTH systems is to reduce overall energy use. However, energy savings will not be realised in the heat input to zones, but rather in the generation and distribution of the heat. This is out with the model used in this project. It is out with the scope and timeframe of this project to calculate energy saving from generation and distribution in DH and other similar low temperature heat sources. So, to allow for energy efficiency comparison between model iterations it is assumed the heat source is a GSHP, so the COP can be calculated and compared.

The software chosen to carry out the modelling and simulation process was the BEM software ESP-r. This was chosen over alternatives, such as Energy plus and IDA ICE, popular in literature. ESP-r was determined as the most suitable due to previous experience using it, its accurate consideration of physics, easy access compared to commercial programs and the access to in house support if any problems were encountered. Although commercial modelling software is available with nicer user interface they often make assumptions around the physics of the system that can prove to be inaccurate. Due to ESP-r's open nature it is also possible to look under the user interface which can give a better understanding of what is happening in the program and why. ESP-r as explained in the literature review is a white box modelling software that uses detailed physics based calculations to replicate building constructions, subsystems and systems to predict a buildings behaviour, energy use and indoor comfort.

3.1.1 Model Characteristics

A simple model of two geometrically identical rooms was created to carryout out the analysis. The rooms have the same construction and were made to accurately represent two standard rooms in a house The model includes a window, door and a glass partition as shown in Figure 24. Room 1 and 2 both have four walls, two are exposed to the exterior and the other two are exposed to similar zones. The ceiling in both rooms also share boundaries with a similar zone. The rooms differ in the zone below the floors, room one is above the ground and room 2 is above a similar zone. So, Room 1 is representative of a ground floor room, and Room 2 represents a room in a floor above with similar rooms above and below. This was done to compare system operations in a ground floor and first floor room. The Rooms construction details can be found in Table 3.

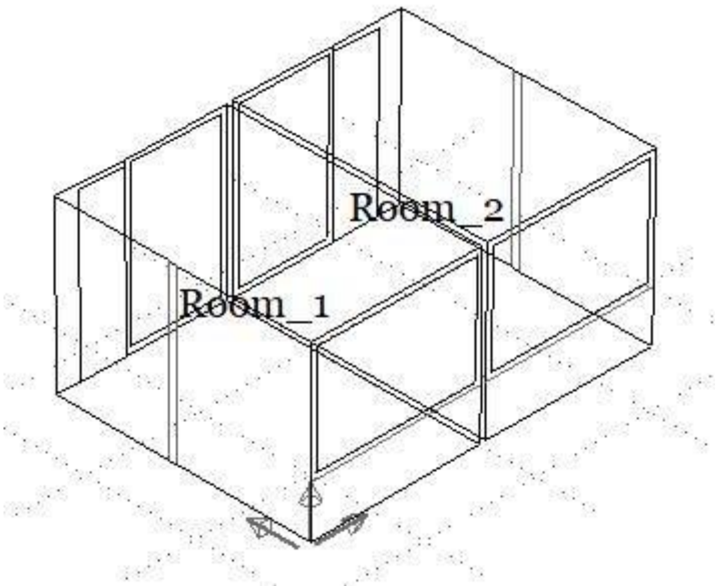

Figure 24: Basic two room model

Before the model was built the model location was decided. The latitude and longitude was then set to represent central Scotland (56.0°N, 4.0°W). A standard UK climate file was used to dictate the climate the model is exposed to. The model site exposure is set as an urban environment. The rooms have a floor area of 13.5m^2 and a volume of 40.5m^3.

Extra operation details are not included in the model. The focus is mainly on space heating systems so there is no need to include these in the analysis. The main heating operational details change in the various iteration of the model so will be described for each simulation. With the model set up in the desired geometry, construction and operation, the next phase was to run some simulations and observe how the model works using different space heating systems.

Table 3: Construction materials

Surface	Constriction
Internal wall	Surface|Mat|Thick |Conduc-|Density |Specif|IR |Solr| Description layer |db | (mm) |tivity | |heat |emis|abs | Inside_wall is composed of gyp_gyp_ptn and is opaque: 1 108 12.0 0.190 950.0 840.0 0.91 0.22 white gypboard 2 0 50.0 0.000 0.0 0.0 air gap (R= 0.170) 3 108 12.0 0.190 950.0 840.0 0.91 0.22 white gypboard ISO 6946 U values (hor/up/dn heat flow) for gyp_gyp_ptn is 2.144 2.292 1.975 (partn) 1.798
External wall	1 6 100.0 0.960 2000.0 650.0 0.90 0.70 Lt brown brick 2 211 150.0 0.040 250.0 840.0 glasswool 3 0 50.0 0.000 0.0 0.0 air gap (R= 0.170) 4 22 100.0 0.240 750.0 1000.0 aerated conc block 5 108 12.0 0.190 950.0 840.0 0.91 0.22 white gypboard ISO 6946 U values (hor/up/dn heat flow) for extern_wall is 0.214 0.215 0.212 (partn) 0.210
Window	1 242 6.0 0.760 2710.0 837.0 0.83 0.05 plate glass 2 0 12.0 0.000 0.0 0.0 air gap (R= 0.170) 3 242 6.0 0.760 2710.0 837.0 0.83 0.05 plate glass ISO 6946 U values (hor/up/dn heat flow) for dbl_glz is 2.811 3.069 2.527 (partn) 2.243 Clear float 76/71, 6mm, no blind: with id of: DCF7671_06nb with 3 layers [including air gaps] and visible trn: 0.76 Direct transmission @ 0, 40, 55, 70, 80 deg 0.611 0.583 0.534 0.384 0.170 Layer| absorption @ 0, 40, 55, 70, 80 deg 1 0.157 0.172 0.185 0.201 0.202 2 0.001 0.002 0.003 0.004 0.005 3 0.117 0.124 0.127 0.112 0.077
Window Frame	1 46 4.0 210.000 2700.0 880.0 0.82 0.72 grey cotd alum 2 281 80.0 0.040 12.0 840.0 glass fibre quilt 3 46 4.0 210.000 2700.0 880.0 0.82 0.72 grey cotd alum ISO 6946 U values (hor/up/dn heat flow) for insul_frame is 0.461 0.467 0.452 (partn) 0.442
Door	1 69 25.0 0.190 700.0 2390.0 0.90 0.65 oak ISO 6946 U values (hor/up/dn heat flow) for door is 3.316 3.682 2.928 (partn) 2.554
Ceiling	1 211 100.0 0.040 250.0 840.0 0.90 0.30 glasswool 2 150 10.0 0.030 290.0 2000.0 0.90 0.60 ceiling mineral ISO 6946 U values (hor/up/dn heat flow) for ceiling is 0.333 0.336 0.329 (partn) 0.323
Floor	1 42 4.0 50.000 7800.0 502.0 0.12 0.20 steel 2 32 140.0 1.400 2100.0 653.0 heavy mix concrete 3 0 50.0 0.000 0.0 0.0 air gap (R= 0.170) 4 67 19.0 0.150 800.0 2093.0 chipboard 5 221 6.0 0.060 186.0 1360.0 0.90 0.60 Wilton ISO 6946 U values (hor/up/dn heat flow) for susp_flr_re is 1.500 1.570 1.415 (partn) 1.321

3.2 Simulation

The model developed in the previous section allowed simulations to proceed to find suitable LTH systems for retrofit. A series of simulations was established to give results to be studied and compared. Initially a base case was established with a traditional heating system and heating schedule. Three LTH systems; floor, ceiling and wall heating systems were proposed to be simulated and compared against the base case and each other. Wall, ceiling and floor heating systems were chosen as from the literature review they seem to be the most prominent. Low temperature forced convection radiators were considered, but it was found that CFD analysis would be required to accurately model and asses them, so they are not included. Analysis would be carried out through evaluating thermal comfort, heat input and COP. All simulation were run with time steps every 5 minutes (12 per hour), this was enough to give sufficiently accurate results for this study. Some basic fabric upgrades are also investigated. Mainly improved insulation levels. Windows were identified as a possible area for significant heat loss, and many homes still have single glazing. However, in this report, as double glazing is now very widely in place and easily accessible, it is assumed in all simulations that double glazing is in place or will be installed if converting to a LTH system.

Another relevant result in the number of unmet heating hours. This is a period during the heating schedule where the set point temperature is not reached. The set point using throughout the simulations was set to 20°C, however 18°C is recognised by some to be thermally comfortable. Therefore, only anything below 18°C will be deemed unacceptable. So, the overall unmet heating hours will be determined, and then the acceptable unmet heating hours, which is between 18-20°C, can also be determined (IESVE, 2013)(Benzschawel, 2015). Although the heating schedule changes, the time periods that the unmet heating hours is based on will remain the same as the base case through the report, as these are the period of expected occupancy, so only during these periods is it important if zone temperatures fall below the minimum thermally comfortable 18°C. This schedule is shown in Table 4. The heat input in each case was also calculated using methods shown in the literature review section from suitable flow and return temperatures (Chen, Jiang, & Xie, 2018).

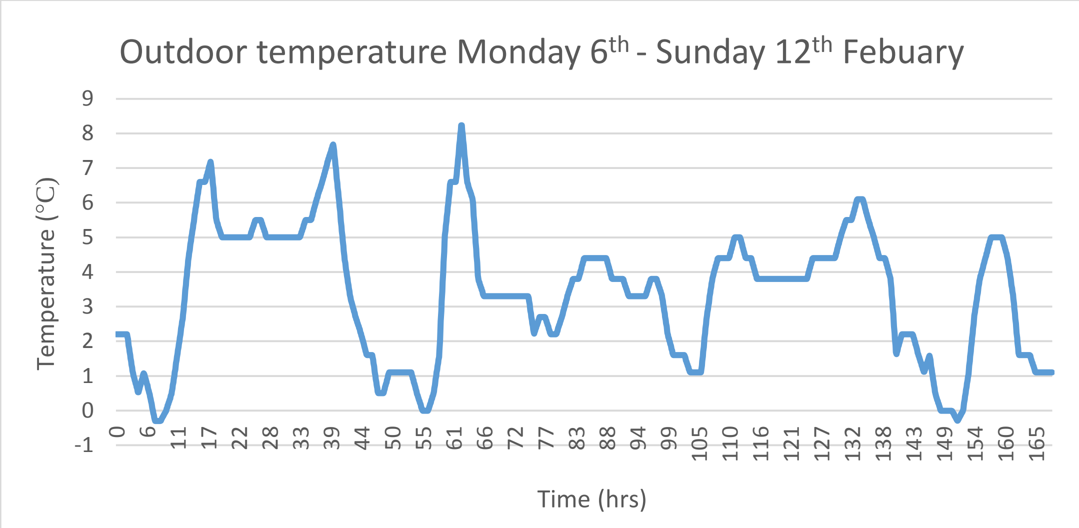

Figure 25: Ambient outdoor temperature

As this study focuses on heating systems, the analysis focuses on performance during winter. A standard winter week, Monday 6th – Sunday 12th of February, was chosen for the simulations to allow for easy comparison between different cases. Significant climate conditions for this week can be seen in Figure 25 (Ambient temperature) and Figure 26 (Direct and Diffuse Solar radiation). From Figure 25 it is seen that the outdoor temperature fluctuates between about 0-8°C. Generally the temperature falls overnight to around 0-3.5°C and during through the day it rises to around 5-8°C, as expected. The diffuse solar radiation follows the same trend daily rising to about 100W/m^2 and falling to zero overnight. Direct solar radiation only occurs on Wednesday and Sunday, and in both occasions reaches around 700W/m^2. This explains the sharp rise in outdoor temperature seen in Figure 25.

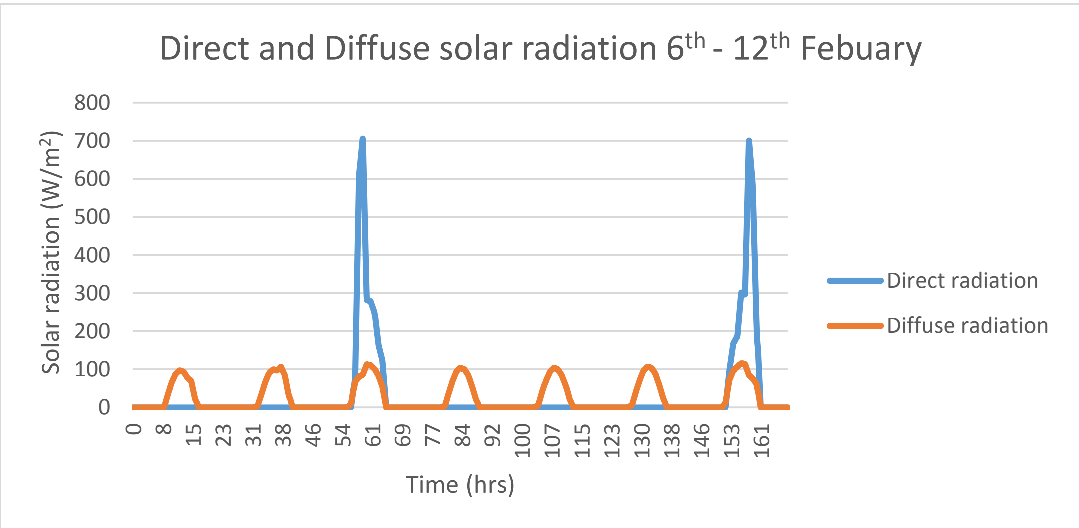

Figure 26: Direct and diffuse solar radiation

4 Results and Discussion

As discussed in the method section, the main focus of the results to assess different LTH systems options is thermal comfort and energy efficiency. Firstly, thermal comfort will be analysed through operative temperature of the zones when compared to a base case systems configuration. This will be supported through important surface temperature, and unmet hours within the prescribed heating schedule. Secondly, the energy usage of the model will be evaluated. This will be through observing the heating load required and the COP of the theoretical heat pump which is the heat source. These results should give sufficient material to discuss and arrive at appropriate conclusions. The majority of results were collected through simulations in ESP-r, and organised using Microsoft excel. Part of the analysis required calculations, these are outlined where required, and sample calculations can be found in relevant sections in the appendix.

4.1 Base Case

To allow for comparison of operation and performance of LTH systems a base case scenario simulation was run with conventional high temperature heating operation. The actuator in this case is the air point of the current zone. A basic heating controller that sense the current zone temperature is in place to modulate the heating load.

Table 4: Base case heating schedule

Heating Schedule	
Morning	*Evening*
Weekday	
06:00 – 09:00	18:00 – 23:00
Saturday	
06:00 – 13:00	18:00 – 23:00
Sunday	
07:00 – 22:00	

The maximum heating capacity was set as 1500W and the heating set point was 20°C. This is the rough heating capacity of a standard two panel high temperature radiator with a height of 0.75m and 1.00m length (Sensecall & Bucknell, 2013). The Heating schedule for the base case is shown in Table 4. This was based on expected occupancy of a domestic use building. For weekdays heating comes on in the morning between 06:00-09:00 when occupant are preparing for their daily undertakings, the heating then turns off for the rest of the morning/afternoon. It then comes back on in the evening from 18:00-23:00, when the occupants are returning from daily activities. Overnight the heating is left idle. A similar heating schedule is used for Saturdays, but with a longer heating period in the morning till 13:00. On Sundays the occupants are expected to be present all day, therefore heating is on from 07:00-22:00.

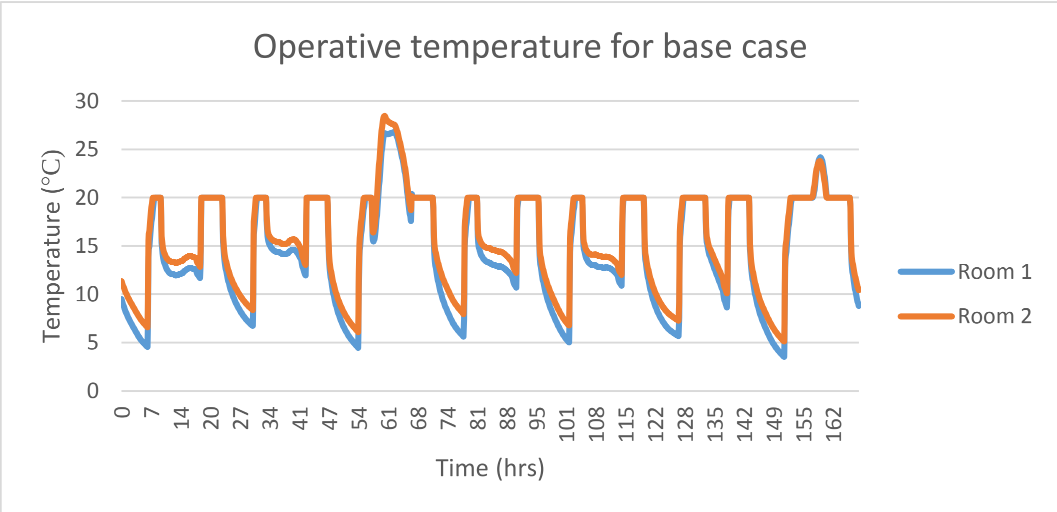

Figure 27: Base case zone operative temperature

The first set of results collected was the operative temperature of the zones, with a regular high temperature heating system. This is shown in Figure 27. From the graph of the plotted temperature it is evident that the temperatures in Room 1 and Room 2 are very similar. The only time they show any significant deviation from each other is during period when the heating is inactive. In these periods the temperature in Room 1 drop slightly lower by a few degrees. Over the week the temperature varies between around 4°C-28°C. However, during the day the temperature in general only ranges from 12°C-20°C, and the temperature only rises above 20°C on two occasion. This rise in temperature can be explained by looking at the direct solar radiation in Figure 26, which peaks during the same time the temperature in the rooms rises. This can be seen on

Wednesday and Friday afternoon. Heating is the focus of this study so cooling is not included, and this would be easily resolved by opening a window or a predictive weather controller. With reference to the heating schedule in Table 4, the heating system can be seen to be working well, with the temperature in both rooms rising quickly to the 20°C set point during all the heating period throughout the week.

The results in Figure 27 show that the model is working as anticipated, and there are no unexpected trends. The temperature in Room 1 is lower, outside heating hours, because it has a boundary with the ground, unlike Room 2 which has a similar zone below. This causes a greater heat loss through floor as the ground is colder. The average ground temperature during the week was 6.5°C, and the average temperature of the similar zone Room 2 is exposed to was 13.4°C. Looking further into the heating system, the reaction time of the system is fast, for example even when the temperature is very low at 4°C once the heating comes on the zone set point is reached in about an hour. This is because the heat is injected directly in to the zone air point. Once the set point is reached it is also easily maintained with no temperature drop off.

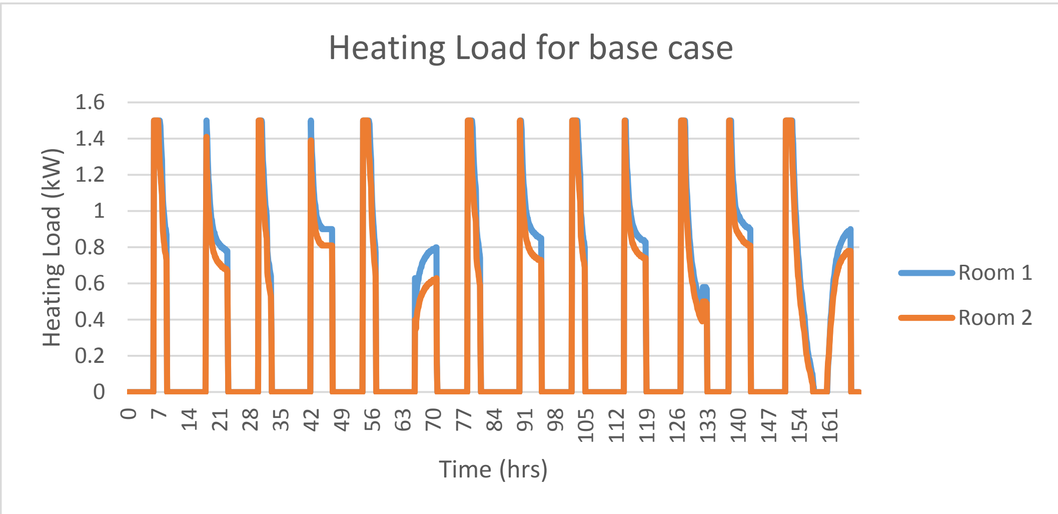

Figure 28: Base case heating load

This falls in line with what is seen in literature. High temperature heating systems are known to have quicker reaction times, due to the higher temperature difference between the distribution temperature and zone temperature. Which cause faster heat transfer. However high temperature radiator have a small surface area, therefore the temperature of the room can often vary, dropping off further away from the heat emitter. This has a detrimental effect on thermal comfort of the zone as a whole. CFD analysis could be carried out to observe the air flow and temperature across a whole room, but this is beyond the scope of this project (Zhou & He, 2015).

The heating load for the base case can be seen in Figure 28. The heating load ranges from 1500W to 0W. The set maximum heat capacity of 1500W is generally fully used during the start of the heating periods throughout the week. This is required to heat up the zone, this heating load then drops off as the temperature set point is reached. The temperature must only be maintained, therefore the heating load simply has to match the heat loss on the zone, which is typically between 600-1000W. As before there is slightly greater heat loss in Room 1, so the heat load is also larger.

Table 5: Base case overall heat input, heating hours, unmet heating hours and COP

	Room 1	Room 2
Total heating input (kWhrs)	60.41	53.62
Total heating hours (hrs)	64.0	63.8
Unmet heating hours (hrs)	7.0	4.7
COP	4.03	4.03

The results in Table 5 show the total heating input, heating hours and unmet heating hours, for the base case in the winter week. As discussed previously the heat loss is greater in Room 1 so the total heating input in greater, 60.41kWhrs compared to 53.62kWhrs. The total heating hours are almost identical, as although Room 2 requires a reduced heat input compared to Room 1, there is still some heating input required throughout the heating schedule to meet the temperature set point. The unmet heating hours for the base case are fairly low, only 7hrs and 4.7hrs for Room 1 and Room 2 respectively. This confirms that thermal comfort in this case is good, with an average one unmet heating hour per day for Room 1, and less than an hour for Room 2.

As described in the method section the COP of a ground source heat pump used in each case will be used to compare overall energy use, not just energy delivered to the zones. Assuming a conventional high temperature heating distribution temperature of 90°C, and 0°C for the heat pump heat source. Although the average ground temperature is 6.5°C the heat pump will "pump" heat from the ground so the ground temperature where the heat pump pipe network is will be lowered to typically about 0°C (Kensa Engineering, 2009). The COP of this system would be 4.03. A sample calculation can be found in Appendix B. This is above 3 which from literature was found to be the minimum for a heat pump to be economically viable. Although, this is likely to drop in the real world so would be an uncertain investment (Sayegh et al., 2018). This will allow for comparisons between different systems configuration in energy efficiency.

4.2 Floor Heating Panel

4.2.1 Regular Control Scheme

To test the feasibility of a typical LTFH system initially a simulation was run with the same heating schedule as a conventional high temperature heating system (Table 4). The actuator in this case is set to the inside surface of the floor construction. A basic heating controller that sense the current zone temperature is in place to modulate the heating load. The maximum heating capacity was kept at 1500W. The temperature set point and expected occupancy periods remained the same.

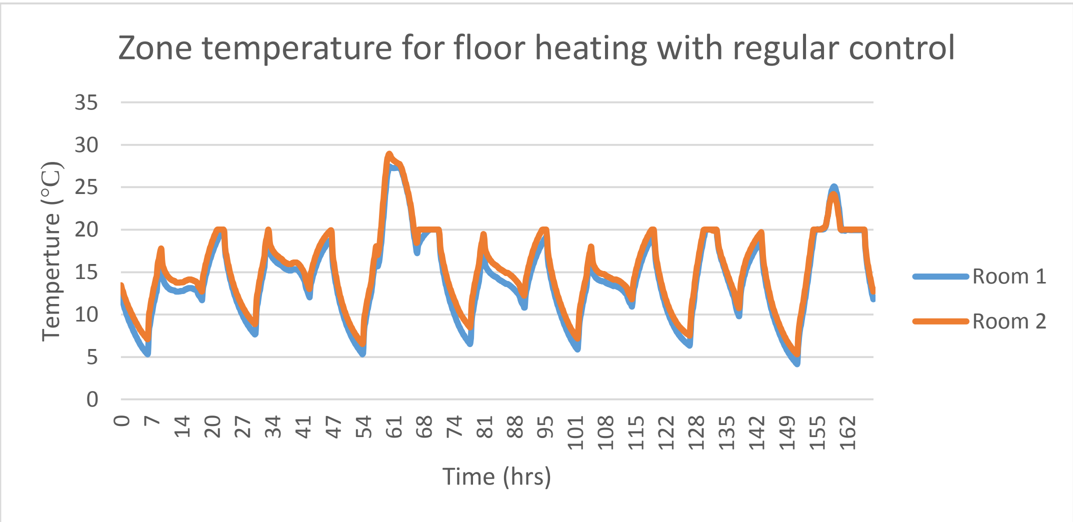

Figure 29: Floor heating with regular control zone temperature

The zone temperature for this case is shown in Figure 29. Similarly to the base case, the temperature in both rooms varies between around 4°C-29°C. These are some similarities in the trend, the temperature does increase during the heating periods. However, unlike the base case the temperature set point is often not met, and even if it is met it is after a few hours. Outside of the two days (Wednesday and Sunday) with high direct solar radiation, both rooms spent very limited time in a comfortable temperature range.

With the floor as the heating surface the reaction time of the systems is much slower. Every time the heating schedule starts there is a much longer period required to reach the temperature set point compared to the base case. Although the maximum heat input is similar compared with the base case heat input is spread over the 13.5m^2 floor area (100W/m^2). This larger surface area means that although the room is heated more evenly it takes longer to heat up, this match what was found when studying the literature. With this control scheme the systems cannot provide enough heat to, either heat the room fast enough or in a constant manner. Another noticeable difference compared to the base case is during the periods directly after the heating turns off. The temperature of the rooms does not fall as instantaneously as in the base, this highlights one of the benefits of floor heating. The floor itself is heated, therefore even if the heat input is removed the floor will retain some heat and continue to emit heat. Floor heating systems are more resilient, and can handle maintain zone temperatures even if heating is turned off for a short period, however they are slow to react.

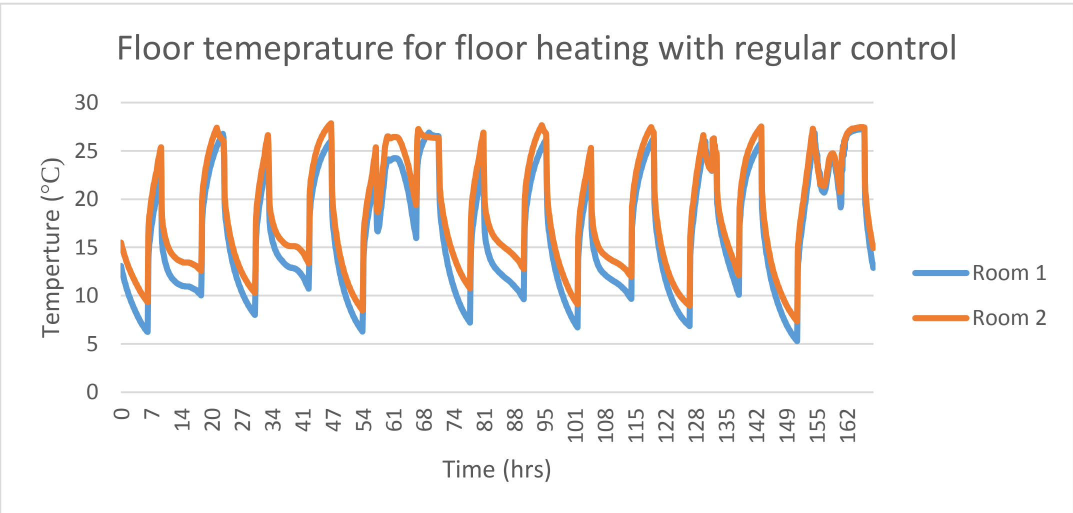

Figure 30: Floor heating with regular control zone floor temperature

The floor temperature of the zones, shown in Figure 30, shows that the model is work as it is meant to in this configuration. It shows that the floor is being heated during the requested heating periods. The floor temperature ranges from around 4°C-28°C. Although the floor is not providing enough heat to consistently maintain the rooms in thermally comfortable conditions. The floor temperature is mainly within 19°C-29°C (during expected occupancy period) which is the range for acceptable floor temperatures (CIBSE, 2016).

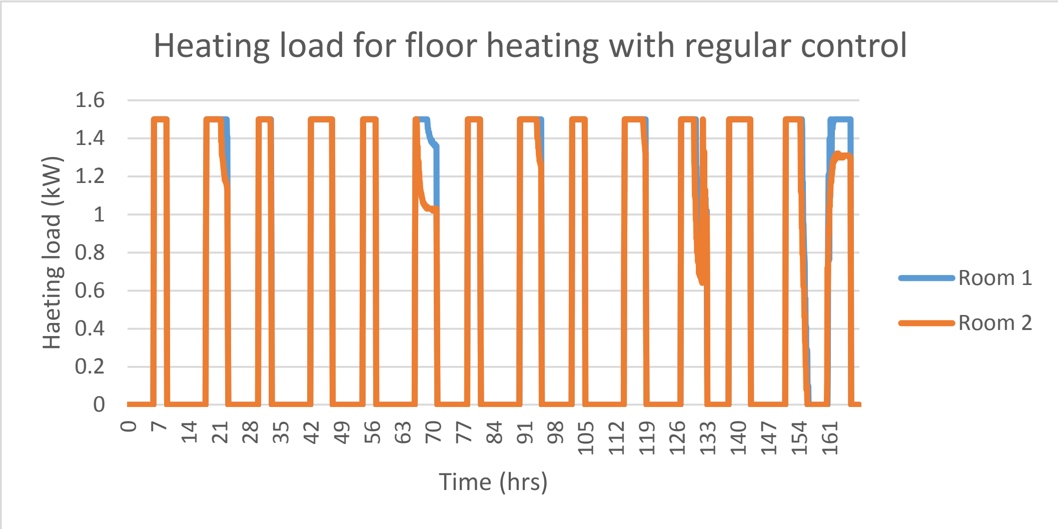

Figure 31: Floor heating with regular control heating load

The heating load displayed in Figure 31, solidifies the fact that this heating system configuration struggles to meet the heating demands. When the heating is active the heat input is almost always at maximum capacity. Only dropping below the maximum during the peaks in solar radiation.

Table 6: Floor heating (regular control) overall heat input, heating hours, unmet heating hours and COP

	Room 1	**Room 2**
Total heating input (kWhrs)	89.05	84.88
Total heating hours (hrs)	62.6	62.6
Unmet heating hours (hrs)	38.8	30.9
COP	8.80	8.80

Table 6 shows the total heating input and hours, and the unmet heating hours. Compared to the base case the total heating load increases despite being less thermally comfortable. The heat input increases by over 20kWhrs for both rooms. This is due to the slow reaction time, as the max heating load is required almost throughout the heating period to reach the temperature set point. Whereas in the base case the temperature set point is reached quickly so the heat load is reduced to maintain the room temperature. This can be seen is the heating loads for both cases in Figure 28 and 31.

The heating hours in this case (62.6hrs) are reduced compared to the base case (64hrs). This is because although the total heating load is less in the base case, the heating is almost always required even if just at a low heat input to maintain zone temperature. Also, the floor retains heat better. So, comparing the heating load on Sunday from Figure 28 and 31, it is clear that the heating load is required for longer in the base case to maintain the temperature set point.

The unmet heating hours can be seen to rise dramatically from the base case. This confirms that this heating system configuration is not acceptable. And the control of the heating schedule must be altered to improve general thermal comfort. However the COP of this system is much higher than the base case due to the low temperature distribution. Assuming a standard 35°C floor heating flow temperature, and again 0°C heat source, the COP would be 8.8. This would greatly reduce energy required in generation and distribution losses overall.

4.2.2 Regular Control with Heat Injection

For this simulation the control remained the same, with the addition of a period of heat injection from 0-6am with the aim of warming up the floor before the general operation. This heat injection was set at 1000W with a 20°C set point. The actuator in this case kept as the inside surface of the floor construction. A basic heating controller that sense the current zone temperature is in place to modulate the heating load. The maximum heating capacity was kept at 1500W. The temperature set point and expected occupancy periods remained the same.

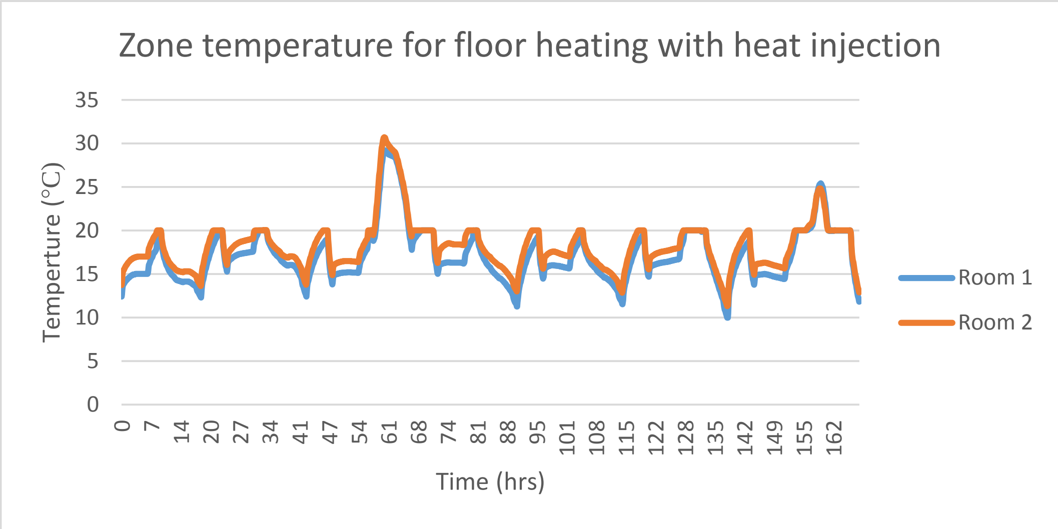

Figure 32: Floor heating with heat injection zone temperature

The zone temperature for this scenario is shown in Figure 32. It is instantly noticeable that the temperature range has reduced. The temperature only ranges from about 10°C-31°C, compared to 4°C-28°C in previous cases. As mentioned previously cooling is not a concern in this study so the upper limit of the temperature is not of importance. However, for this scenario with heat injection the dips in temperature stays significantly higher than in previous cases. Although the minimum temperature is reduced, it is still evident that the unmet heating hours will be greater than the base case.

Nevertheless, there is a significant improvement in the thermal comfort, the heat injection in the morning allows the systems to heat up before the regular heating schedule come in. This means that the slow reaction time of the floor heating system is mitigated to an extent and the set point can be reached for most days. The heat injection in the morning also results in lower temperature drop during the day, as more heat is retained in the floor. Again meaning the rooms reach the set point faster during the evening heating period. Similarly to previous scenarios the temperature in Room 1 on average can be seen to be lower than Room 2, this again is due to the boundary conditions.

The Floor temperature for this set-up is shown in Figure 33. Similar trends are seen in the floor temperature and zone temperature. The floor temperature varies between 10°C-29°C, the minimum for Room 2 is slightly greater dropping just below 15°C.

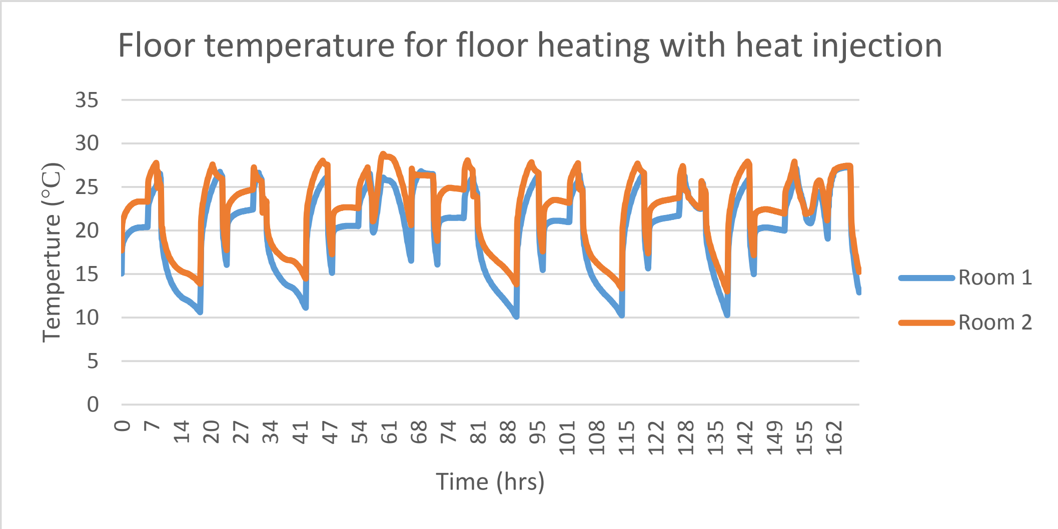

Figure 33: Floor heating with heat injection zone floor temperature

Again this shows a marked improvement, and that the heat injection has a significant improvement on the thermal comfort. In general this systems is able to maintain thermally comfortable floor conditions during expected occupancy times.

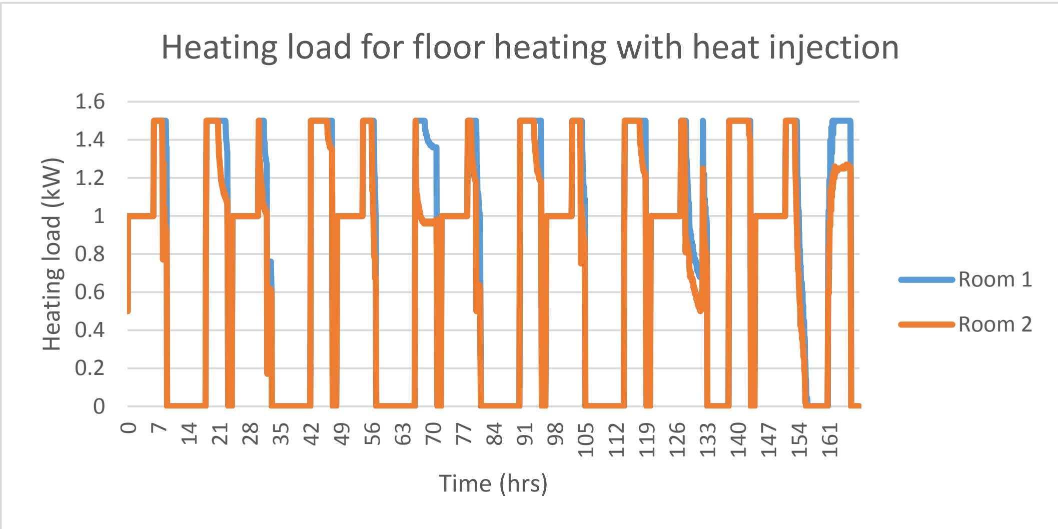

Figure 34: Floor heating with heat injection heating load

The heating load for this case is shown in Figure 34. This shows that during heating period the heating system is almost always operating at maximum capacity, of 1000W during the heat injection period, and 1500W during the regular control period. This is showing that despite this change in control, this floor heating system is still struggling to meet the temperature set point quickly and maintain it.

Table 7: Floor heating (heat injection) overall heat input, heating hours, unmet heating hours and COP

	Room 1	Room 2
Total heating input (kWhrs)	128.36	118.76
Total heating hours (hrs)	106.3	106.1
Unmet heating hours (hrs)	25.3	12.3
COP	8.8	8.8

Table 7 shows the total heat input, heating hours and unmet heating hours. Compared to the previous case, the total heating load has increased significantly from 89.05kWhrs to 128.36kWhrs for Room 1. The same is observed for Room 2. The total heating hours has also increased greatly from 62.6hrs to 106.3hrs. This increase in heating input and hours has resulted in a decrease in unmet heating hours from 38.8hrs to 25.3hrs for Room 1, and 30.9hrs to 12.3 hours in Room 2. The COP remains the same as previously supply temperature is still 35°C and the heat source is 0°C. Including a heat injection before the start of the regular heating control, significantly improves thermal comfort of the floor heating system. However, the unmet heating hours are still about three times greater than the base case, with a greater heat input. The increased COP would increase the overall energy efficiency of the system, but the feasibility of this system would still be questionable.

4.2.3 Better Control and Insulation

This case uses a control schedule that is more suitable for floor heating systems. The main heating schedule is shown in Table 8. The heating period was moved an hour ahead to try and counteract the slow reaction time of floor heating. The heating is also reduced earlier in the evening than in the base case to take advantage of the ability of the floor to retain heat. The set point is kept at 20°C, but the heating capacity is changed to 1350W to represent the output of a typical floor heating system. This was taken from literature, where 100W/m^2 is the maximum floor heating output. As the rooms have a floor area of 13.5m^2, the maximum heating capacity was 1350W. Also, using equation (4) taking the maximum floor temperature as 29°C the maximum heating capacity was also calculated as 1350W. A sample calculation is shown in Appendix B. The rest of the day between 0-5am and 22:00 – 00:00 is heated to 15°C with the same maximum heating capacity, with the aim of keeping the floor warm to avoid heating the floor from a cold temperature.

Table 8: Better control heating schedule

Heating Schedule
Weekday
05:00 – 22:00
Saturday
05:00 – 22:00
Sunday
06:00 – 21:00

In this case the model construction has also been changed to improve the performance of the heating system. The air gap in the original floor construction was changed to an underfloor foam insulation with a conductivity of 0.03W/m°C (Meng et al., 2018). This should ensure the majority of heat transfer is into the rooms, and should minimise heat loss to the ground and surroundings. The Results from a simulation with the better control scheme but no floor insulation can be found in the Appendix E.

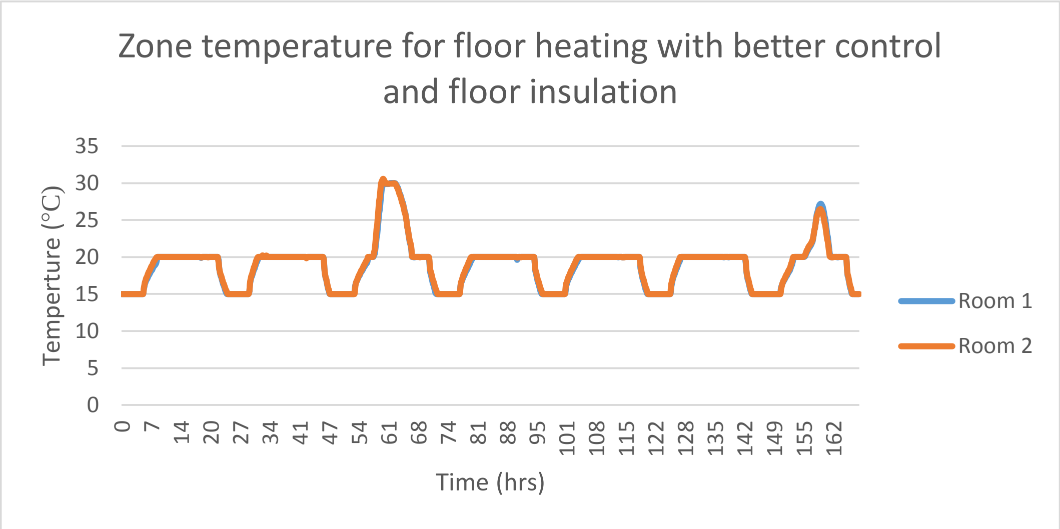

Figure 35: Floor heating with better control and floor insulation zone temperature

With these changes in place the model was run is a standard simulation. The zone temperature from this is shown in Figure 35. It is immediately clear there is a considerable change in the trend when matched against the other cases. The temperature zone temperature in this scenario varies from around 15°C-31°C. However, discounting the peaks, which as discussed previously are not important in this study, the temperature only varies from 15°C-20°C. The improved control and insulation has given a very regular and consistent pattern in the zone temperature. The temperature is easily maintained at 15°C and 20°C, during the respective heating periods.

The temperature set point during the main heating period of 05:00-22:00 is also met quickly compared to the other floor heating configurations. The reaction time is almost as fast as the base case, this is facilitated by maintaining the temperature at 15°C overnight. Keeping the heating on during the day also means there is no heating up period in the evening when occupants are expected to return from daily activities. There is also no discernible difference in the temperature between the two rooms. The insulation should improve the performance of both rooms but it has had a more significant effect on Room 1, which was consistently at a lower temperature in previous simulations. Although, this could be due to the change in control. This should become clear through looking at the heating load. This is what is expected from studying literature, where a constant heating load is often used, and floor insulation is a must in floor heating systems.

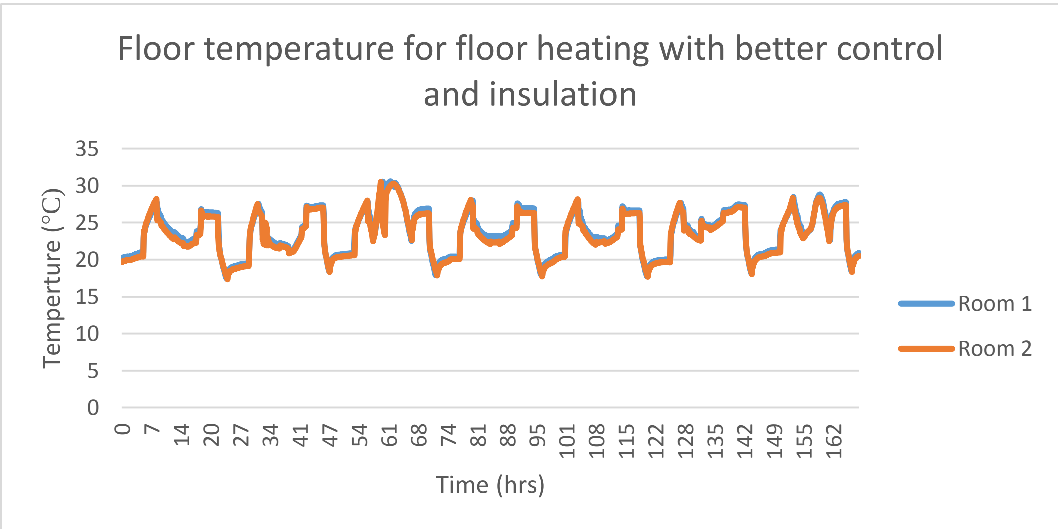

Figure 36: Floor heating with better control and insulation floor temperature

The floor temperature for this simulation is shown above in Figure 36. The floor temperature ranges from 17°C-30°C. Discounting the peaks the floor temperature consistently remains between thermally comfortable conditions during periods of expected occupancy, about 17°C -28°C. In other cases the trends of the zone and floor temperature follow very similar trends. With improved insulation and control, it is observed that during the day the floor temperature generally drops off from around 27°C to 22°C. Despite the floor temperature dropping, the zone temperatures remain at 20°C. This is likely due to the rise in outdoor temperature, which reduces heat loss and therefore reduces the required heating load. However, this this also shows that even if the floor temperature changes it is still able to provide sufficient heating to maintain zone temperature. The floor temperature of Room 1 and 2 also show little deviance from each other. Although the floor in Room 1 is sometimes warmer. This is likely because there is still more heat loss through the floor in Room 1 compared to Room 2, therefore the floor temperature must be slightly higher to maintain the temperature set point of the room. This could also be down to outdoor weather conditions and the orientation of the room.

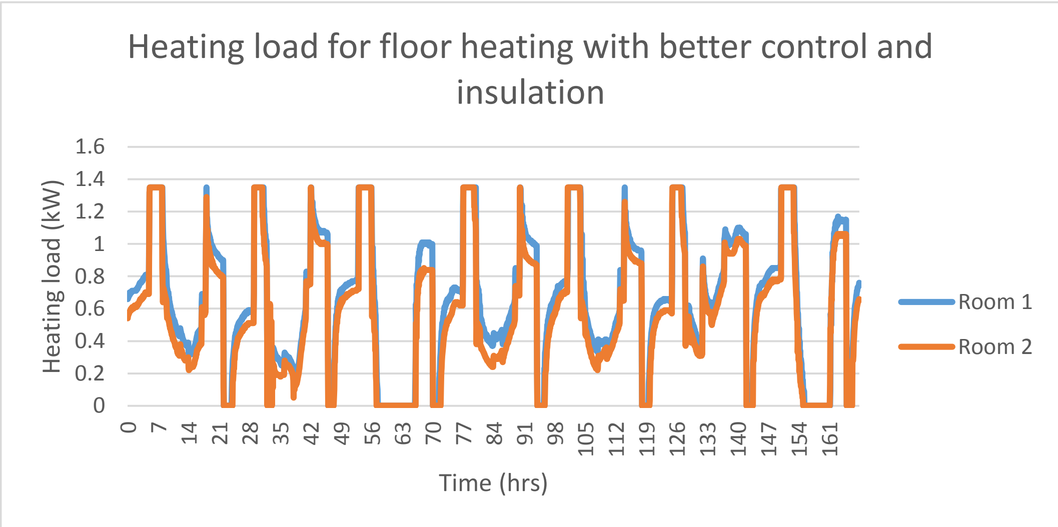

Figure 37: Floor heating with better control and insulation heating load

The heating load through week is shown in Figure 37. The heating load in this simulation does require the maximum capacity at times. However, in general the control scheme and insulation means that the system is able to cope will with the heating demands and can operate at a lower heat input. To meet the heating demands and temperature set point, Room 1 does generally require a slightly larger heat input than Room 2. The insulation does reduce the deficit but the boundary with the ground still does cause more heat loss. From literature it was found that floor heating can usually operate at between 35-75W/m^2 to maintain a temperature of 20°C. For the rooms in this analysis this equates to 472.5-1012.5W/m^2 (CIBSE, 2016). Looking at Figure 37 it is observed that outside periods of temperature increase, the heating load is almost always within or lower than this range.

Table 9: Floor heating (better control and floor insulation) overall heat input, heating hours, unmet heating hours and COP

	Room 1	**Room 2**
Total heating input (kWhrs)	110.56	98.08
Total heating hours (hrs)	143.2	143.2
Unmet heating hours (hrs)	8.1	6.5
COP	8.8	8.8

Table 9 shows the total heat input, heating hours and unmet heating hours for this scenario. With reference to previous iterations and the base case, these results are positive. Firstly, the total heating hours are much greater than the base and previous cases. However, the total input, while still much greater than the base case, is lessened when compared to the heat injection control model. Looking at the unmet heating hours, these results are very similar to the base case. In this case 8.1hrs and 6.5hrs for Room 1 and Room 2 respectively, compared to 7hrs and 4.7hrs in Room 1 and Room 2 for the base case. The base case is still lightly better, but as before the COP is over double the base case here. This offsets the higher total heating input.

Although the unmet heating hours here are similar to the base case, the average temperature is much higher in this scenario. Therefore, thermal comfort over the whole week is likely to be better. With a simple change in control and building fabric, it was possible to acquire similar if not better thermal comfort than the base case. Although, the total heating input is greater, the overall energy efficiency of the system is likely to be equal to or less than the conventional high temperature heating system in the base case.

A final simulation was also carried out with the inclusion of both floor and wall insulation. The wall insulation was placed in the air gap in the external wall construction. The insulation used was glass wool which has conductivity of 0.04W/m°C. The control in this simulation remained the same. The overall total heat input, heating hours and unmet heating hours are shown below in Table 10.

Table 10: Floor heating (better control and floor + wall insulation) overall heat input, heating hours and unmet heating hours

	Room 1	**Room 2**
Total heating input (kWhrs)	58.62	49.5
Total heating hours (hrs)	114.5	99.4
Unmet heating hours (hrs)	7.1	5.6

The addition of wall heating does not have a large effect on the unmet heating hours only reducing slightly. However, the total heating input is almost halved in both rooms. This control configuration with floor and wall insulation gives total heating input and unmet heating hours very similar to the base case. The total heating input is even slightly reduced in this case. With some basic fabric improvement, it is possible to achieve very similar results with a floor heating system compared to the high temperature base case. The COP of the floor heating system is also over double, at 8.8, compared to the base case, 4.4, which would give significant energy efficiency improvements.

4.2.4 Comparison of Floor Heating Configuration

In this section the floor heating system iterations and base case will be compared in more detail. To allow for easy comparisons between cases the zone temperature for one day was represented graphically. This is shown in Figure 38. Only results for Room 1 were used, to provide clarity in the graph. Also Differences between the two rooms have already been discussed, Room 1 is also likely to require more heating, so it will represent the worst case scenario.

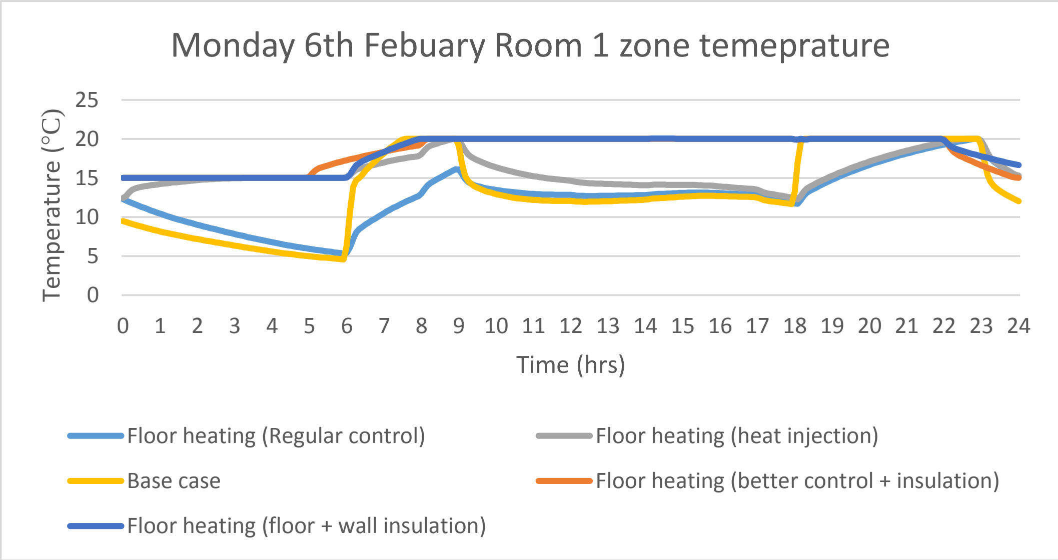

Figure 38: Monday 6th February Room 1 zone temperature

Table 11: Summary of floor heating total heating and unmet heating hours for Room 1

System Configuration	Total heating input (kWhrs)	Unmet heating hours (hrs)
Base case	60.41	7.0
Regular control	89.05	38.8
Heat injection	128.36	25.3
Better control + insulation	110.56	8.1
Floor + wall insulation	58.62	7.1

From Figure 11 the daily trends of the system iterations can be seen. It is immediately clear that overall the floor hearting configuration with better control and insulation is the most thermally comfortable, consistently maintaining 20°C during the day and 15°C overnight. The other floor heating simulations are clearly uncomfortable. Both struggle to meet the set point in the morning, and in the evening require 4 hours to reach the set point in the evening heating period. The base case meets the thermal demand quickly in both the morning and evening. The floor heating with better control scheme has a slow reaction time, but as the heating comes on an hour earlier, it reaches thermally comfortable conditions above 18°C at around the same time. This configuration doesn't turn off during the day so there is no warm up period in the evening occupancy period. This would also allow variation in expected occupancy times as the system is always heated, and temperature in the room is maintained. The case with both wall and floor insulation shown that wall insulation also improves the reaction time of the heating system reaching the set point in about 2hrs rather than 3 hours. Floor heating system also give a better vertical thermal comfort profile, as shown in Figure 38 in Appendix A.

The total heating input and unmet heating hours are shown in Table 11. The Base case and floor + wall insulation case provides the best results here with by far the lowest heating input, and unmet heating hours just below other simulations. Similar to the zone temperature the regular control and heat injection cases are not able to meet thermally comfortable condition for long periods. With an increase to 38.8 and 25.3 unmet heating hours in these cases, even with a significant increase in total heating output. However, the COP of all the floor heating systems (8.8) is over double that of the base case (4.03). The best Floor system with floor + wall insulation matches the base case in unmet heating hours and total heating input. However, the COP is over double. The more constant temperature would also allow for more variable occupancy without having to change the heating control at all.

The inclusion of insulation in the floor ensures that most of the heat is transferred in to the room and limits the heat loss to the ground. This reduced the total heat input compared to the heat injection case, even though the number of heating hours rose from 106.3hrs to 143.2hrs. Moving the heating period forward and for the whole day, reduced effect of the slow reaction time of floor heating systems, which is what increases the number of met heating hours. Overall the floor system is likely to be the best option in this case. As a whole the system will likely be more energy efficient due to the higher COP, and although the unmet heating hours is less in the base case the thermal comfort over for floor systems in generally better than conventional high temperature radiators (Brown, 2011). A CFD analysis could be used to verify this. One drawback of under floor heating systems is that they can be disruptive, challenging and expensive to retrofits in current homes (Wang et al., 2015). Therefore, other options are sometimes explored such as a heated ceiling. In the UK floors should achieve a U-value of 0.25 W/m2K or less. To achieve this at least 70mm of high performance foam insulation will need to be installed, or 150mm of mineral wool, but this will vary with floor type. (Energy Saving Trust, 2018).

4.3 Ceiling Heating Panel

4.3.1 Regular Control Scheme

To test the feasibility of a typical LT ceiling heating system initially a simulation with the same characteristic to the base case was run, but with actuator set as the inside surface of the ceiling construction. The heating schedule used is shown in Table 4 and the maximum heating capacity and set point were kept as 1500W and 20°C.

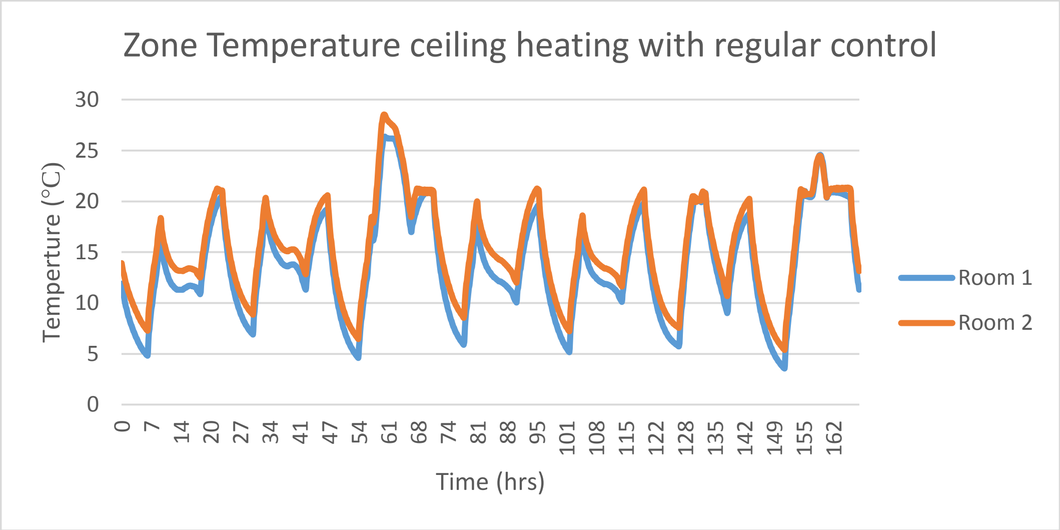

Figure 39: Ceiling heating with regular control zone temperature

The zone resultant temperature is shown in Figure 39. Again when compared to the base case the temperature ranges from around 4°C-29°C, and the trends are similar. The temperature does increase during heating periods. This configuration shares many similarities with the floor heating system with regular control. Firstly it is clear that this control cannot provide comfortable conditions for sufficient time periods, with little time spent at the temperature set point. The reaction time of the system is much slower than the base case. As observed in the floor heating system, the larger surface area results in more even heating, but it also take longer to heat the room from lower temperatures. Similar to the floor heating, when the heating turns off the temperature drop off is slower here than the base case. However, the floor heating retains heat better so the temperature drops off slightly more for the heated ceiling panel.

As seen here and in literature ceiling heating has a slightly quicker reaction time than floor heating, but this is balanced by the intermittent heating control and the floor heating systems ability to more effectively retain heat. The floor is used as a heat store, which is not effectively possible with ceiling heating panels. For the ceiling heating system the temperature difference between Room 1 and Room 2 is also greater than the floor heating system. Although the model constructions are the same, the heated floor provide a buffer and effectively also insulates the zone, unlike the ceiling heated system where the floor is colder and uncontrolled. The resultant temperature of the zone also tends to overshoot the set point by a few degrees. This is because the heat is radiating from the top down and the ceiling also gets hotter than the floor, so although the zone air temperature is 20°C the observed temperature is higher.

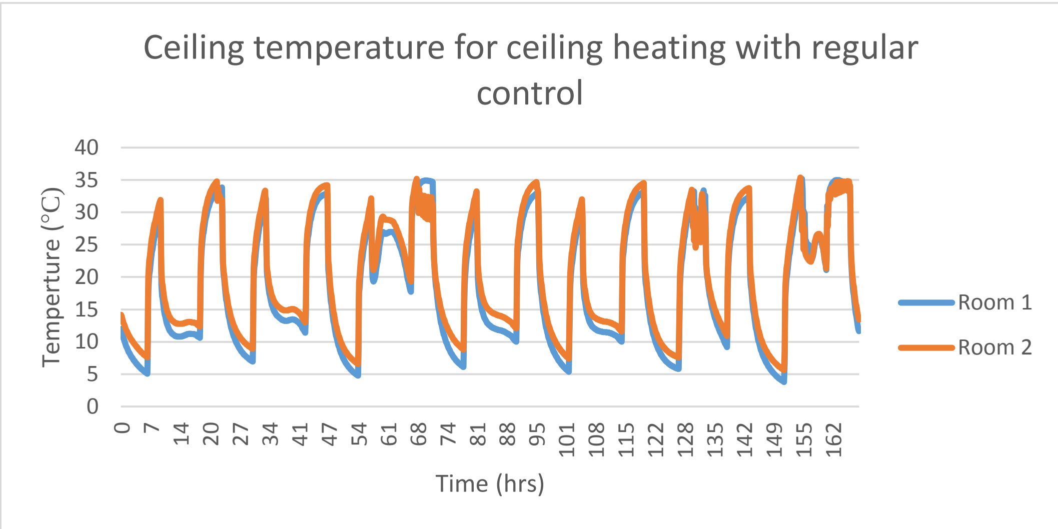

Figure 40: Ceiling heating with regular control ceiling temperature

The ceiling temperature for this scenario is shown in Figure 40. This confirms the heat input is to the ceiling. The ceiling temperature ranges from about 4°C-35°C. This is slightly higher than the floor temperature in floor heating systems because although the maximum heat capacity is the same, the ceiling construction contains an insulation layer, and the ceiling outside boundary is a similar zone. This higher temperature would too high for UFH systems, but ceiling panels can be heated up to 46°C. This is because the heated surface is not in direct contact with any occupants, so is still thermally comfortable at higher temperatures. This allows for a higher flow temperature and heat output (Ovchinnikov et al., 2017).

The Heating load for this scenario is shown in Figure 41. This shows that the heat capacity is almost always at the maximum during heating periods. Proving that this system configuration cannot consistently meet the set point or reach thermally comfortable conditions for the expected occupancy periods.

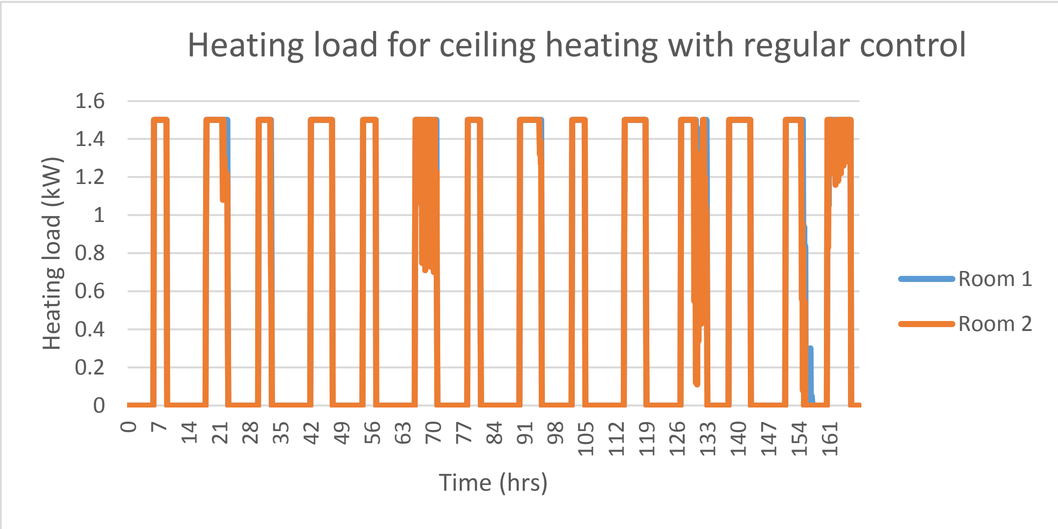

Figure 41: Ceiling heating with regular control heating load

The total heating input, hours and unmet heating hours for this ceiling heating arrangement is shown in Table 12. Similar to the floor heating the total heating input here is greater than the base case, by around 30kWhrs, although the thermal comfort is inferior. While the ceiling heated panels do have a quicker reaction time than floor heating, it is still slower than regular system, therefore the maximum capacity is often required and total heating input increases. The total heating hours are similar to both floor heating and the base case.

Compared to the base case the unmet heating hours has increased from 7.0 and 4.7 for Room 1 and 2 in the base case, to 36.1 and 27.9 in this case. However, when comparing to the equivalent floor heating system the unmet heating hours is slightly reduced. This is likely due to the slightly quicker reaction time and higher temperature of the heated surface in ceiling heating systems. The COP of this system was calculated assuming a typical low temperature flow of 50°C and heat source of 0°C. This gives a COP of 6.46, which is higher than the base case, but lower than floor heating. This would improve energy efficiency compared to the base case, however the thermal comfort is still too low so a new system control must be used.

Table 12: Ceiling heating (regular control) overall heat input, heating hours, unmet heating hours and COP

	Room 1	Room 2
Total heating input (kWhrs)	90.02	85.71
Total heating hours (hrs)	63.1	62.0
Unmet heating hours (hrs)	36.1	27.9
COP	6.46	6.46

4.3.2 Better Control with Floor Insulation

In this simulation, the control of the heating system was changed. The main heating periods were kept the same, but the other periods using left free floating between 23:00-06:00 and 09:00-18:00, now included a basic heating control with a 15°C set point, with the aim of maintaining a more stable temperature. The maximum heating capacity was also changed to a typical ceiling heating panel using equations and graphs in section 2.4.2. Assuming a maximum panel temperature of 46°C, the maximum heating capacity for ceiling heating was calculated as 156.4W/m^2, and 2111W/m^2 for each room. Full sample calculation can be found in Appendix B. The construction of the floor was changed to include insulation, an underfloor foam with conductivity of 0.03W/m°C was utilised. The focus of the results in this section will be on the model with floor insulation, but results from a simulation without floor insulation can be found in Appendix F.

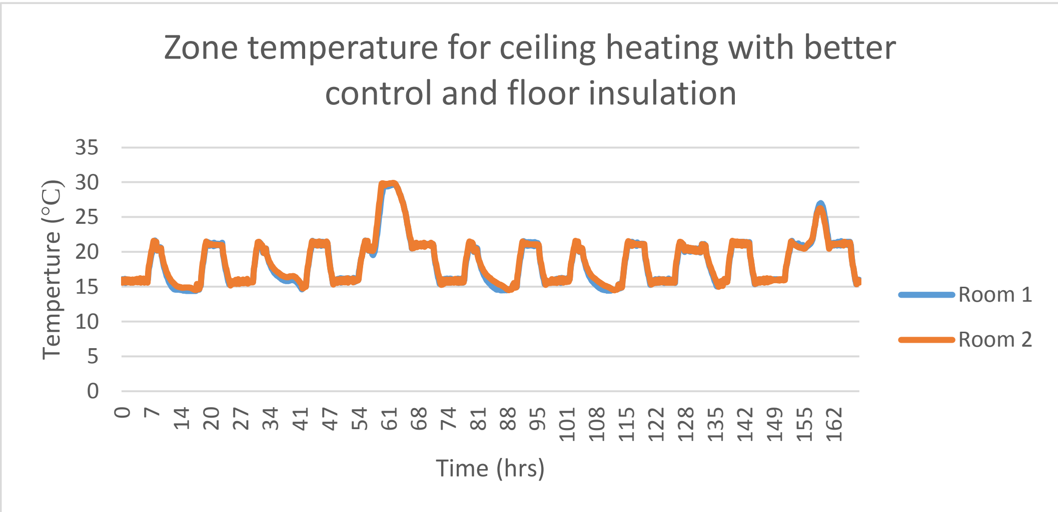

Figure 42: Ceiling heating with better control and floor insulation zone temperature

The zone temperature is shown in Figure 42. Similarly to the better floor heating control scheme, disregarding the outliers the temperature only ranges between 15°C-22°C. The temperature also is generally within thermally comfortable conditions, during expected occupancy periods. This is through the improved control. The floor insulation has a specific effect on Room 1. It reduces the heat loss to the ground and the temperatures in the two rooms now match very closely. Again looking at the beginning of heating periods, the ceiling heating systems has a slower reaction time than the base case. However, compared to the floor heating system the time required to reach the set point is lower. This is what allows a reduced set point during the day in this case, unlike the floor heating system which requires heating all day to achieve similar unmet heating hours to the base case. This falls in line with information found in the literature review.

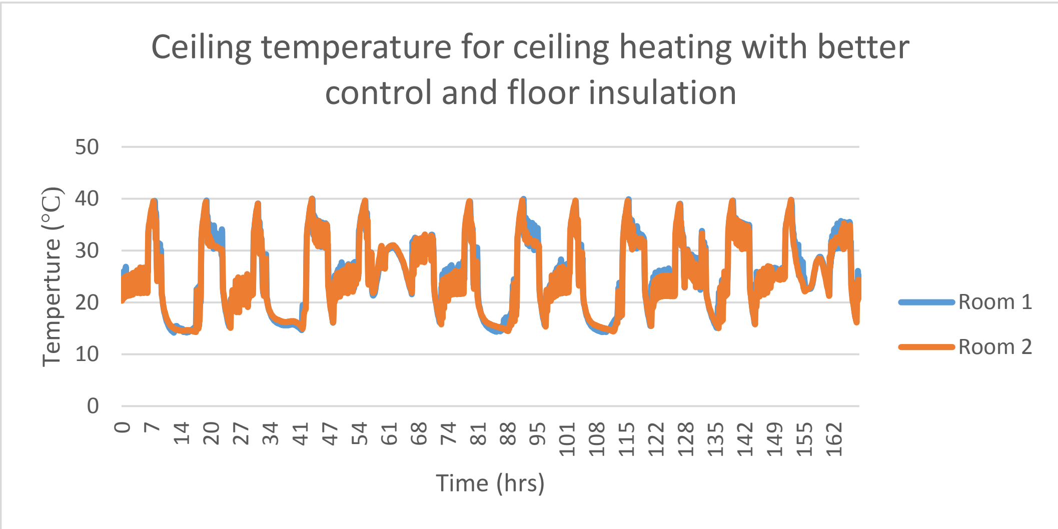

Figure 43: Ceiling heating with better control and floor insulation ceiling temperature

Figure 43 above shows the ceiling temperature. The ceiling temperature ranges from around 15°C-40°C. At no point does the temperature rise above the thermally comfortable maximum of 46°C. The key difference here is the drop-off in temperature compared to the floor heating. The fall in ceiling surface temperature is faster here than floor systems. The concrete in the floor construction acts as a thermal store and continues to release heat, however the ceiling does not have the same attributes and when heat input to the panel stops so does heat input to the room. The ceiling temperature is also more erratic than floor temperature in UFH systems, specifically when zone temperature is being maintained rather than increased. This may be due to its faster reaction time, where it heats up quickly to meet the temperature set point, then cools quickly as no heat is stored in the construction, then heats up again.

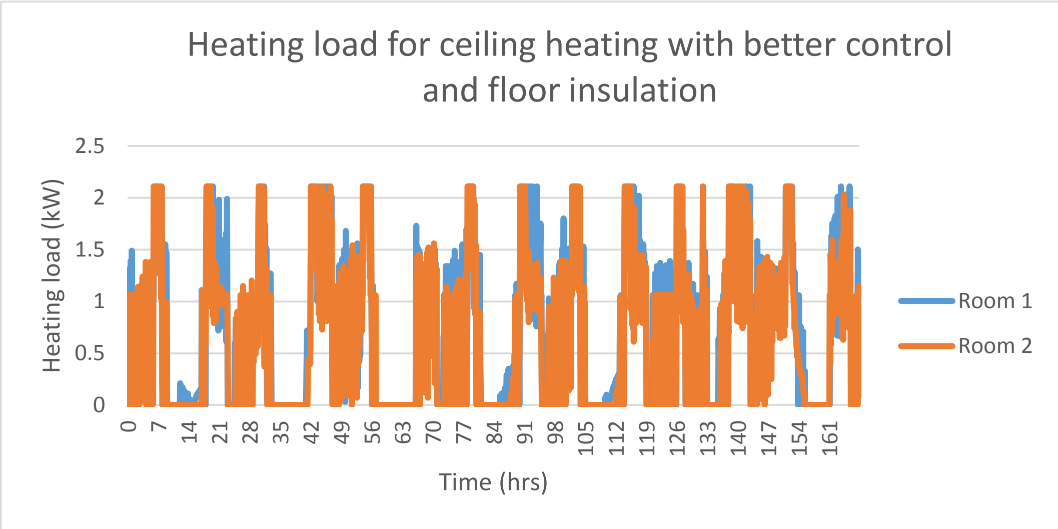

Figure 44: Ceiling heating with better control and floor insulation heating load

This variable ceiling temperature is mirrored in the heating load shown in Figure 44. The heating load in constantly varying between 0W and the max of 2111W. Despite the floor insulation Room 1 still requires larger heat input during various periods.

Table 13: Ceiling heating (better control) overall heat input, heating hours, unmet heating hours and COP

	Room 1	Room 2
Total heating input (kWhrs)	170.85	111.13
Total heating hours (hrs)	134.1	98.2
Unmet heating hours (hrs)	5.7	4.1
COP	6.46	6.46

Tables 12 and 13 show the overall heat input, heating hours, unmet heating hours and COP for this scenario without and with insulation. Firstly, for Room 2 the insulation has little effect, only reducing unmet heating hours by 0.1. The total heating input and hours is even increased slightly, possibly as the insulation stores some heat and the floor is not exposed to a cold area. However, for Room 2 the insulation significantly reduces heating input and heating hours. The unmet heating hours are also slightly reduced. This shows the importance of floor insulation in LTH systems for zones with a floor that shares a boundary with the ground. It is important not only for UFH but also ceiling heating panels.

Table 14: Ceiling heating (better control and floor insulation) overall heat input, heating hours, unmet heating hours and COP

	Room 1	**Room 2**
Total heating input (kWhrs)	126.18	111.85
Total heating hours (hrs)	115.2	98.8
Unmet heating hours (hrs)	4.4	4.0
COP	6.46	6.46

With insulation the total heating hours are similar to the floor heating simulation in section 4.2.3, showing an increase of about 15kWhrs (Table 14). The reverse is seen in the total heating hours, with significant decrease in heating hours for this case. This can be attributed to the faster reaction time. This ceiling heating configuration also has the lowest unmet heating hours of any simulation so far, including the base case. With its moderate reaction time and effective control in can achieve thermal comfort levels very similar if not better than the base case. The COP as before was based on flow temperature of 50°C to give COP=6.46. This is directly in-between the base case COP=4.03 and the floor heating case COP=8.80. This system has an intermediate COP so could be more energy efficient. It has very low unmet heating, so is very thermally comfortable, however this does come at the cost of a high total heating input.

4.3.3 Better Control with Floor and Wall Insulation

A final simulation was run with the same control as before, but with both floor and wall insulation. The same wall insulation is used as in the floor heating system. The maximum heating capacity remained as 2111W. The results from this simulation for the zone temperature, ceiling temperature and heating load, were similar to previous cases. The system characteristics have been discussed in detail already, so it was felt that discussing these results which came out as expected would be repetitive and trivial. These results can be found in Appendix F for reference if required.

Table 15: Ceiling heating (wall and floor insulation) overall heat input, heating hours, unmet heating hours and COP

	Room 1	**Room 2**
Total heating input (kWhrs)	73.36	58.43
Total heating hours (hrs)	75.1	64.1
Unmet heating hours (hrs)	3.6	2.6
COP	6.46	6.46

Table 15 shows the overall heat input, heating hours, unmet heating hours and COP for this control scheme. The unmet heating hours here are very low, below 4 hours for both rooms. The results here are provide better unmet heating hours than the base case, however this comes with an increase in total heating input. Compared to the similar floor heating simulation with floor and wall insulation, the unmet heating hours in this case are again lower. However, the floor heating system has lower total heating input and a higher COP of 8.8.

4.3.4 Comparison of Ceiling Heating Configurations

In this section the ceiling heating system iterations and base case are compared. Only results from Room 1 are presented so the graph is not cluttered, and Room 1 is likely to require more heating so represents the worst case scenario. One day is chosen to allow for in-depth detail. This is shown in Figure 45.

Although it has been established that the ceiling heating panel has a faster reaction time than UFH, it is clear that the base case is still the fastest. The scenario with regular control shows that the control has to be changed as the zone temperature is rarely within thermally comfortable conditions. The simulation with better control and insulation reaches the set point quickly due the preheating of the zone. It does this before the base case, however when the temperature drops during the day the reaction time of the base case in the evening heating period is much quicker, with the ceiling heating system reaching the set point over an hour later.

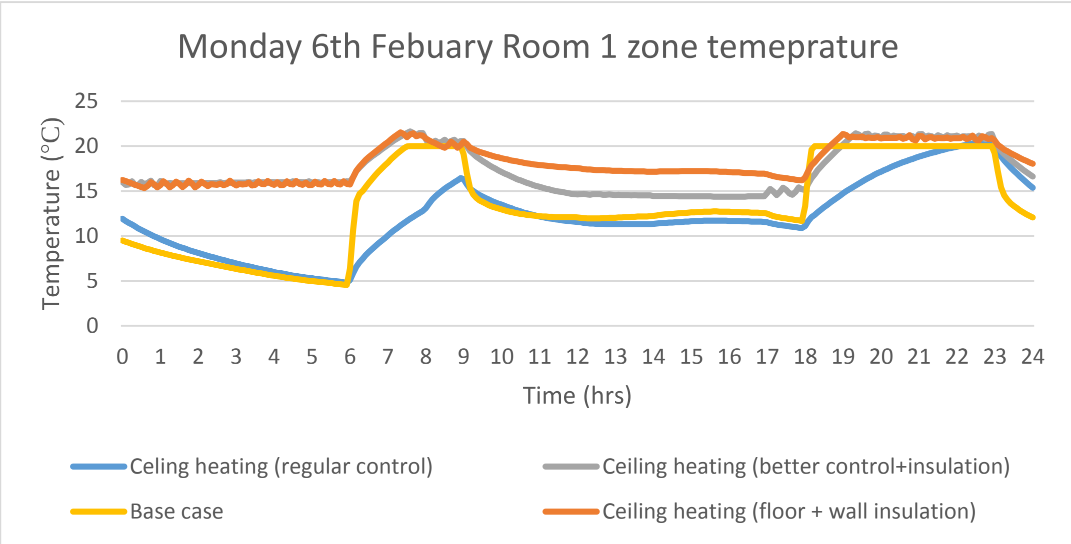

Figure 45: Monday 6th February Room 1 zone temperature ceiling heating systems

The temperature of the room can be seen to fluctuate more for the ceiling heating than in the floor heating. The faster reaction time means that the heating comes on and off a lot when maintaining temperature and the heating load fluctuates also as the heat is provided directly to the zone. UFH is slower so a more even heating load can be applied and temperature remain more constant. Ceiling heating systems also primarily rely on radiation rather than convective heat transfer, unlike UFH which typically has a 50/50 split between the two. Therefore, the air zone temperature is effected more. Resultant temperature also takes into account surface temperatures and as the ceiling varies a lot so does resultant temperature to a lesser extent. The temperature is seen to reduce at a slower rate with the wall insulation, which reduces the heating input over the period.

Table 16: Summary of ceiling heating total heating input, unmet heating hours Room 1

System Configuration	Total heating input (kWhrs)	Unmet heating hours (hrs)
Base case	60.41	7.0
Regular control	90.02	36.1
Better control + insulation	126.18	4.4
Floor + wall insulation	73.36	3.6

The total heating input and unmet heating hours are shown in Table 16. The lowest unmet heating hours come with the better heating schedule and floor and wall insulation, this also gives reasonable total heating input. The base case and floor + wall insulation case give the best balance of both low total heating input and low unmet heating hours. However, the COP of heat pump in the base systems would be 4.03, compared to 6.46 for ceiling heating systems. The system with floor and wall insulation is the one with the best balance of low unmet heating hours, high COP and lower total heating input. Ceiling heating systems are simpler to install in current buildings in most cases. So, although they are less energy efficient than UFH, they can provide better thermal comfort and over the lifetime of the system it may be easier and more economical (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016). In the similar floor heating system with floor and wall insulation the total heating input is less and the COP is higher, but if the zone requirements are for very low unmet heating hours then although the ceiling heating system is less energy efficient it can provide better thermal comfort.

4.4 Wall Heating Panel

4.4.1 Regular Control Scheme

The next LTH system to be tested is to use the wall as the heat emitter. It is more common when using the wall as the heating surface to have a panel that covers a portion so the wall not the whole surface. This increases the convective heat transfer of the panel. Therefore, the exterior wall was split vertically into two equal sections, the section near the door was chosen as the heat emitting section for this analysis. The area of this section was 6.75m^2. Assuming a maximum panel temperature of 46°C, the maximum heating capacity was calculated as 280.0W/m^2. So, the heat output for this case was 1890W, full sample calculations can be found in Appendix B. The same control schedule as the base case was used.

The resultant zone temperature is shown in Figure 46. Compared to the previous two LTH system (floor and ceiling heated panels) simulations with regular control, the

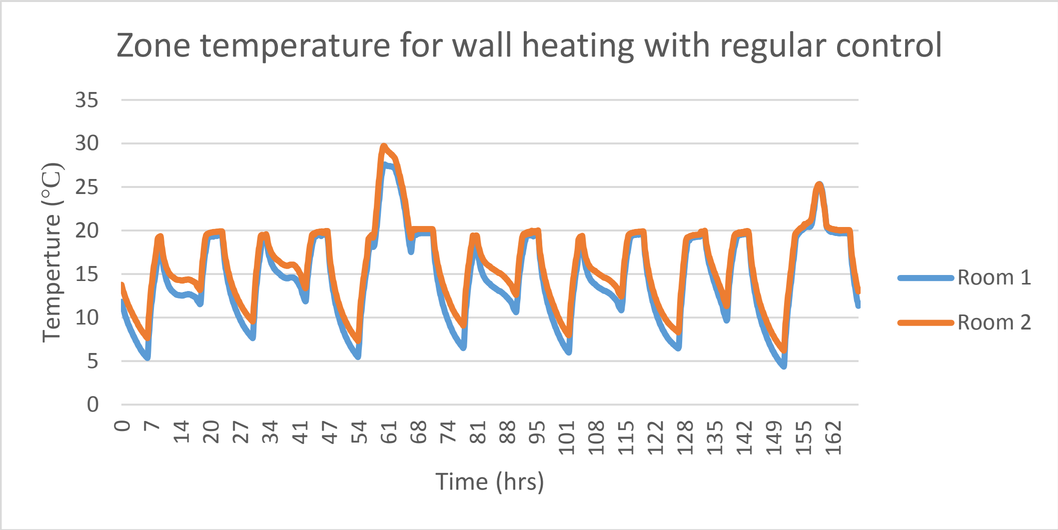

Figure 46: Wall heating with regular control zone temperature

temperature here reaches the set point more often. The temperature range remains the same, however the time taken to reach the 20°C set point is reduced. This is because, unlike floor heating the wall panel temperature can be allowed to reach a higher temperature, so has a higher heat output and can react faster. This system also out performs the ceiling panel for these characteristic. As although the panel area is smaller the heat output is very similar due to the increase in convective heat transfer. This results in the hot air being distributed around the rooms faster. The wall panel also heats the bottom and top of the room at the same time, unlike the floor and ceiling systems. The panel is also positioned on the external wall which would typically be colder, so this area stay warm and the other wall shares a boundary with another room so stays warmer.

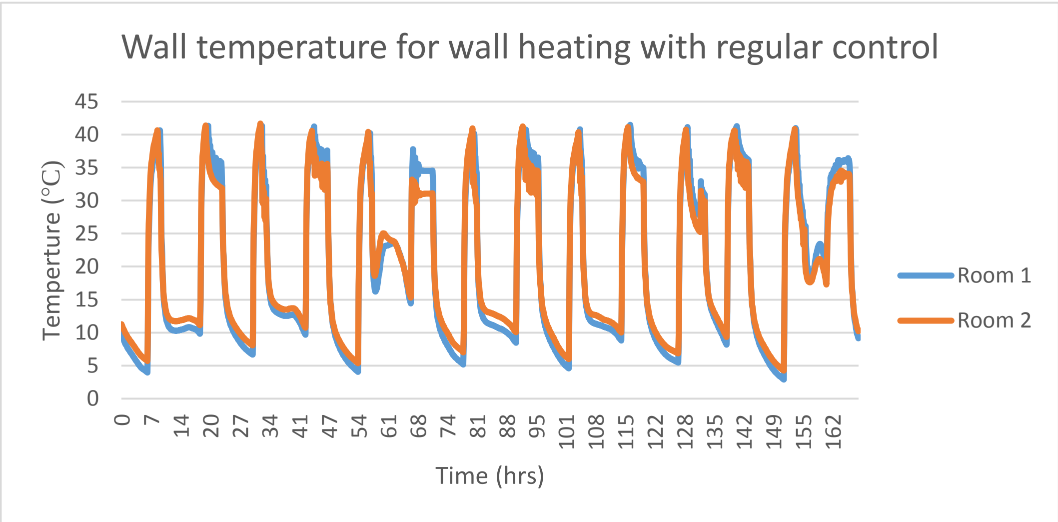

Figure 47: Wall heating with regular control wall temperature

Figure 47 shows the wall panel temperature. The wall surface temperature is seen to peak at around 42°C, this is below the set maximum of 46°C so the wall remains within comfortable conditions. The heated surface temperature rises quicker than the ceiling heated systems, because although the heat input is less it is added to a smaller area. The total heating load for this case can be found in Appendix G, they show nothing already not discussed, and the ceiling temperature show the period of heat input. The temperature of the wall falls very quickly once the heating period ends. This outlines one of the benefits that UFH has over wall panels. Similar to the ceiling panel, there is no large thermal mass to store heat in the wall so temperature falls quickly. In UFH systems heat in stored in the floor so heat input can be stopped and the floor temperature will remain high for longer.

Table 17: Wall heating (regular control) overall heat input, heating hours, unmet heating hours and COP

	Room 1	Room 2
Total heating input (kWhrs)	96.32	85.88
Total heating hours (hrs)	62.7	61.8
Unmet heating hours (hrs)	23.6	18
COP	6.46	6.46

Similarly to the other LTH system this wall heating configuration struggles to meet thermal comfort conditions for extended periods, with a significant increase in unmet heating hours compared to the base case. The overall heat input, heating hours, unmet heating hours and COP are shown in Table 17. This systems total heat input closely matches that of both other LTH systems, but the unmet heating hours see a reduction of between 10-15 hours. As explained previously this can be attributed to the increase in convective heat transfer, and higher heat output per m^2. The COP For the wall heating panel the same as the ceiling systems, with a flow temperature of 50°C. In this configuration this system provides the best thermal comfort of the three LTH systems with very similar total heat input. However, the UFH is more energy efficient due to its very low flow temperature.

4.4.2 Better Control with Floor and Wall insulation

In analysis of previous LTH systems it has clearly been established that the control and insulation improvements are required for effective operation. Therefore this systems includes both floor and wall insulation improvements, using the same materials as in previous cases. The main heating periods remain the same, but outside the periods of expected occupancy a basic heating controller is used to keep the zones at a 15°C set point. The maximum heating capacity was not changed.

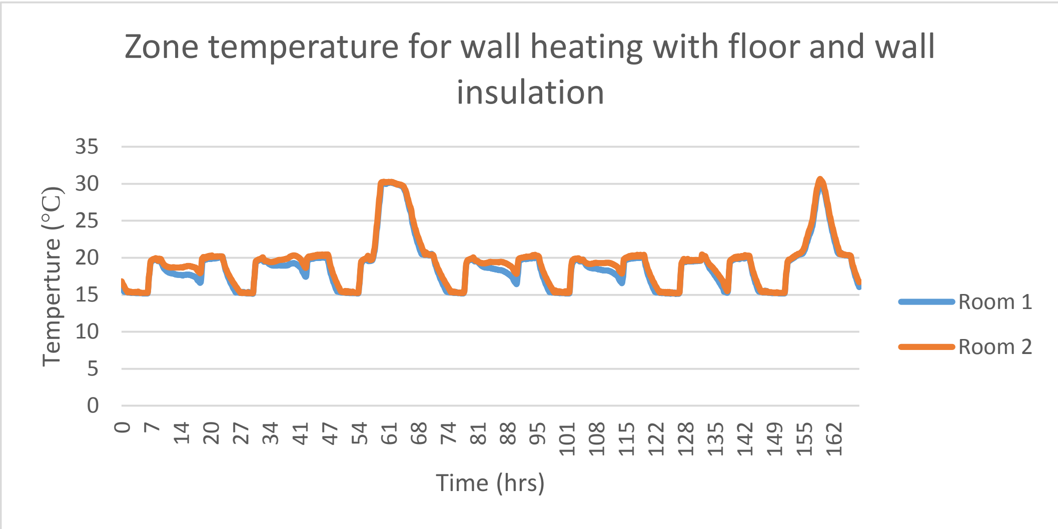

Figure 48: Wall heating with better control and floor+wall insulation zone temperature

The temperature of the rooms, shown in Figure 48, confirm that this wall heating system can easily meet the heating requirements of the rooms. The temperature is consistently within thermally comfortable conditions during periods of expected occupancy. The reaction time of the systems is the fastest of any of the LTH systems. Even during the heating downtime from 09:00-18:00 the temperature often remains above 15°C. This shows that the insulation is reducing heat loss and generally there is no heating load required during the day. Although the insulation prevent excessive heat loss the temperature still falls quite quickly overnight, because unlike UFH there is not stored heat that is released slowly.

The wall temperature is shown below in Figure 49. The floor temperature remains with comfortable conditions during expected occupancy, peaking at around 43°C. The temperature drop off sees a reduction in rate due to the wall insulation, however it still doesn't come close to UFH systems ability to retain heat. The temperature is variable, which is due to its fast reaction time.

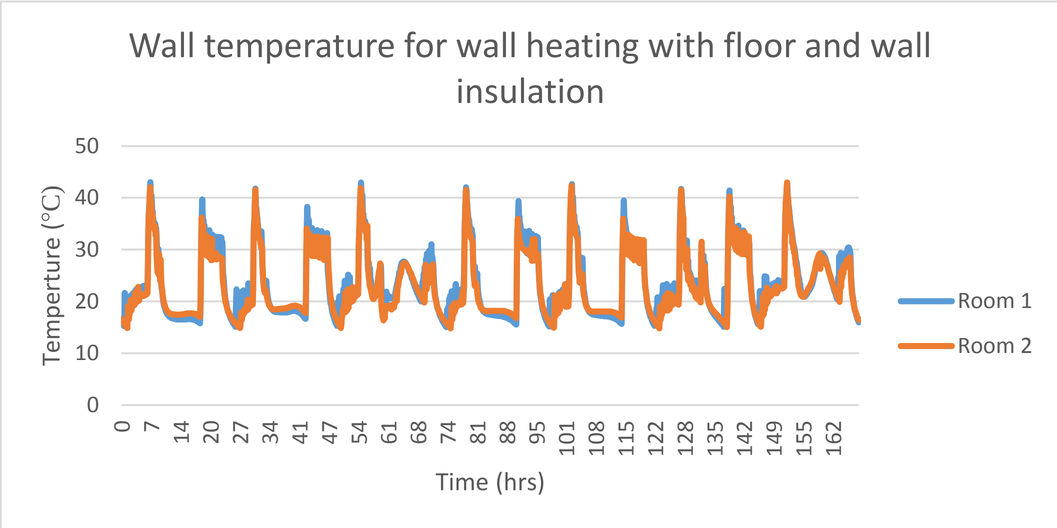

Figure 49: Wall heating with floor and wall insulation wall temperature

Finally, the overall heat input, heating hours, unmet heating hours and COP is shown in Table 18. This wall heating system requires the lowest heating input of all the previous LTH systems and the base case. The unmet heating hours are also low, not as low as the ceiling heating system, but lower than the UFH and base case. However, this system has the same supply temperature as the ceiling heating. Therefore, the UFH has a better COP and is more energy efficient. This wall heating configuration can achieve thermal comfort levels very close to ceiling heating, with similar energy consumption to UFH. Wall heating could provide a good middle ground between the thermal comfort of ceiling heating and the energy efficiency of UFH.

Table 18: Wall heating (floor and wall insulation) overall heat input, heating hours, unmet heating hours and COP

	Room 1	**Room 2**
Total heating input (kWhrs)	56.65	46.19
Total heating hours (hrs)	81.2	69.4
Unmet heating hours (hrs)	4.1	3
COP	6.46	6.46

4.4.3 Comparison of Wall Heating Configurations

In this section the wall heating system iterations and base case are compared. Only results from Room 1 are presented so the graph is not cluttered, and Room 1 is likely to require more heating so represents the worst case scenario. One day is chosen to allow for in-depth detail. This is shown in Figure 50.

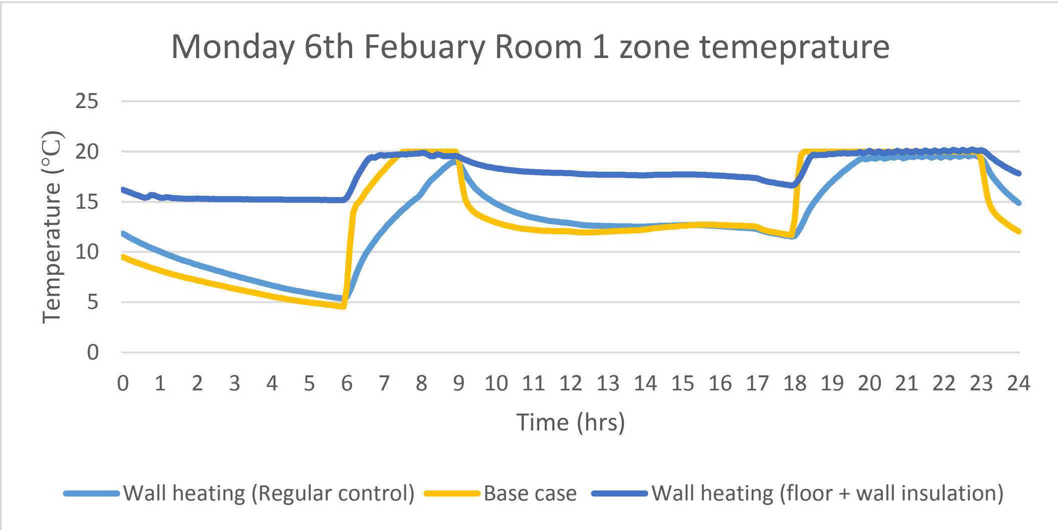

Figure 50: Monday 6th February Room 1 zone temperature wall heating systems

The base still has the fastest reaction time. However the wall heating panel is the only LTH system to reach thermally comfortable conditions in the morning heating period with regular control. This can be accredited to the higher convective heat transfer which helps to distribute heated air around the room more effectively. With the temperature maintained at 15°C outside of the main heating periods the temperature set point is reached by the wall heating faster or at the same time as the base case. The insulation also reduced heat loss so the temperature stays high even when the heating turns off.

Table 19: Summary of wall heating total heating and unmet heating hours for Room 1

System Configuration	Total heating input (kWhrs)	Unmet heating hours (hrs)
Base case	60.41	7.0
Regular control	96.32	23.6
Floor and wall insulation	56.65	4.1

The wall heating total heating input and unmet hours for Room 1 is shown in Table 19. The lowest results are from the wall heating system with better control and floor and wall insulation. The total heating input and unmet heating hours are slightly lower than the base case, and the COP for the base case is higher and therefore less energy efficient. The wall heating panel like the ceiling heating panel would most likely, be easier to retrofit into a current building. So, although they are less energy efficient due to higher flow temperatures, it could be more economically viable to have a wall heating system in the long term. Wall heating panel can also provide improved thermal comfort, as shown here and in other similar studies (Karabay et al., 2013). The inclusion of floor and wall insulation would incur greater initial costs, but these would be balanced by energy savings over the lifetime of the system. The insulation also seems to be crucial in all of the LTH system iteration, without it the required total heating input to maintain comfortable conditions typically doubles. As the rate of heat input is slow the rate at which heat is lost must also be reduced to increase the reaction time of the systems.

4.5 Alternative Simulation Route

The previous simulations introduced to the heat input at the inside surface of the selected heating surface. Although, this gives a good representation of the actual operation of the system, with having to model detailed plant components it does overlook some characteristics of the real life operation. Firstly, particularly for Floor heating systems, the pipes are embedded in an underfloor layer. This is typically concrete. Although it is possible to have the heat input to a node within the surface, it was felt that it was better to accurately calculate the typical output of the floor using methods from literature, and input this data into ESP-r. This overlooks that generally the heat is first transferred from the pipes to concrete, then to the floor surface. In the previous model the concrete layer would still heat up as although heat isn’t directly introduced into it. So, it still represents the system well. This concept is less important in ceiling and wall systems, as the work more like conventional radiators but with a larger area and lower temperature. Where heat is transferred from pipes to a metal panel that heat the desired zone (Hand, 2015).

With this in mind, through studying possible controls and model configurations in ESP-r and other similar studies, an alternative modelling process was investigated. It was found that it was possible to accurately model a UFH system in ESP-r using the multi sensor heating/cooling sensor. The multi sensor control is used to inject or remove heat in one zone based on conditions in another zone using auxiliary sensors. This type of control is on/off so a short time step is used.

Therefore, to allow for this control to be utilized a thin zone below the two original rooms is modelled, this represents the floor construction. The floor in the room is replaced with just a layer screed to represent the top of the floor. The thin floor zone construction is composed of a typical floor construction (same used in previous cases), with an air gap to represent where the pipes would typically be located. To represent the fluid that delivers that heat, heat is injected into the air node and high heat transfer coefficients were used to ensure heat is transferred to the construction above and into the rooms. The heat transfer occurs over the whole area as the air is used, in real life the pipes clearly wouldn’t be able to achieve this so this is also taken into account in the heat transfer coefficients (Hand, 2015).

The controller for this floor zone, senses the temperature in Room 1, and if this is below the set point heat is then injected into the air node. The temperature of the heat injection can also be controlled which allows for direct control of the flow temperature rather than estimated the heating capacity. A simulation was run using this method. The same model as used before was altered to accommodate this. Already mentioned an extra thin zone was introduced to represent the floor, and the floor in the room was changed to just the top layer of a floor construction. The rooms were also changed so that they are identical, and include wall insulation as this has been established as crucial to effective performance. The control used here is the same as the control used for the floor heating configuration with better control in section 4.2.3, with a 20°C set point during the day and 15°C over night. The “flow” temperature was set as a typical UFH system of 35°C. The temperature of Room 1 and the floor temperature are shown in Figures 51 and 52.

The same simulation method was used to model a ceiling heating system. Again including a thin zone to represent the ceiling construction. The same control schedule is used with a 50°C flow temperature. Figure 51 and 52 show the Room 1 zone and floor temperature.

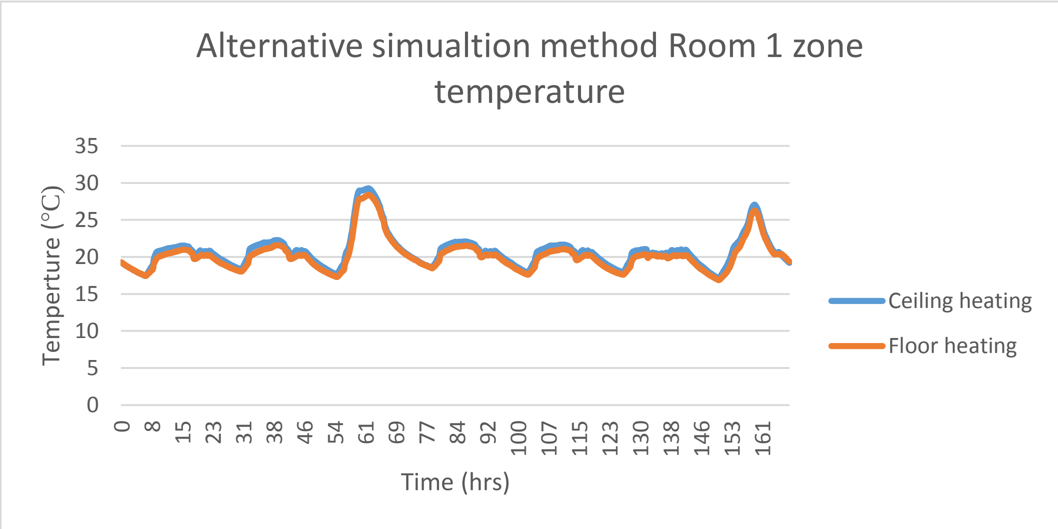

Figure 51: Room temperature for floor and ceiling panel alternative simulation method

The temperature in the room follows very similar trend for both the floor and ceiling heated panel systems. The resultant temperature of the room is also generally a few degrees over the set point, especially in the ceiling heated panel systems. This is as heat is injected into the system up to the point when the set point is reached, the heat input then stops but heat continues to be released by the warm surface. Also in this scenario the flow temperature is fixed at 35°C, so when the temperature drop below the set point again there is a significant heat input and the temperature is likely to overshoot the set point. The surface area of the heat emitter is also high, so the resultant temperature is higher than the air temperature.

The temperature only falls to a minimum of around 17°C. Again showing the ability of the heating system to retain heat and release it slowly. The two systems simulated here have very similar zone temperature results because their construction is very similar. However, ceiling heating panel are often not built into the ceiling constriction, and sometime installed hanging from the ceiling. So, typical ceiling panels may give different result, more similar to previous simulation. The ceiling panel in this case still shows a slightly faster reaction time due to the higher flow temperature and therefore higher heat input.

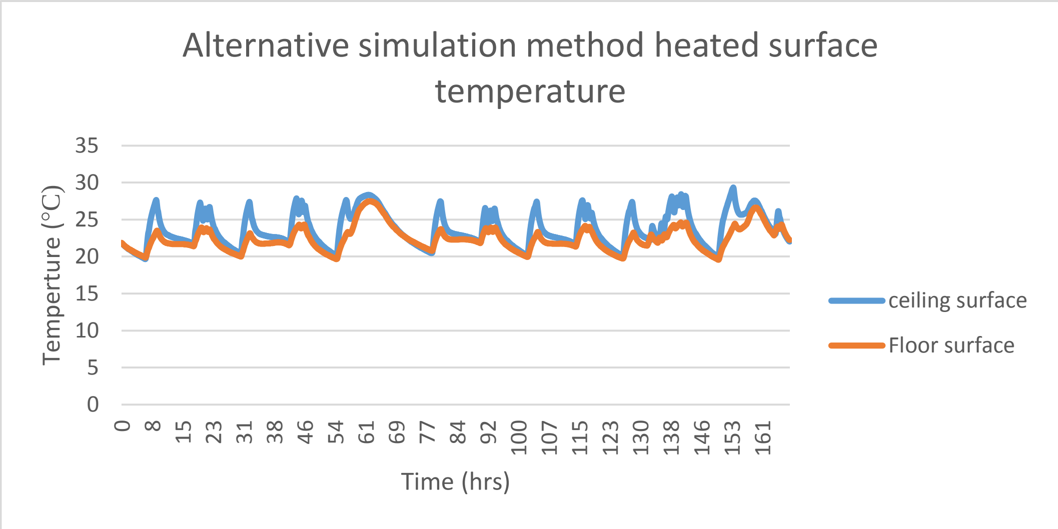

Figure 52: Surface temperature for floor and ceiling panel alternative simulation method

The temperature of the heat emitting surface for Room 1 can be seen in Figure 52. Firstly at no point does the temperature of the heated surface move outside the thermally comfortable temperature range. The ceiling heated panel, like previous scenarios, reaches higher temperatures the floor heating panel, due to the higher flow temperature and higher surface temperature upper limit. This is what allows for a faster reaction time and improved thermal comfort. The results here are similar to results from the previous simulation process, showing that although there were assumptions the system overall gave a good representation on the real operation.

Table 20: Alternative simulation method overall heat input, heating hours, unmet heating hours and COP

	Floor panel	**Ceiling panel**
Total heating input (kWhrs)	38.75	56.75
Total heating hours (hrs)	40.9	34.7
Unmet heating hours (hrs)	5.3	2.25
COP	8.80	6.46

The overall heat input, heating hours, unmet heating hours and COP for these cases are shown in Table 20. The total heating input for the two system are both almost 20kWhrs less. This is most likely due to the extra construction which would reduce heat loss, and the boundaries of the floor. The heat transfer rate may also be unrealistically high resulting in a much quicker heat transfer than what is observed in reality. Similar to previous cases with alike control and construction, the ceiling panel can provide more heat with reduced heating hours, due to the higher flow temperature. This also gives lower unmet. The heating hours are also reduced as the controller is on/off so there is variability in the heat input. The final observation here is the same as before. Ceiling heating panel provide better levels of thermal comfort, but require a higher total heat input and a lower COP so are less energy efficient. Therefore, if the aim of the system is high thermal comfort ceiling panel are better, but if energy efficiency is the main focus UFH provides much better energy efficiency with similar thermal comfort. Ceiling panel are generally easier to retrofit so may be more suitable in such cases. Although this model gives reasonable results it would benefit from additional development.

4.6 Results Summary

An assortment of results have been presented in this section from suitable simulations, to carry out analysis of what LTH systems and fabric upgrades are required to accommodate the continuing shift to lower temperature distribution and heating systems. In this section key results from the analysis are summarised.

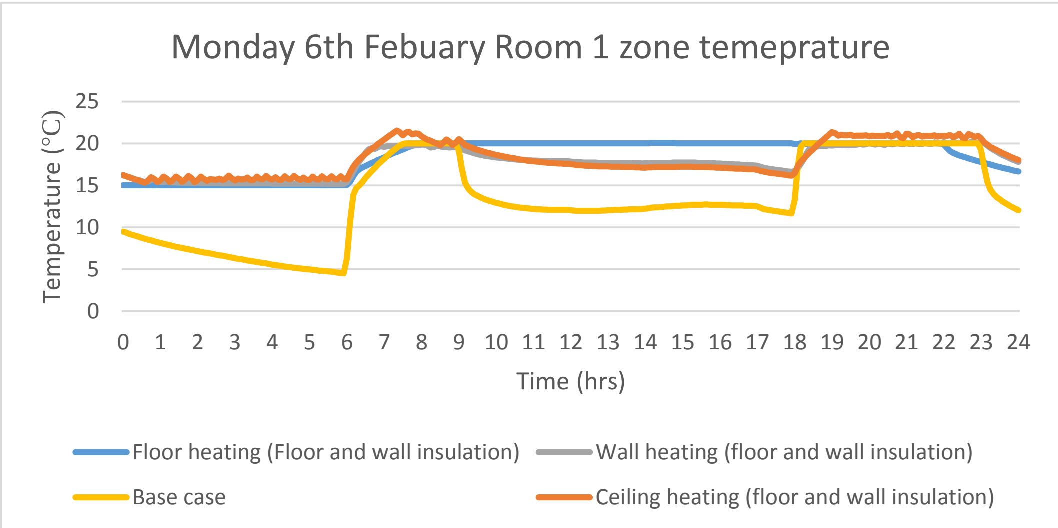

Figure 53: Best floor, ceiling and wall heating configuration using original simulation method

Figure 53 above shows the daily trend of the temperature for Room 1 in the most effective iterations of each LTH system. Throughout the results the base case has the fastest response in terms of temperature increase when heat is input to the system. All the LTH systems have a slower reaction time, so the control was changed to maintain a higher set point throughout the day outside of expected occupancy. This allowed the LTH systems to reach the temperature set point at a similar time to the base case, limiting the number of unmet heating hours. The most effective LTH systems utilised more suitable better control schemes, and the inclusion of floor and wall insulation. The floor insulation was particularly effective in the ground floor Room 1.

The floor heated panel provides most constant high temperature, but the ceiling and wall panel outperform it in terms of response time. The ceiling and wall panel provide very similar temperature trends as they operate with similar flow temperatures and heat output per m^2. The wall and ceiling mounted panels have a faster response as they can reach higher temperatures, unlike the floor panel which is limited to 29°C. The external wall and floor insulation are crucial in all cases to have similar results to the base case in terms of total heat input. The wall heating panel is also able to match the temperature of the ceiling panel despite being half the size. This is due to the increased convection which mean a panel half the size give a similar heat output. Ceiling systems are sometimes installed with cold strips around the edge or hanging from the ceiling to increase convection, so this could be investigated further in future (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016).

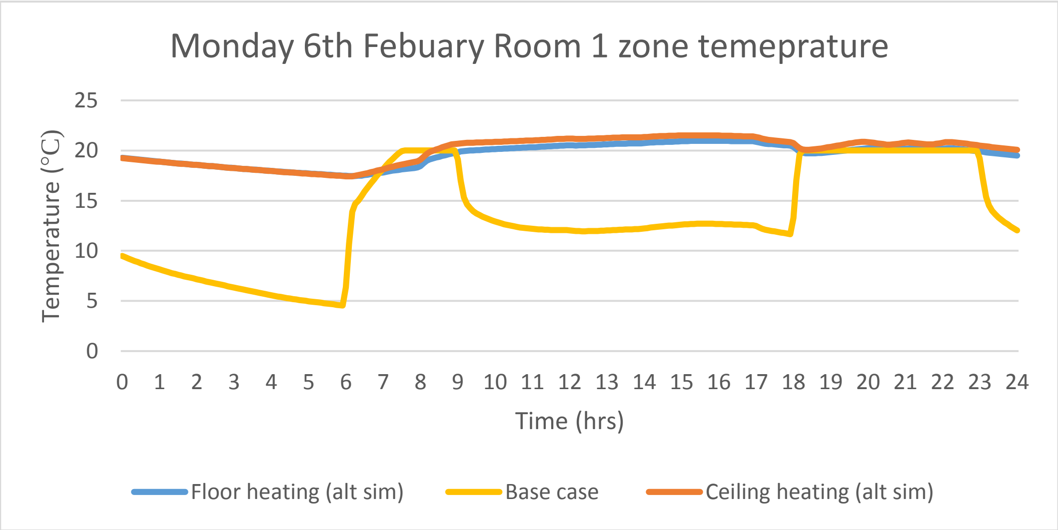

Figure 54: Floor and ceiling heating using alternative simulation method

The Room 1 daily temperature trend for the systems modelled using the alternative simulation method are shown in Figure 54. Firstly, temperature of the Room maintains a higher temperature even during heating downtimes, because of the residual heat in the separate thin floor and ceiling zones. This is accurate for most UFH systems, but ceiling system are not commonly built into the fabric of the building so may be slightly misleading. The two systems match very closely, both have a slow reaction time due to the location of the heat injection. As previously discussed ceiling panel floe temperature can be higher so the reaction time is slightly quicker, which can also be observed here. This model and simulation method was briefly investigated and would require more development to provide truly accurate results. As highlighted by the constant high temperature, which is beneficial, but would be a waste of heat in conventional expected occupancy periods.

Table 21: Summary of LTH system total heating input, unmet heating hours and COP

System Configuration	Total heating input (kWhrs)	Unmet heating hours (hrs)	COP
Base case	60.41	7.0	4.04
Floor heating	58.62	7.1	8.80
Ceiling heating	73.36	3.6	6.46
Wall heating	56.65	4.1	6.46
Floor (alt simulation)	38.75	5.3	8.80
Ceiling (alt simulation)	56.75	2.25	6.46

The total heating input, unmet heating hours and COP of the significant system configurations are shown in Table 21. The best results are provided in the alternative simulation method, however since this model still requires work to be totally accurate the focus is on the previous results. The floor panel provided very similar total heating input and unmet heating hours as the base case, but with a COP over double the base case. Therefore, would give much better energy efficiency. The ceiling panel has a higher heating input than other systems, but gives the lowest unmet heating hours, with an intermediate COP. The wall panel gives the most balanced energy input, efficiency and thermal comfort in low unmet heating hours. It does this despite the reduced heated surface area. The wall and ceiling systems are generally easier to retrofit than UFH.

5 Conclusion

The built environment is estimated to consume over 30% of global energy, and therefore is also for one third of greenhouse gas emissions. Consequently, there has been a rise in the focus and uptake of energy efficient and sustainable technology in the building sector. With the aim of reducing emissions and reaching emission reduction targets set by many governments worldwide. Space heating in a significant energy usage so energy reduction methods here are particularly important. One such technology is using low temperatures for space heating.

With improvements in LT supply and distribution technology, there is increased focus on these types of system from both academics and governments. With a large portion of existing buildings still expected to be in use for many decades, the challenge is to find a way to effectively implement LTH systems into current buildings. This report has focused on LTH technology and its place in current and future of space heating systems. Particular focus has been on the current housing stock and what LTH systems can be realistically retrofitted into existing buildings.

5.1 How the Aims and Objectives were Accomplished

The aim of the project was to find a suitable route for retrofitting current housing to allow for use of LTH, with fabric and plant system upgrades. A set of objectives was devised to be followed, and achieve the aim. These can found in the introduction.

The first two objectives were simple to achieve through an in-depth research in relevant topics. They were completed through the literature review, which gave a better understanding of the topic and how to proceed with the study.

The next two objectives were completed through the BEM software ESP-r. A simple two room model was created to allow for analysis of a generic building. Once a base case system had been established and simulated, selected LTH systems were simulated in various iterations. This gave an insight into the behaviour and operation of these system, which in turn allowed for an in-depth understanding of them. The fabric of the zones were also changed to analyse the effect of such alterations.

Data was collected throughout from ESP-r, and analysed. These were then discussed and compared to the base case and each other to allow suitable conclusions to be drawn. This ultimately enable the aim of the study to be reached.

5.2 Key Findings

Through analysis of results from a range of different LTH model and system iterations in a simple Room model, it was possible to address the issue of what LTH systems and fabric upgrades are suitable or required to allow the shift to a low temperature space heating network in an existing building. Results showed that if installed correctly common LTH systems with fabric upgrades and better control can effectively replace conventional high temperature space heating systems, with varying success. However, some systems provide greater challenges when retrofitting.

Firstly, a base case with a conventional heating system on a ground floor room was simulated. In standard winter week this room had a total heat input of 60.41kWhrs and the unmet heating hours totalled to 7 hours. The COP of a heat pump is this systems was also calculated as 4.03.

Three LTH systems most prevalent in literature were chosen to be modelled. These were UF, ceiling and wall heated panels. The first to be simulated was the UFH system. The floor system was found to have slow reaction time, and poor results initially. However, after a number of system iterations with various improvements, including improved control and fabric upgrades. The best iteration gave similar results to the base case with a much improved energy efficiency. A result of the low flow temperature of 35°C, which gave a COP of 8.8. The total heat input came to 58.62kWhrs and unmet heating hours were 7.1hrs. The UFH system also gave very consistent temperature throughout the day, therefore would be suitable for zone with variable occupancy periods. The very low temperature here gives the best COP of all the systems in this study, however from the literature UFH systems can be challenging and expensive to retrofit. The whole floor structure of the zone would have to uprooted and replaced, resulting in a lengthy and disruptive process. However, the greater energy saving could be worth investing into for a long term project.

The second LTH systems to be tested was a heated ceiling panel. This system was found to have a faster reaction time than the floor system, but still not as fast as the base case. Again through various iterations the final simulation gave good results. The flow temperature here is higher (50°C) here as the panel temperature is not limited to a lower temperature as is the case in floor constructions. This gave faster reaction times and therefore better levels of thermal comfort, however this negatively effects the total heat input and COP. The total heat input increased to 73.36kWhrs and the COP dropped to 6.46. The unmet heating hours fell by almost half to 3.6hrs. Ceiling heating panels are easier to retrofit than UFH systems. They can often be installed over the current ceiling construction or even as a hanging panel. This reduces the cost of installation and disruption. Although, the energy efficiency is reduced, reaction time and thermal comfort is improved, so ceiling panel may be more suitable to zones with high thermal comfort requirements and zones with changing occupancy and heating loads.

Finally, heated wall panel were analysed. This systems was found to have very similar characteristics to the ceiling panel despite the panel having half the surface area. The flow temperature in this case was the same as the ceiling panel so gave a COP of 6.46. Again the reaction time here was reasonable, and the total heating input dropped to 56.65kWhrs and unmet heating hours was 4.1hrs. The increased convective heat output of the wall panel allowed it to closely match the ceiling panel. The wall panel gives a good balance between the other two systems, giving similar thermal comfort to the ceiling panel without sacrificing energy input and energy efficiency. Wall heating panels are possibly the easiest to install in a current building of all three. And can be installed in the middle of a room to provide even heat distribution.

The alternative simulation method gave some promising initial results, but is was felt that to provide any concrete conclusions from the results the model and simulations would have to be developed further first.

Throughout the three system simulations it was found that improvements in the floor and wall insulation were crucial to the success of the system. Along with an improved control schedule. Overall the most suitable system identified to be retrofitted along with these insulation improvements is likely to be the heated wall panel. However, if there is are specific requirements of high thermal comfort or energy efficiency, then the ceiling panel or UFH systems may be more suitable, despite their shortcomings.

5.3 Limitations of the Project

Although the findings of the project gave some encouraging results in the possibility of retrofitting low temperature heating systems to current buildings, a number of limitation have been identified.

Firstly during the model a generic model was used, housing types and construction vary so results from different housing archetypes may changes. During the simulations a range of assumptions were made in terms of construction, control, occupancy which would affect the outcome of the results. These was acknowledged and taken account of during analysis of the results. The heat injection point was also generally the inside surface which doesn't take account of the heat distribution network at the supplied and lost there.

The actual energy efficiency and energy saving as a result of installing a LTH systems were not quantified exactly. This proved out with the scope to calculate direct energy saving from using a heat sources such as DH or a LT boiler. Therefore it was assumed a heat pump was used to simplify this.

It is also difficult to quantify how hard it would be to retrofit a system as each house is different and the challenges are always different, it is more of an art that a science. The project also took account of thermal energy the electrical load was not considered, specifically towards the heat pump.

5.4 Future Work

Firstly, the simulation period only considered one week. With more time it would be valuable to observe how the systems behave in different weather conditions, and if they are still effective over a whole year. The model could also be developed into a whole house to model how these systems would behave in a whole house rather than just a room. A mixture if system could be used which is sometime applied, for example UFH in the ground floor and forced convection upstairs.

Something that could be done is to accurately model the plant systems. This would give a very accurate representation of how the whole system works. The reduction in distributions losses of the systems could be quantified. Reduced losses one of the advantages of LTH system. With regards to the actual systems, a larger range of systems variation could be simulated. For example, specialised low temperature radiators with forced convection and air to air heat pumps. More simulations could also be carried out with the current systems, such as altering the flow temperature of the supply or including cold strips in the heated ceiling to increase convection.

A CFD analysis could be carried out to observe the air flow of the different system configurations. More accurate energy saving through converting to LTH system could be accurately quantified. Finally, an economic analysis of a LTH system could be carried out to assess the lifetime feasibility of such a system, through the initial investment required, energy saving, lifetime of the system and payback period.

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Appendices

Appendix A – Thermal Comfort

Thermal comfort in general is controlled by a building's HVAC systems. ASHRAE defines thermal comfort as "that condition of mind which express satisfaction with the thermal environment and is assessed by subjective evaluation." There are seven factors that influence thermal comfort: activity level, clothing, an individual's expectation, air temperature, radiant temperature, humidity and air speed (McDowell, 2007)(T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016).

Comfort profiles for various situations are shown in Figure 55. It shows that UFH provides better thermal comfort closer to the ideal, than conventional high temperature radiators (Bleicher & Vatal, 2016).

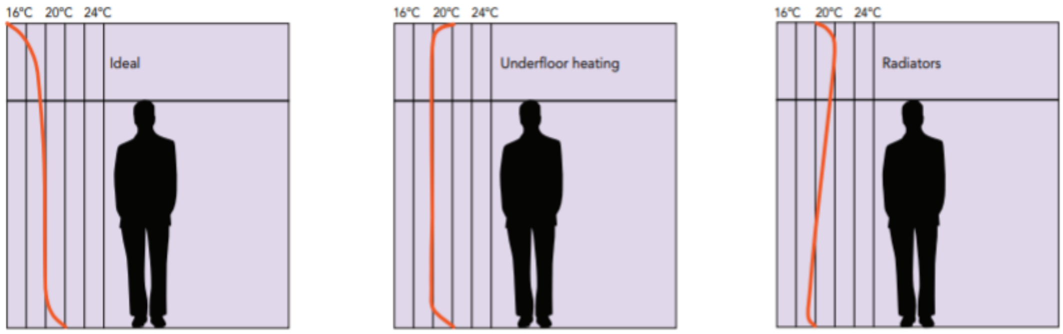

Figure 55: Thermal comfort profiles (ideal, UFH and radiators)
(Bleicher & Vatal, 2016)

Appendix B – Sample Calculations

UF Heat Output

The heat output from a floor heating system can be calculated using the following equation:

$$(4)\ \emptyset = 8.92\ (\theta_{fm} - \theta_i)^{1.1}$$

Where, $\emptyset$=heat output per unit area of floor (W/m^2), θ_{fm}=average floor temperature (˚C) and θ_i=room operative temperature (˚C) (CIBSE, 2016).

To calculate the maximum heating capacity, the room operative temperature was 20˚C. The maximum comfortable floor temperature is 29˚C, so this was used as the average floor temperature here. This is a change in temperature so ˚C or K can be used.

$$\emptyset = 8.92\ \left(\theta_{fm} - \theta_i\right)^{1.1}$$

$$= 8.92\ (29 - 20)^{1.1}$$

$$= 100W/m^2$$

This matches with the maximum heating capacity found in literature. With a floor area of 13.5m^2 this gives a maximum heating capacity of the room as:

$$= 13.5m^2 \times 100\frac{W}{m^2} = 1350W$$

Ceiling Panel Heat Output

Imperial units are used in these equations so the following conversion factors are used (Dincer & Zamfirescu, 2011):

$$°F = 1.8.(°C) + 32 = 1.8.(20°C) + 31 = 68°F$$

$$1\frac{BTU}{h.ft^2} = 3.1525\frac{W}{m^2}$$

The radiant heat output per unit area (heat flux) $\dot{q}_{rad}$ for radiant panels can be represented by the Stefan-Boltzmann equation:

$$\dot{q}_{rad} = \varepsilon_{eff}.F_{rp-uhs}.\sigma[(T_{rp} + 460)^4 - (T_{uhs} + 460)^4]$$

Where, T_{rp}=Panel surface temperature (˚F), T_{uhs}=area weighted unheated surface temperature (AUST) (˚F), ε_{eff}= $(1/\varepsilon_{rp}+1/\varepsilon_{uhs}-1)^{-1}$= effective emittance of space, where rp in the heated panel and uhs in the unheated surface, ε_{eff} is typically 0.87, F_{rp-uhs}=view factor between the heated and unheated surfaces=1.0, σ=the Stefan-Boltzmann constant=5.67x10^{-8} W/m^{2}K^4. This equation can be simplified for low temperature heating systems to give:

$$\dot{q}_{rad} = 0.15 \times 10^{-8}[(T_{rp} + 460)^4 - (AUST + 460)^4]$$

For indoor spaces AUST can be taken as the indoor air dry-bulb temperature (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016). To calculate the maximum heating capacity the indoor temperature was taken as 20˚C or 68˚F, and the maximum ceiling temperature was assumed as 46˚C or 114.8˚F. Therefore to maximum radiative heating capacity was calculated as:

$$\dot{q}_{rad,Max} = 0.15 \times 10^{-8}[(114.8 + 460)^4 - (68 + 460)^4] = 47.16\frac{BTU}{h.ft^2}$$

$$= 47.16 \times 3.1525 = 148.67\frac{W}{m^2}$$

The convective heat transfer can be calculated using the equation below:

$$\dot{q}_{con} = 0.02.(T_{rp} - T)^{0.25}(T_{rp} - T)$$

Assuming the same temperatures where T is the indoor air temperature the Maximum convective heat transfer was calculated as:

$$\dot{q}_{con,Max} = 0.02.(114.8 - 68)^{0.25}(114.8 - 68) = 2.45\frac{BTU}{h.ft^2}$$

$$= 2.45 \times 3.1525 = 7.72\frac{W}{m^2}$$

The total maximum heating capacaity for the 13.5m^2 panel is equal to:

$$\dot{q}_{rad,Max} + \dot{q}_{con,Max} = 148.67 + 7.72 = 156.39\frac{W}{m^2}$$
$$= 156.39 \times 13.5 = 2111.27W$$

This was rounded down to 2111W for use in the model.

Wall Panel Heat Output

Imperial units are used in these equations so the following conversion factors are used:

$$°F = 1.8.(°C) + 32 = 1.8.(20°C) + 31 = 68°F$$

$$1\frac{BTU}{h.ft^2} = 3.1525\frac{W}{m^2}$$

The radiant heat output for the wall panel utilizes the same equations and condititons as the ceiling panel so the output is the same:

$$\dot{q}_{rad,Max} = 148.67\frac{W}{m^2}$$

The convective heat transfer can be calculated using the equation below (T. Agami Reddy, Jan F. Kreider, Peter S. Curtiss, 2016):

$$\dot{q}_{con} = 0.26.\left(T_{rp} - T\right)^{0.32}\left(T_{rp} - T\right) = 0.26.(114.8 - 68)^{0.32}(114.8 - 68)$$
$$= 41.66\frac{BTU}{h.ft^2} = 131.33\frac{W}{m^2}$$

The total maximum heating capacaity for the 6.75m^2 panel is equal to:

$$\dot{q}_{rad,Max} + \dot{q}_{con,Max} = 148.67 + 131.33 = 280.00\frac{W}{m^2}$$
$$= 280 \times 6.75 = 1820W$$

COP

The COP of the heat pump that provided the heat in the systems was calculated using the following euation (Sayegh et al., 2018):

$$COP = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}$$

Where T_h the high tempertaure and T_c is the cold temperature. For example in the UFH system the flow temperture was assumed as 35°C and the heat source was assumed as 0°C. The temperture must be converted to kelvin. This give a COP of 8.80 as shown below:

$$COP = \frac{308}{308 - 273} = 8.8$$

Appendix C – Extra UFH Information

This section includes some extra information on UFH systems that are not crucial to the report, but can aid in better understanding such systems.

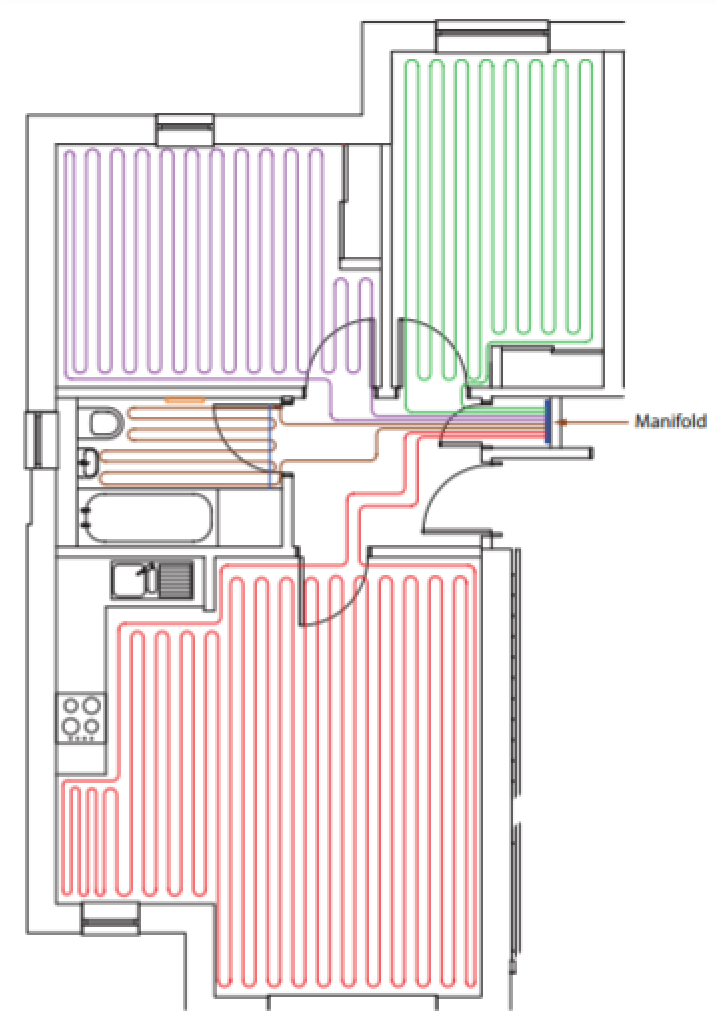

Figure 56: Typical UFH piping system layout for an apartment (Bleicher & Vatal, 2016)

(Bleicher & Vatal, 2016)

Mean water temperature	Design room temperature	Pipe spacing intervals VA mm									
		100		150		200		250		300	
		Pipe requirement Lm/m²									
		10		6·7		5		4		3·4	
MWT	TR	1. Heat emission q				2. Average floor space temperature AFST					
°C	°C	1. W/m²	2. °C	1. W/m²	2. °C	1. W/m²	2. °C	1. W/m²	2. °C	1. W/m²	2. °C
30	15	92·0	23·3	79·0	22·3	68·5	21·4	59·7	20·6	52·0	20·0
	18	73·2	24·8	62·9	23·9	54·5	23·2	47·5	22·6	41·4	22·0
	20	60·6	25·7	52·1	25·0	45·1	24·4	39·3	23·9	34·3	23·4
	22	47·9	26·6	41·1	26·0	35·7	25·5	31·1	25·1	27·1	24·7
	24	34·9	27·5	30·0	27·0	26·0	26·6	22·6	26·3	19·7	26·1
35	15	123·2	25·9	105·8	24·5	91·8	23·3	80·0	22·3	69·6	21·5
	18	104·5	27·4	89·7	26·2	77·8	25·2	67·8	24·3	59·1	23·6
	20	92·0	28·3	79·0	27·3	68·5	26·4	59·7	25·6	52·0	25·0
	22	79·5	29·3	68·3	28·4	59·2	27·6	51·6	26·9	44·9	26·3
	24	66·9	30·2	57·5	29·4	49·8	28·8	43·4	28·2	37·8	27·7
40	15	154·3	28·3	132·5	26·6	114·9	25·2	100·1	24·0	87·2	22·9
	18	135·6	29·9	116·5	28·3	101·0	27·1	88·0	26·0	76·7	25·1
	20	123·2	30·9	105·8	29·5	91·8	28·3	80·0	27·3	69·6	26·5
	22	110·7	31·9	95·1	30·6	82·5	29·6	71·9	28·7	62·6	27·9
	24	98·3	32·9	84·4	31·7	73·2	30·8	63·8	30·0	55·6	29·3
45	15	185·3	30·8	159·2	28·7	138·0	27·1	120·3	25·6	104·8	24·4
	18	166·7	32·3	143·2	30·5	124·2	29·0	108·2	27·7	94·2	26·5
	20	154·3	33·3	132·5	31·6	114·9	30·2	100·1	29·0	87·2	27·9
	22	141·9	34·4	121·8	32·8	105·7	31·5	92·1	30·3	80·2	29·4
	24	129·4	35·4	111·1	33·9	96·4	32·7	84·0	31·7	73·2	30·8
50	15	216·4	33·2	185·8	30·8	161·2	28·9	140·4	27·3	122·3	25·8
	18	197·7	34·7	169·8	32·6	147·3	30·8	128·3	29·3	111·8	28·0
	20	185·3	35·8	159·2	33·7	138·0	32·1	120·3	30·6	104·8	29·4
	22	172·9	36·8	148·5	34·9	128·8	33·3	112·2	32·0	97·8	30·8
	24	180·5	37·8	137·8	38·0	119·5	34·6	104·2	33·3	90·7	32·2

	Occupied area
	Peripheral area
	Not recommended

Source: CIBSE Underfloor Heating Design and Installation Guide

Figure 57: Performance and heat output of underfloor heating pipes embedded within a floor screed (Brown, 2011)

(Brown, 2011)

Master controller	Dedicated controller or building management system (BMS) outstation to receive input from various sensors and zone controllers and control the operation of electric valves, pumps and heat source(s) as necessary.
Zone controller	Controls the temperature of one or more zones, together with night set-back, frost protection and clock functions.
Space temperature sensor	Usually an air temperature sensor located on a convenient wall in the controlled zone; may be integrated with the zone controller. Some systems employ space temperature thermostats rather than sensors. These are connected to a wiring box that provides the interface to the electrothermal actuators on the manifold.
Outside air temperature sensor	Screened sensor ideally located on the north wall of the building. Used as an input to the weather compensation control algorithm.
Underfloor temperature sensor	A sensor embedded in the screed. This is used to set maximum and minimum temperature limits for the floor and can also be used as part of an optimum start algorithm.
Thermostatic supply valve	Sometimes called an injection control valve. A self-actuating two-port valve with capillary sensor fixed to the flow (or return) manifold to control the flow temperature. The valve mixes system water into re-circulating return water entering the flow manifold.
Thermostatic mixing valve	A self actuating three-port valve that blends the heat source flow with the underfloor heating circuits return water, typically with an installer preset temperature band between 35°C to 60°C. This type of valve proportionally changes both flow and return apertures to produce a mixed flow into the manifold.
Water temperature Controllers - constant	Typically a three-way (or four-way) rotary shoe valve construction. They can be actuated by either a motorised head with a remote system temperature sensor, or a thermostatic radiator valve head with remote capillary heat sensor. They maintain a constant mixed flow temperature.
Water temperature controllers - variable	Typically a three-way rotary valve, with variable orifice capability; sometimes a four-way valve. The valve can also be a three-way ball valve construction. They can be actuated by a motorised head, typically when using a weather compensation controller and its sensors.
Weather compensation controller	Normally using data signalled from more than one sensor, typically both internal and external to the building, these signal the motorised head using algorithms with different flow temperature curves, to reduce or increase the flow temperature.
Flow temperature	Water temperature sensor in the flow manifold linked through the controller to a motorised three-port valve. This enables variable flow temperature control such as for a multi-zone weather-compensated system.
Flow manifold with regulating valves	The regulating valves are used to adjust and balance the flow through multiple circuits in the zone. Some regulating valves incorporate visual flow indicators. The flow manifold may also be fitted with a dial pressure gauge.
Return manifold with two-port control valves	Valves in the return manifold are usually electro-thermal or solenoid operated but may be absent for single zone systems where the pump can be used to start or stop the flow. The manifold may also be fitted with a dial temperature gauge.
Pump	The zone pump is a conventional heating circulator. For small systems the zone pump may be supplied as part of the manifold assembly. Variable-speed pumps with pressure sensing control can minimise energy consumption.
Differential pressure bypass valve	The differential pressure bypass valve allows water to flow around the primary circuit when all the underfloor heating circuit two-port valves are closed, but the pump may still be running.

Figure 58: Control elements associated with underfloor control (Brown, 2011)

(Brown, 2011)

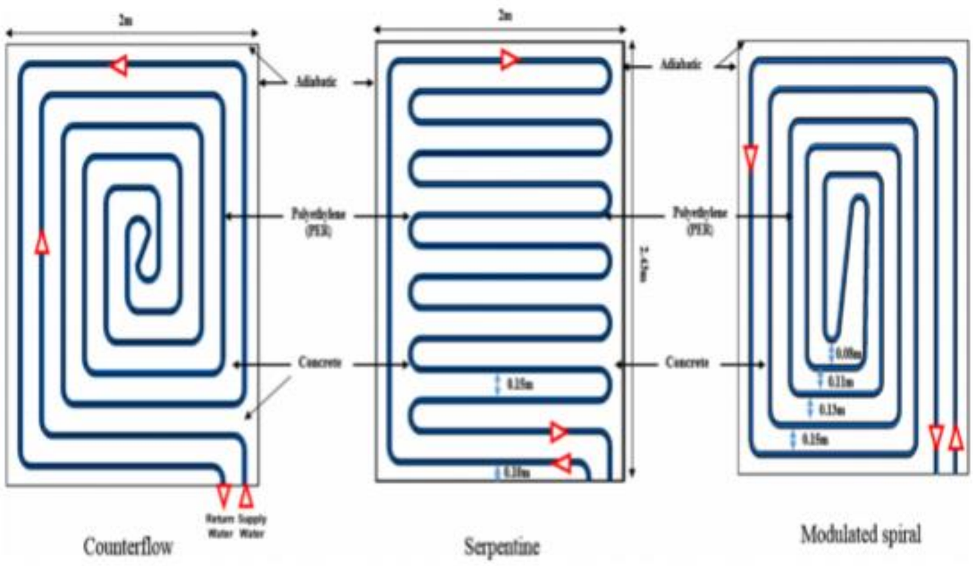

Figure 59: Three possible pipe configurations for UFH (Oubenmoh et al., 2018)

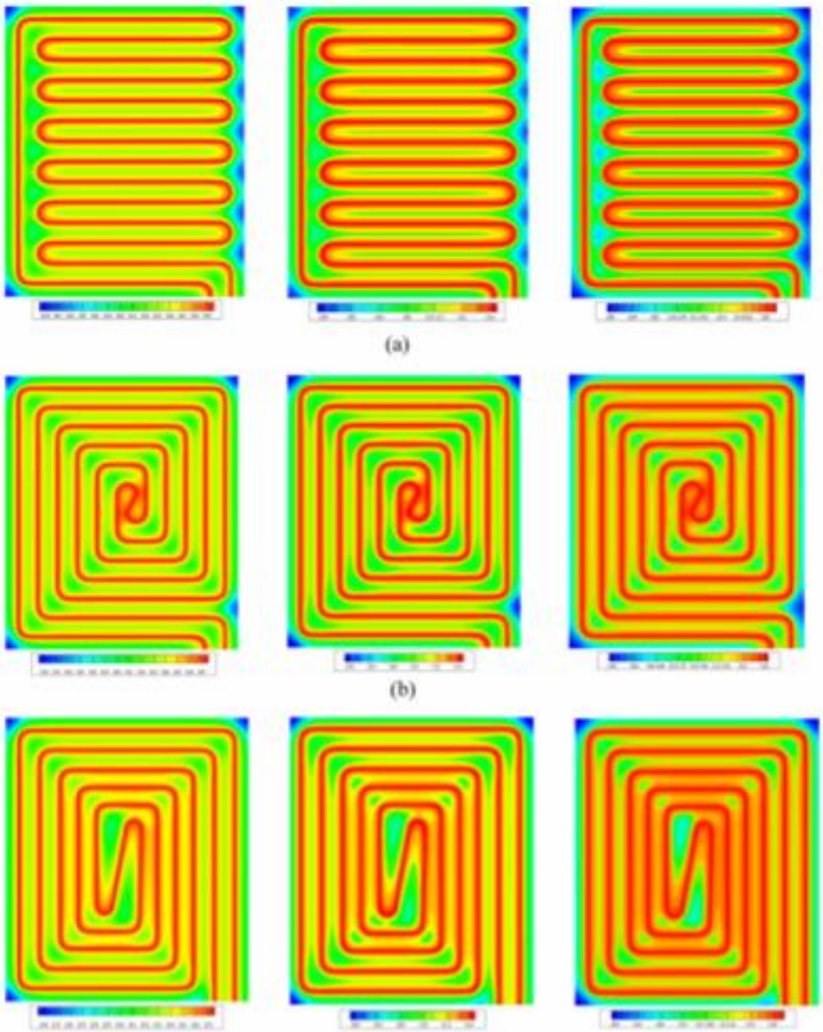

Figure 60: Floor surface temperature of three configuration from 35-50°C left to right (Oubenmoh et al., 2018)

Comparing serpentine, counterflow and modulated spiral pipe layouts, it is found that the modulated spiral configuration allows a more homogenous temperature of the floor. Also, the Modulated spiral configuration leads to the lowest pressure losses (Oubenmoh et al., 2018).

Screeded Floors		UFH System Output (W/m²)					
Floor Finish	Resistance of Floor Finish m²K/W	Flow/Return Temperatures & UFH Pipe Centres (mm)					
		65-55°C		60-50°C		55-45°C	
		200 mm	300 mm	200 mm	300 mm	200 mm	300 mm
10mm Timber	0.070	123	101	107	88	91	75
20mm Timber	0.140	90	79	78	69	66	58
10mm Carpet/Hard Tile	0.100	113	94	98	82	83	70
10mm Carpet & Underlay	0.150	91	80	79	70	67	60
4mm Vinyl – Linoleum	0.018	150	114	131	99	112	85
10mm Ceramic Tiles	0.012	151	118	132	103	112	87
25mm Marble	0.011	140	111	122	97	103	82

Floating & Battened/Joisted Floor		UFH System Output (W/m²)		
Floor Finish	Resistance of Floor Finish m²K/W	Flow/Return Temperatures & UFH Pipe Centres (mm)		
		65-55°C	60-50°C	55-45°C
		200 mm	200 mm	200 mm
10mm Timber	0.070	79	75	56
20mm Timber	0.140	86	65	64
10mm Carpet/Hard Tile	0.100	75	70	52
10mm Carpet & Underlay	0.150	63	61	47
4mm Vinyl – Linoleum	0.018	86	55	64
10mm Ceramic Tiles	0.012	87	75	65
25mm Marble	0.011	79	76	59

Figure 61: Heat output for screed, floating and batten/joisted UFH systems (WAVIN, 2006)

(WAVIN, 2006)

Appendix D – Measures to bring current Dwelling up to B EPC Rating

House type	Typical package of measures to bring to a new build standard (an EPC band "B")
19th century end-terrace house	• Insulated roof • Internal solid wall insulation • Insulated suspended timber floor • Windows – double glazed, timber frames 1.50 W/m²K (BFRC g-value of glazing – 0.45 W/m²K) • Doors – insulated panel **Services improvements** • Mechanical ventilation with heat recovery • Regular condensing boiler, 89% efficiency, programmer, room thermostat and thermostatic radiator valves • Water storage cylinder (110 litre capacity) 80mm factory cylinder insulation, all pipework insulated. • 100% dedicated low energy lighting
Early 20th century detached home	• Insulated roof • Solid walls – internal insulation • Insulated replacement concrete floor • Windows – double glazed, timber frames • BFRC g-value – 0.45 W/m²K 1.50 W/m²K • Doors – insulated panel **Services improvements** • Mechanical ventilation with heat recovery • Regular condensing boiler • Room thermostat and thermostatic radiator values • Water storage cylinder – 160 litre capacity, 80mm factory cylinder insulation, all pipework insulated. • 100% dedicated low energy efficient fixed light fittings.
Mid 20th semi-detached home	• Insulated roof • Unfilled cavity party wall • insulated roof Insulated cavity walls – internal insulation • Insulated replacement concrete floor 0.12 W/m²K • Windows – double glazed, timber frames 1.50 W/m²K (BFRC g-value – 0.45 W/m²K) • Doors – insulated panel **Services improvements** • Mechanical ventilation with heat recovery 85% efficiency, specific fan power 0.75 W/l/s, air leakage rate reduced to 3 m³/hr/m² @ 50Pa. • Regular condensing boiler – 89% efficiency, weather compensation and delayed start, programmer, room thermostat and thermostatic radiator values (no secondary room heating needed). • Water storage cylinder – 110 litre capacity, 80mm factory cylinder insulation, all pipework insulated. • 100% low energy efficient lamps in fixed light fittings.
1980s mid-floor flat	• Cavity walls – internal insulation • Edge sealed clear cavity party walls • Windows – triple glazed, timber frames • 1.50 W/m²K • (BFRC g-value of glazing – 0.45 W/m²K) • Doors – insulated panel **Services improvements** • Mechanical ventilation with heat recovery 85% efficiency, specific fan power 0.75 W/l/s, air leakage rate reduced to 3 m³/hr/m² @ 50Pa. • Heated corridors. • Electric convector room heaters, programmer and room thermostat. • Instantaneous hot water at point of use. • 100% dedicated low energy efficient fixed light fittings.

Figure 62: Potential combination of measures to bring a variety of dwelling types up to B EPC rating

(DECC, 2014)

Appendix E – Floor Heating Extra Results

Better control with concrete actuator

This systems uses the same better control system for floor heating systems, but the actuator is changed to the concrete layer in the floor construction. The results shows the importance of insulation in floor heating systems. The floor temperature in Room 1 is significantly cooler. With no insulation there is nothing limiting downward heat flow from the concrete layer to the ground.

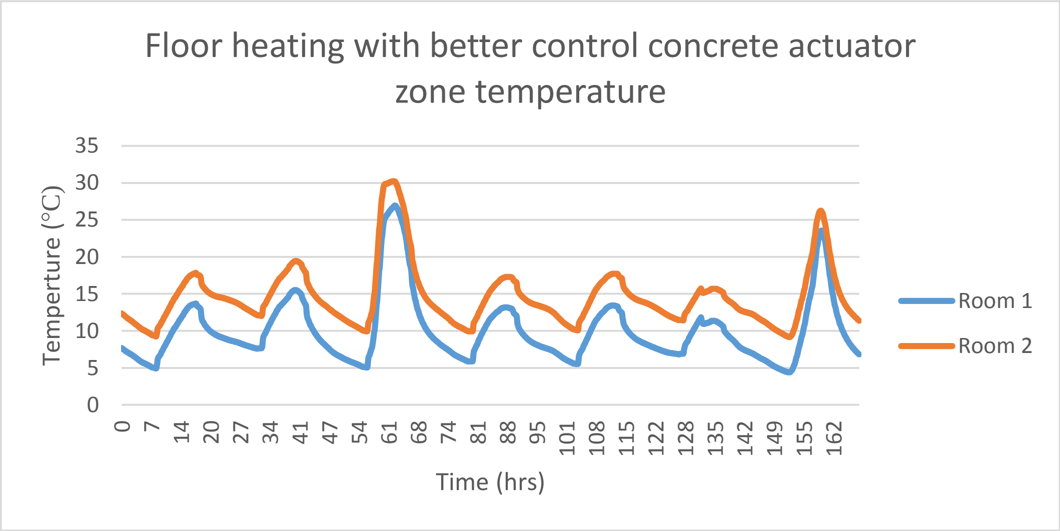

Figure 63: Zone temperature for floor heating with better control concrete actuator

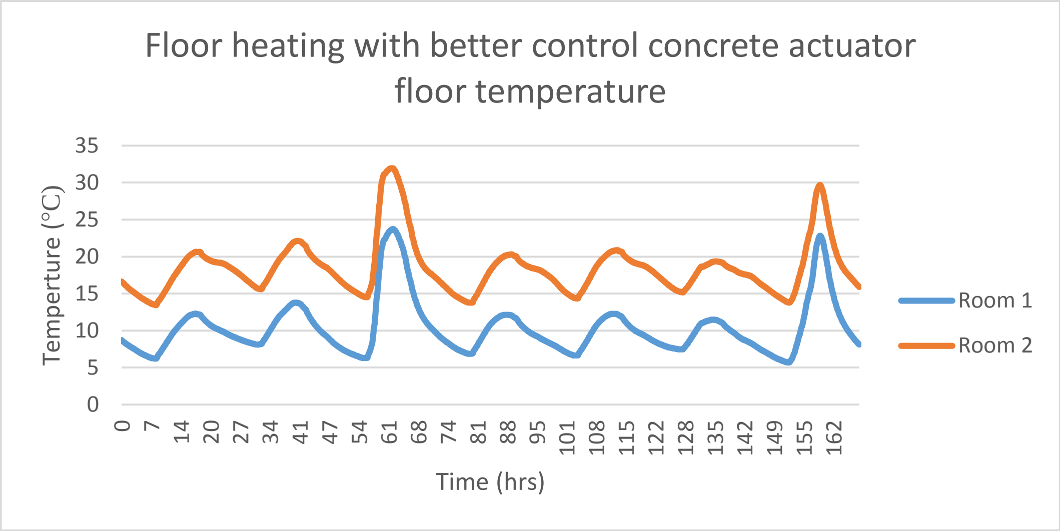

Figure 64: Floor temperature for floor heating with better control and concrete actuator

600W constant heat input

The systems was tested with a constant 600W heat capacity, to see how the system reacts to a constant heat load, which is sometimes used in floor heating systems.

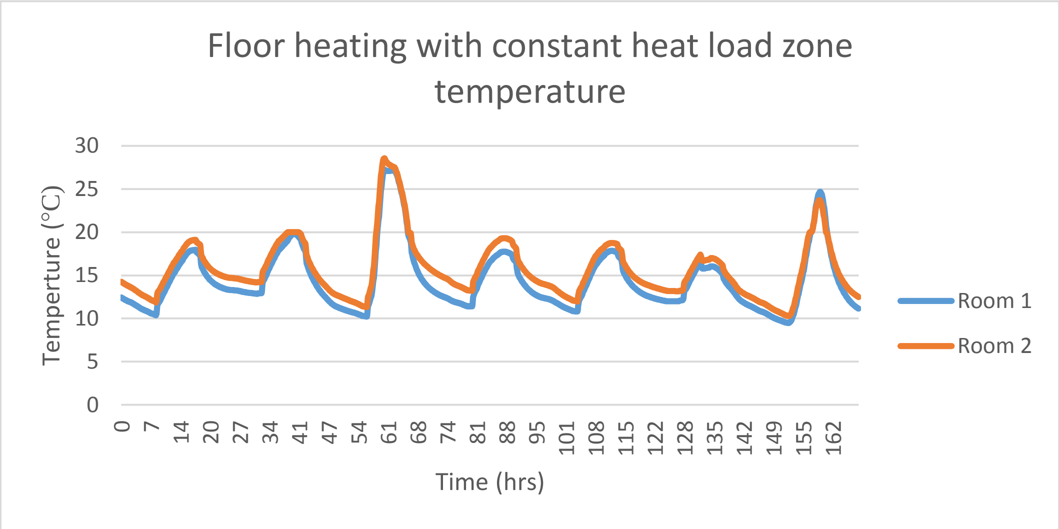

Figure 66: Zone temperature for floor heating with constant 600W heat input

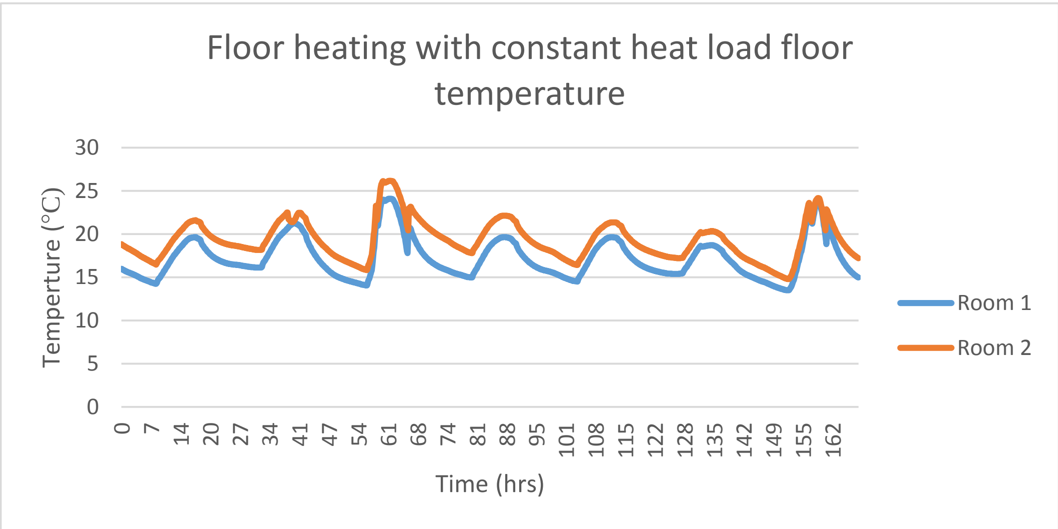

Figure 65: Floor temperature for floor heating with constant 600W heat input

Appendix F – Ceiling Heating Extra Results

Ceiling heating with better control and no floor insulation

This system utilised the better control scheme from the ceiling panel section in the report, but does not include floor insulation

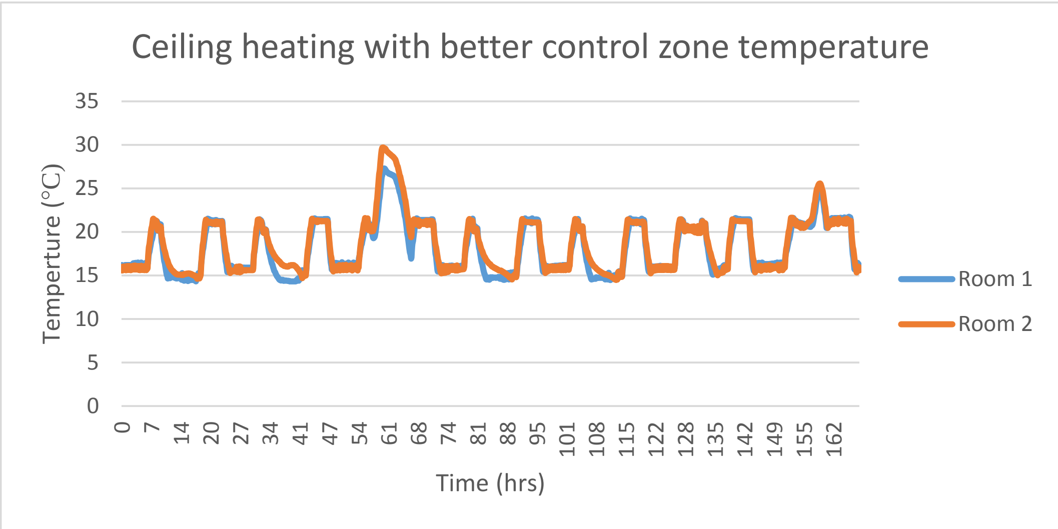

Figure 68: Zone temperature for ceiling heating with better control no floor insulation

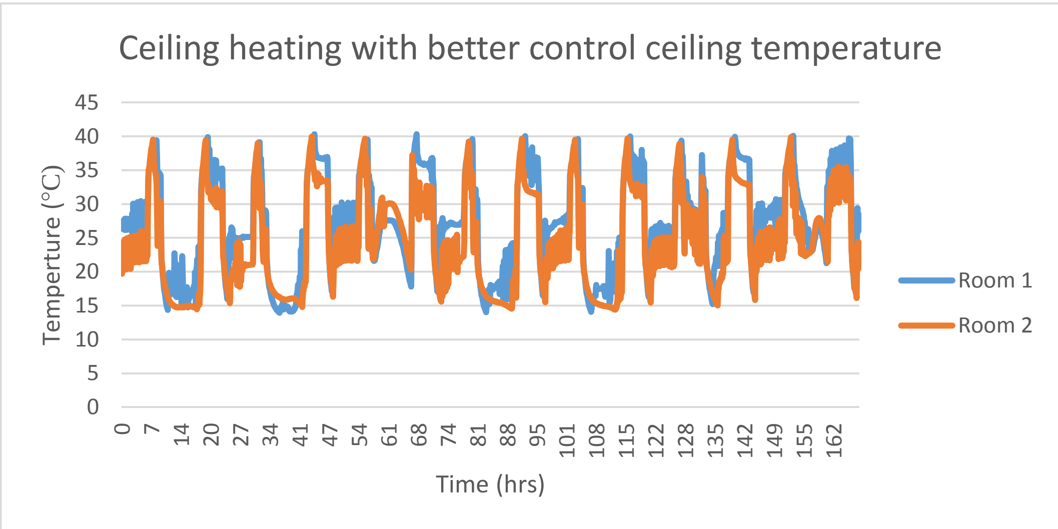

Figure 67: Ceiling temperature for ceiling heating with better control no floor insulation

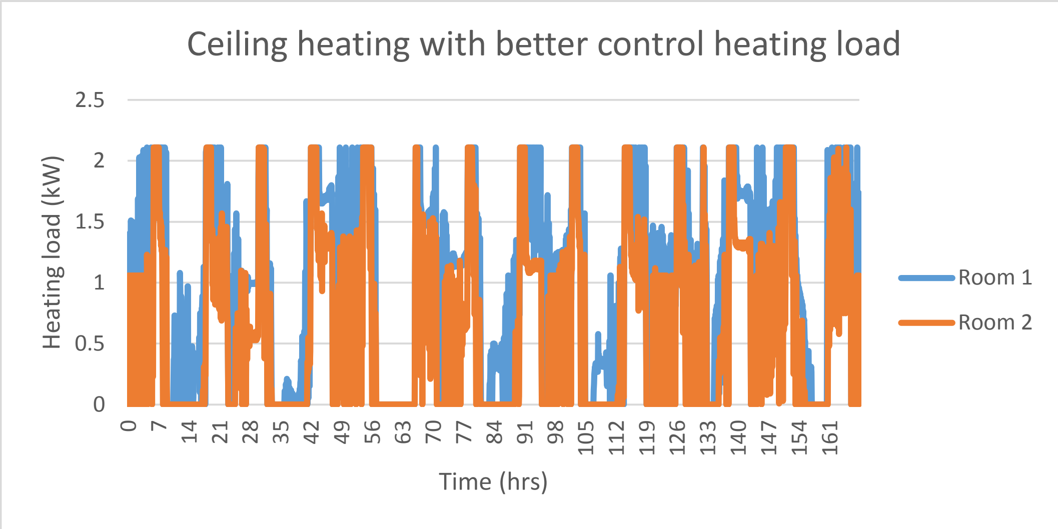

Figure 69: Heating load for ceiling heating with better control no floor insulation

<u>Ceiling all day heating with only floor insulation</u>

This iteration involves the same control scheme as was used in the better control section of the floor heating system.

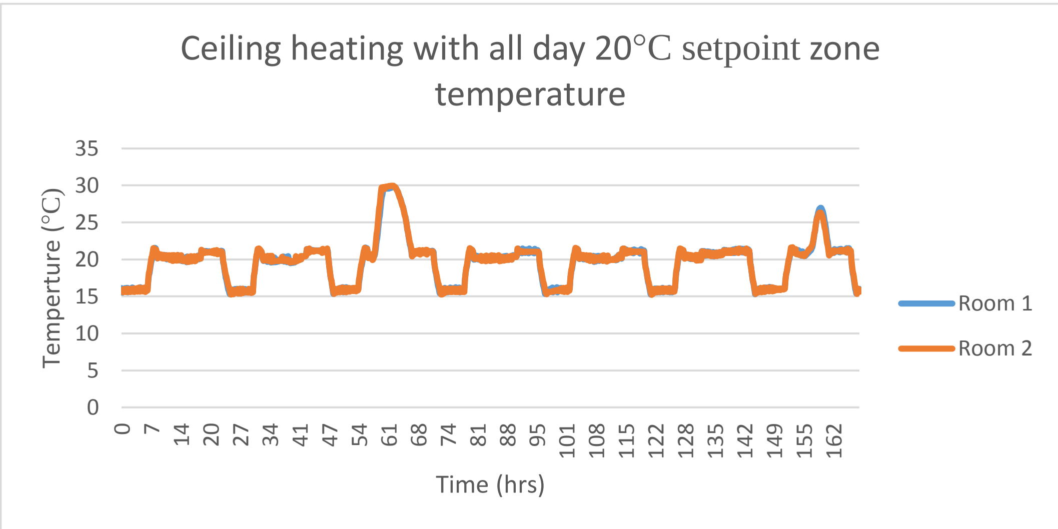

Figure 70: Zone temperature for ceiling heating with better control 20°C set point

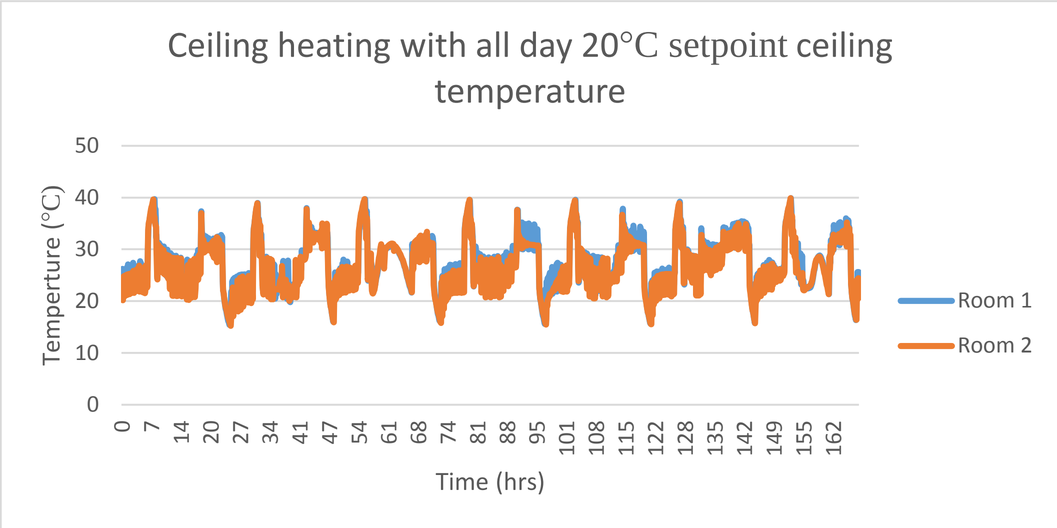

Figure 71: Ceiling temperature for ceiling heating with better control 20°C set point

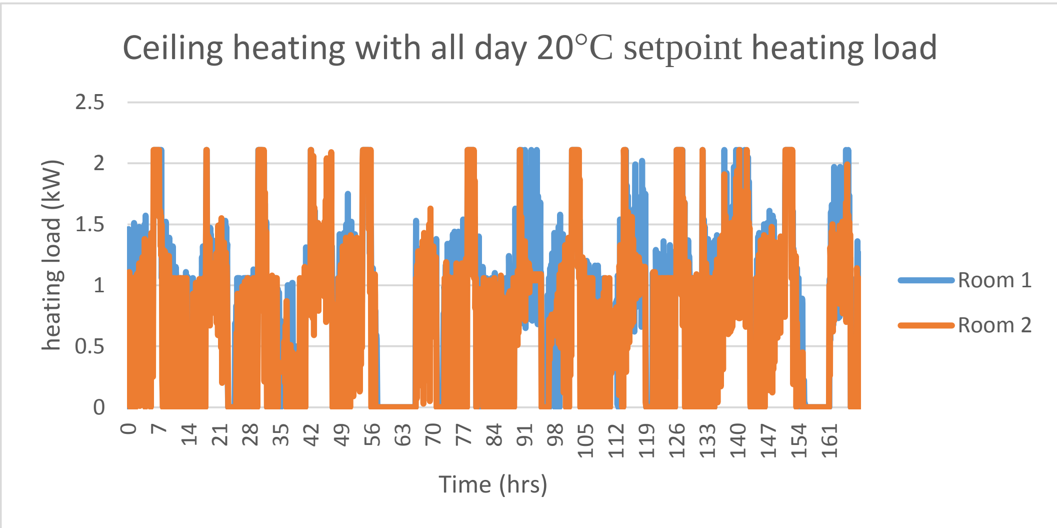

Figure 72: Heating load for ceiling heating with better control 20°C set point

Appendix G – Wall Heating Extra Results

Wall heating with regular control heating input

The case is the wall heating system with regular control. **Wall heating with better**

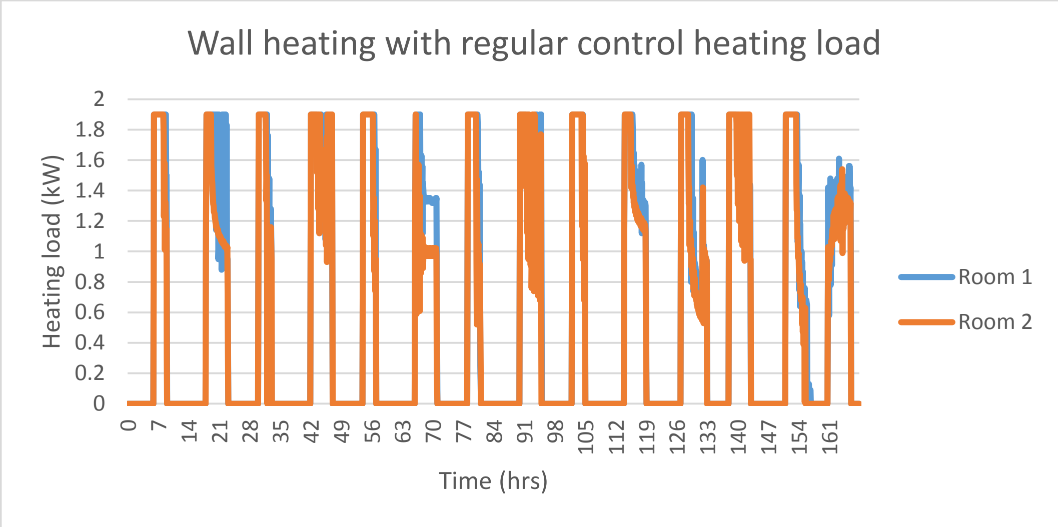

Figure 73: Heating load for wall heating with regular control

control and floor and wall insulation

In this system the wall heating system utilised better control and the inclusion of Floor and external wall insulation.

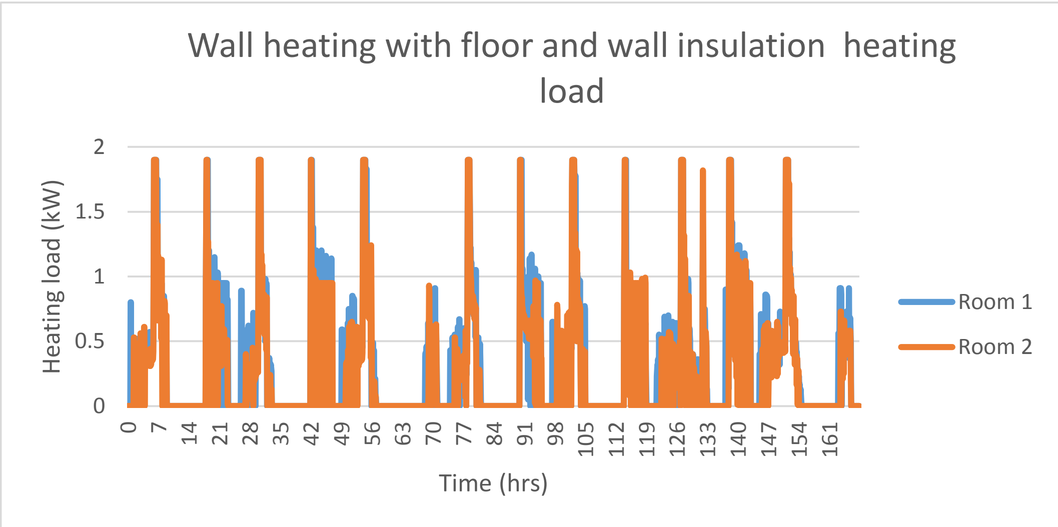

Figure 74: Heating load for wall heating with better control and floor and wall insulation