Department of Mechanical and Aerospace Engineering

The Integration of Renewable Technologies to Provide Domestic Heat: Grid Demand, Carbon and Financial Impacts

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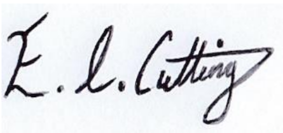
Signed:  Date: 26/08/20

Abstract

This thesis aimed to quantify the grid, environmental and financial impacts associated with the electrification of heat. To achieve this, space heating and DHW demands were simulated for archetype detached houses in the UK of two standards: typical insulation and modern passivehouse standard. The performance of various heating systems were then modelled to meet the simulated heating demands. Four cases were modelled: a base case analysing the demands of both a gas and direct electric (DE) boiler system; a combination of DE and heat pump; DE, heat pump and PV; and finally DE, heat pump, PV and battery storage.

The necessity of highly insulated homes is presented, as it results in electrical grid demands being at least 52% lower (at 4874 kWh annually) than a typical UK home using an electrified heating system. With heat pumps, PV and an 8 kWh battery bank, this grid demand can be further halved to 2044 kWh annually. It is displayed that a gas boiler system has significantly higher emissions than an electrified system in Scotland, however electrified systems are highly sensitive to grid carbon intensity, which varies across the UK. The financial analysis of the modelled systems presented that gas is significantly cheaper than the other systems. The capital costs of the heat pump systems present major barriers to uptake, however this is aided by RHI payments and upcoming grants.

Acknowledgements

I would first of all like to thank Dr Nicholas Kelly for his clear guidance on this thesis and throughout this MSc.

I would also like to thank the “ESP-r Crew” for their help with troubleshooting in the modelling process and for moral support. Additionally, all of the classmates on the RESE course who have helped make this year such an enjoyable experience.

Finally, I would like to thank my family and friends for listening to me talk about nothing but heat pumps and insulation all summer.

The COP equation used in the heat pump modelling was derived in a previous MSc thesis for this course, and is not the product of my work [62].

The regional grid carbon intensity data for the UK in 2019 was provided by Dr Alastair Bruce, from the Grid Carbon API.

The archetype housing models used were provided by the ESRU, with operational details being modified for this thesis.

Figures 1, 3, 4 and 5 are not products of my own work, and are displayed with the sources referenced in the figure captions.

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Nomenclature		**Description**	**Units**
AC	–	Alternating Current	
AC/h	–	Air Changes per Hour	AC/h
ASHP	–	Air Source Heat Pump	
COP	–	Coefficient of Performance	
DC	–	Direct Current	
DE	–	Direct Electric	
DHW	–	Domestic Hot Water	
DoD	–	Depth of Discharge	%
ECO	–	Energy Company Obligation	
EV	–	Electric Vehicle	
HP	–	Heat Pump	
kWh	–	Kilowatt-hour	kWh
LCOE	–	Levelised Cost of Energy	£/kWh
LCOH	–	Levelised Cost of Heat	£/kWh
NPV	–	Net Present Value	£
PCM	–	Phase Change Material	
PV	–	Photovoltaic	
RHI	–	Renewable Heat Incentive	£/kWh
SOC	–	State of Charge	%

1. Introduction

The electrification of heat in the UK, which is required to meet our climate targets, presents a paradigm shift in the UK energy sector and for the production of heat as a whole. This is a multifaceted issue which will have a significant technological, environmental, and financial impact on society. In recent decades, as a response to the growing threat of climate change, the UK government has been implementing policies and targets to decarbonise our energy systems. Specifically, the Climate Change Act 2008 has set the net zero target for 2050, aiming for a reduction in our emissions of at least 100% lower than our 1990 levels [1]. This requires the decarbonisation of the electrical grid, and the electrification of highly emitting sectors such as transport and heat [2]. Significant progress has been made in the decarbonisation of the electrical grid through the implementation of renewable energy, leading to renewables accounting for 37.1% of the UK's electricity generation in 2019 [3]. An issue arising from this is the fact that renewable energy is a largely non-dispatchable energy source which will be required to provide electricity to a national heating load.

The domestic heating sector in the United Kingdom is responsible for approximately 19% of the nation's carbon dioxide emissions, accounting for 65.2 MtCO_2 in 2019 [4]. Therefore, electrifying this CO_2 emitting sector is of great benefit to reducing the UKs emissions. However, this presents two key issues, the significant electrical load this will exert on the grid, and the high cost of electricity when compared to gas.

Building integrated renewable technologies, such as heat pumps and PV panels, allow for this heating load to be provided with a reduced grid demand, when compared to a direct electric heating system. Additionally, the implementation of PV provides the opportunity for demand reduction when integrated with a building.

However, as stated, with the high cost of electricity, combined with the capital costs of these technologies, the transition to an electrified heating system poses the threat of pushing households into fuel poverty [5 ,6]. Fuel poverty is defined as a household which spends 10% or more of its income on energy, and in 2017 affected 2.53 million households in England (approximately 10% of all English households) [7]. Fuel poverty can result in poorly heated homes, which has also been attributed to higher rates of mortality in the winter months [8].

2. Aims and Objectives

Aim: to determine the grid demand, carbon footprint and costs associated with various electrified heating systems applied to archetype UK housing models, comparing these with a gas heating base case.

Objectives:

- Complete a literature review examining the scope of domestic heating systems currently in use in the UK to gain an understanding of typical and contemporary domestic energy systems
- Generate space heating and DHW demands representative of current and future housing stocks, by use of open source software ESP-r and DHWCalc
- Create a visual basic code to simulate the performance of an electrified grid connected heating system working with PV generation and battery storage
- Use the visual basic code and Excel to model the grid demands associated with electrified heating systems
- Determine the associated carbon footprints using grid carbon intensity data and embodied carbon footprints for chosen technologies
- Perform financial analysis on the modelled heating systems to determine the costs for households

3. Literature Review

3.1. Building Standards and Policy

A passive solution to the issue of decarbonising heat is to improve the quality of new build homes in the UK, improving the insulation and airtightness of the builds, as well retrofitting existing properties to higher standards of insulation [5]. This change to the built environment provides the potential to cut the load from an electrified heating system required to provide adequate thermal comfort with reduced energy consumption. Over the last decade, the government has made efforts to increase the efficiency and effectiveness of heating homes through policies such as the Green Deal and the Energy Company Obligation (ECO) [9].

The Green Deal provided subsidies to home owners wishing to improve the heating of their homes through improvements to their insulation, reducing draughts, improving their heating systems (for example replacing an inefficient gas boiler with a condensing boiler), installing double glazing or integrated renewables such heat pumps or solar panels [9]. Which technology is installed depends largely on the type of building and age, for example an old building with cavity walls will benefit from the simplest improvement – insulation. The Green Deal was initially implemented by the UK government in 2013, however after only two and a half years, the Green Deal was terminated by the government due to a lack of uptake from consumers with a total of 14,000 homes utilising the policy during its lifetime, and additionally the lack of effectiveness of the policy to successfully implement improved efficiency and carbon reductions [10].

The Energy Company Obligation (ECO) can provide similar benefits to a household in terms of technology and retrofitting insulation however the key difference is the ECO scheme obligates energy suppliers to provide subsidy and assistance to consumers [11]. The ECO scheme has proven more successful than the Green Deal, as it is currently in its third phase of policy, ECO3, running from December 2018 to March 2022. The ECO scheme is focused around the Home Heating Cost Reduction Obligation (HHCRO), which aims to limit the cost of heating homes for the fuel poor by improving the efficiency of heating systems and providing fuel subsidy like the Winter Fuel Payment [11].

Major steps have been taken to implement high standards of insulation in new build homes, with the government announcing "The Future Homes Standard" in its 2019 Spring Statement [12]. This includes a plethora of changes to domestic building standards coming into effect in 2025, with an emphasis on high insulation, airtightness (reduced infiltration), low carbon heating systems (heat pumps), and high levels of ventilation. The inspiration for many of these updates could be attributed to the "Passivhaus" building standard, originating in Germany, which are designed to utilise minimal energy for heating and cooling [13, 14]. This standard seeks to produce dwellings which provide high occupant comfort with minimal energy expenditure, utilising highly insulated surfaces, triple glazing with insulated frames, attention to thermal bridges and solar gains, and systems such as mechanical ventilation with heat recovery to ensure fresh air with minimised heat loss to the environment [13]. Considering the scale of the housing stock, a vast retrofit effort would be required to bring existing builds up to a low energy standard. Nottingham Council has adopted the "Energiesprong" standard (similar to Passivhaus), originating in the Netherlands, which is applied to new build and retrofit properties [13].

3.2. Boilers, Gas and Electric

Current government policy has brought in a ban on gas boilers in all newbuild homes from 2025 in an effort to phase out gas boilers to reduce emissions [12]. As the UK is currently reliant on gas for heating systems, this is a major move to tackle emissions from the nation. Recent decades have seen dramatic increases in gas boiler efficiency, as the pinnacle of modern gas boilers are the condensing boiler which can have an efficiency of up to 98% [15]. However, many UK homes utilise outdated boiler systems giving a national gas boiler average efficiency of approximately 75% [16].

Direct electric boiler systems have efficiency of up to 99% [17], however, a major disadvantage when compared to gas is the price per kWh. In the UK, the cost per kWh of electricity is approximately 16.36 pence/kWh whereas gas costs approximately 4.13 pence/kWh [18]. This is a major source of concern for fuel impoverished households, as the switch from gas to electric heating systems presents a serious risk of pushing households currently suffering deeper into fuel poverty, as well as pushing more homes into the threshold of fuel poverty [6]. A potential technological solution to this issue is the adoption of heat pumps.

3.3. Heat Pumps

The 2nd law of thermodynamics is commonly expressed by the Clausius Statement:

"It is impossible to construct a device that, operating in a cycle, produces no other effect than the transfer of heat from a cooler body to a hotter body." [19]

This follows the natural flow of heat from warmer bodies to cooler bodies, for example the transfer of heat from within a building to its surroundings. It is possible however to transfer heat from a cooler body to a warmer body if work is done in the process, such as in a heat pump. In the case of a heat pump, this work is done by a compressor on a working fluid – a refrigerant – and allows the transfer of heat from a cold body to a hot body.

Heat pumps are a well established technology utilised extensively with applications such as AC, refrigeration and space heating. Heat pumps are an emerging source of renewable heat in the UK which can be utilised at the domestic level to provide space heating and contribute to the production of domestic hot water (DHW). This transferred heat is considered renewable as it is ambient heat from the environment which is constantly replenished by solar energy [20].

$$\text{Heat Pump, } COP_{HP} = \left|\frac{Q_2}{W}\right|$$

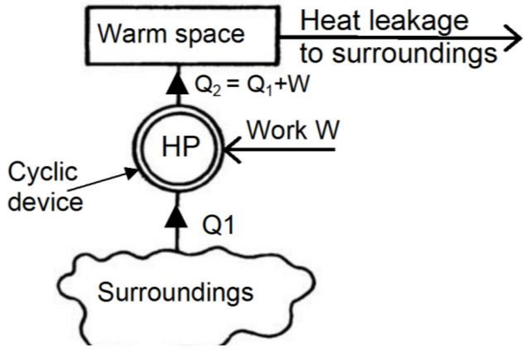

Figure 1, Refrigeration Cycle Utilised in a Heat Pump and corresponding coefficient of performance equation (Image Source: Dr Paul Tuohy, Energy Systems Analysis Lectures [21]).

Figure 1 displays a simplified diagram of a heat pump, alongside its coefficient of performance (COP), commonly referred to as a heat pumps “efficiency”. In terms of electrified heat, work would be the power drawn by a heating system. As a heat pump uses power to drive a refrigeration cycle, transferring ambient heat from the environment to the interior of a house, for example. This results in the heat delivered being greater than the quantity of power utilised to run the heat pump. As domestic heat pumps can have COPs of 3 or more, this results in an “efficiency” of over 300% [22].

Heat pumps can take several forms, ground source, river source, solar and air source heat pump. Ground and river source require larger infrastructure than air and solar, as well as proximity to a suitable thermal reservoir or body of water, and are often used for district heating systems [23]. In the case of ground source heat pumps, they utilise large piping systems either buried in coils under the ground or installed in deep boreholes as their ground heat exchanger, which are expensive to construct [20]. Below a certain depth underground, the temperature remains largely constant over the course of the year, providing the “hot” reservoir for ground source to draw heat from. This provides a constant and predictable temperature reservoir when compared to river source and particularly air. However, as this is a relatively static environment underground, it is possible for ground source to deplete the heat from this reservoir if the heating load required has been underestimated in the design stage.

This is not an issue faced by air source, as the thermal reservoir it utilises – the Earth’s atmosphere – is too vast, however the COP of an air source heat pump will vary with changes in air temperature. Although this will lower the performance of an air source heat pump when it is most required in the winter months, ASHPs are capable of providing effective COP ranges year-round. Additionally, in the urban environment, ASHPs will likely provide better performance in winter when compared to ASHPs in the rural environment due to the effect of the urban heat island [23].

As a result of their size and relative simplicity of installation when compared to other types of heat pump, ASHPs are seen as a more practical solution to integrate with individual homes, replacing fossil fuel based heating systems [23]. Additionally, not all homes will have the roof space to allow for the use of a solar heat pump.
ASHPs can transfer heat to the interior of a building by use of either an air to air system or air to water. An air to air configuration uses a ventilation system to pass warm air into the interior of a building, whereas air to water transfers the heat to an internal water heating loop, as is typical in a wet central heating system utilising a boiler. Due to the lower flow temperatures produced by an ASHP radiators in an air to water system are oversized, or use increased surface area, when compared to radiators fed by a boiler [24]. For example, they will often use underfloor heating [24]. This is to allow the ASHP radiator, at lower temperatures, to emit the same quantity of heat to a space as a higher temperature, smaller radiator.

As an ASHP is transferring heat from the surroundings to the inside of a building, the seasonal changes in ambient temperature affect the COP of the pump. As air temperature is highly changeable throughout the year, this has an impact on the effectiveness of a heat pump, which can be examined in its change of COP with ambient air temperature:

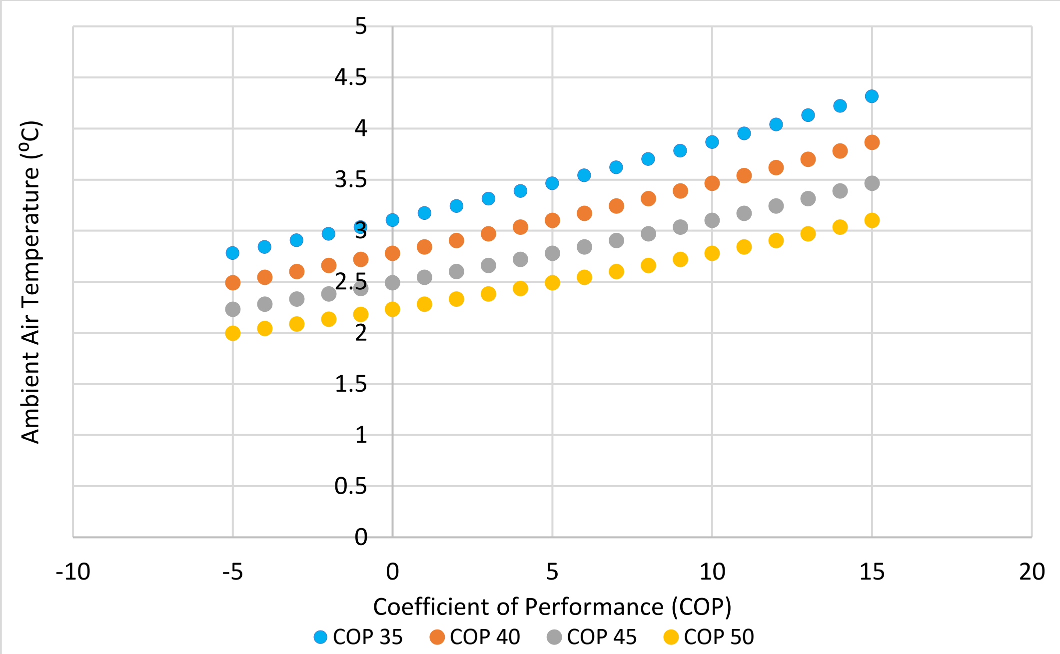

Figure 2, COP of an air source heat pump vs outside air temperature for various water T supplies. COP 35, 40, 45 & 50 correspond to supply water temperature from the ASHP.

Figure 2 displays the COP variation when an ASHP is required to provide water at temperatures ranging from 35 to 50 ºC. As the ambient air external temperature decreases, so too does an ASHPs COP, as there is less heat in the air to be transferred. Additionally, the higher the supplied water temperature, the lower the ASHP COP. This results in an ASHP not being able to provide DHW entirely be itself, but it can preheat the water reducing the heat input required from a direct electric heating coil [25].

To incentivise the uptake of heat pumps, the UK government is offering payments via the renewable heat incentive (RHI) scheme to individuals and organisations within the UK, paying a fixed rate per kWh delivered to a building over a 7 year period [26].

	Solar	Ground Source	Air source	Biomass
pence/kWh	21.36	21.16	10.85	6.97

Table 1, Heat pump type and corresponding domestic RHI payment (pence/kWh delivered) [20, 26]

For example, with an air source heat pump, the owner will be paid a fixed price of 10.85 pence/kWh of heat delivered to their property over a 7 year period. This can result in a substantial payment over the 7 year period, during which a home owner has the potential to significantly offset the cost of heat pump adoption.

3.4. Thermal Storage

Thermal storage allows for the storage of heat in a reservoir to be utilised later for space or hot water heating. Thermal storage can come in come in many forms, with the most common being a water storage tank, a well established technology dating back to the 19th century [27]. Thermal storage requires any mass which can absorb heat and release at a later time on command, or gradually release it. Other than water storage tanks, they can take the form of solid brick storage (i.e. magnate or ceramic bricks), heated via D.E. elements, or more contemporary forms can utilise phase change materials (PCMs) [28].

- **Water Storage Tanks:**

A typical hot water storage tank will utilise a large vessel with either a gas or electric heating system. The stored heat in this case is referred to as "sensible" heat, as it is energy stored within a mass and can transfer freely to surroundings without any form of phase or chemical change [28]. This allows for a large mass of hot water to be on demand at any given time and is most appropriate in larger homes with greater DHW demand and storage space to house the water tank. Water is a useful storage medium when compared to alternatives, such as PCMs, due to its high efficiency for thermal storage, with the trade-off being its space requirement [29]. Domestic storage tanks require the storage of water at temperatures of at least 60 ºC to mitigate the risk of legionella growth, and with a delivery temperature of no more than 41 ºC at outlets to minimise scald risk [30, 31].

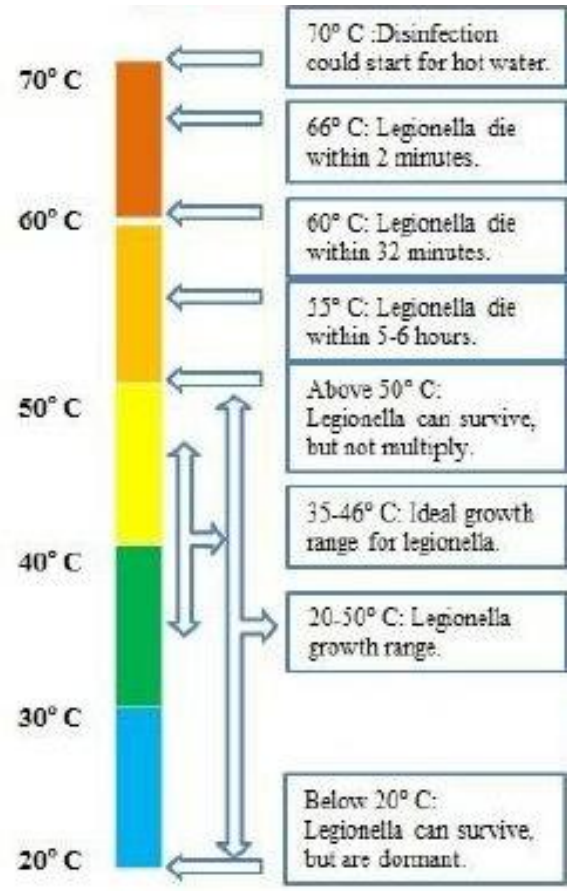

Figure 3, Temperature ranges for legionella growth.
(Image Source:[32])

Figure 3 displays the temperature ranges at which legionella is dormant, able to reproduce and thrive, and the temperatures at which it is killed off [32]. To maintain this temperature, a storage tank requires energy input over time, as it will otherwise gradually transfer heat to its surroundings.

- **<u>Phase Change Materials:</u>**

Phase Change Materials (PCMs) are materials which absorb or release heat when transitioning from one state of matter to another, for example from liquid to solid [33]. This absorbed or released heat is referred to as “latent” heat, as it is transferred via the phase change of a material. PCMs can come in multiple chemical forms, commonly organic materials such as paraffin waxes or fatty acids and inorganic materials such as salts or metallics [34].

Organic PCMs are an attractive thermal storage medium due to their wide range of supply temperatures, compatibility with other materials, being noncorrosive and recyclable [34]. However, a major issue facing organic PCMs is their lack of thermal conductivity which lowers their effectiveness as a thermal storage medium as this requires additional energy to store heat as well a reduced effectiveness at releasing heat when compared to alternative methods such as water thermal storage [35]. Some of the most common methods researched for incorporating PCMs into the built environment are by having them integrated into materials such as plasterboard within buildings. This has been proposed to maintain thermal comfort in a space longer than would be maintained without any PCMs, thereby creating the potential to reduce heating loads [36, 37].

An advantage of inorganic PCMs over organic is their high conductivity, however this also comes with the disadvantages of corrosion and supercooling, when a PCM does not solidify below its freezing point [37]. Inorganics have made their way onto the market in commercial forms such as “heat batteries” from the company SunAmp, for example [38]. Such heat batteries utilise inorganic PCMs encapsulated in a tank which is then used to preheat DHW to reduce gas usage.

- **<u>Direct Electric Storage Heater:</u>**

Another form of storage heating is direct electric which utilises an electric resistive heating element to provide heat to charge a thermal mass for later use [28]. A typical example would be electric storage heaters common throughout the UK which utilise blocks of inorganic material, such as asbestos in the past, or ceramic blocks in present day, for example. An issue with this form of storage is the lack of control over when the energy can be released or used, as it naturally escapes to the environment.

As the cost per kWh of electricity is approximately four times as high as the cost per kWh of gas, direct electric heating systems are likely to be more costly to use than electric [18]. One solution to this are tariffs offered by utility companies which offer users periods of time in which they can use electricity at reduced prices. Such tariffs, such as Economy 7 tariffs, offer reductions in the price per kWh typically between 11pm – 7am [39].

3.5. Domestic PV

Within the last decade, photovoltaics have seen large uptake in the UK, particularly in the domestic setting, driven by government feed-in tariffs. This has resulted in the installed capacity of PV in the UK rising from approximately 17 MW at the beginning of 2010, to approximately 13493 MW installed capacity in April 2020 [40].

Photovoltaic panels are composed of multiple solar cells which convert energy from light into high grade electricity. This occurs within individual solid state pn junctions, with electricity generated when photons of light excite electrons into a higher state within the material, causing a voltage drop across the junction, and therefore driving a flow of current when connected to a resistive load (i.e., domestic load) [41]. Due to the band structure of these pn junctions, a given band gap within the materials will correspond to an energy of light which it can absorb to produce electricity [41]. As a result, of all the solar radiation incident on a PV panel, only a specific fraction of the light can be converted to electricity. In terms of efficiency, domestic solar panels vary from 15-20%, inverters have efficiencies in the range of 93-96% typically [42].

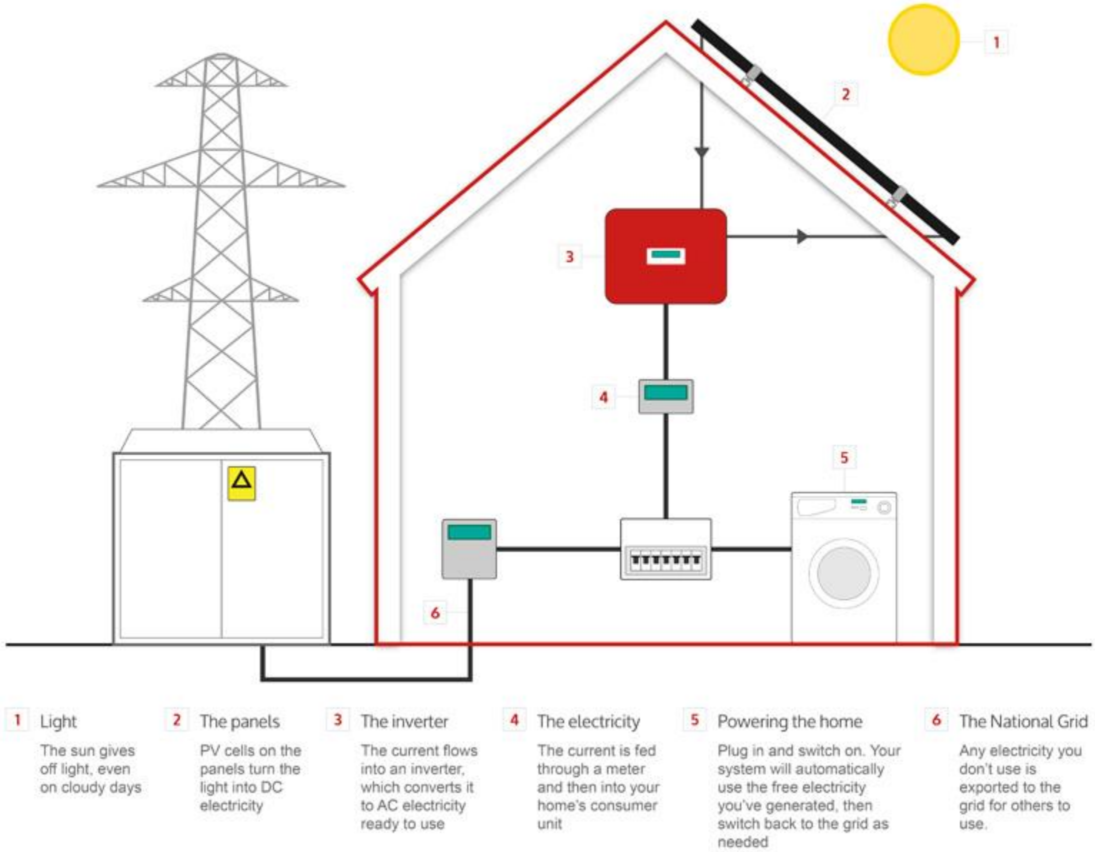

Figure 4, Domestic solar schematic, displaying a grid connected domestic PV system. (Image Source: EvoEnergy [43])

Figure 4 displays a schematic of a typical domestic solar set up. This displays the solar panel collecting energy from the sun, which then generates DC electricity. In order to integrate this electricity with both modern domestic technology and the grid, this electricity must be converted from DC to AC. As displayed in the schematic, this is then utilised by any domestic load which is active during solar generation, however when the domestic load is not sufficient to utilise the solar generation, this energy is fed back into the grid. This can cause issues to the low voltage electricity network due to higher voltages as a result of solar generation or reverse power flows which can damage substations which were not designed for bidirectional power flow [44]. To remedy this issue, domestic load shifting can be utilised to align loads with solar power generation, or alternatively battery storage can be utilised to save generated electricity for later.

The Feed in Tariff for PV closed to new applicants on the 31st of March 2019, however, the government launched the Smart Export Guarantee (SEG), which legally obligates all utilities with more than 250,000 customers to pay households for excess PV energy exported back to the grid [45, 46]. The rate at which utilities pay their customer varies widely from 1.5 to 5.5 pence / kWh exported and is subject to change [47].

3.6. Battery Storage

Domestic battery storage is a technology which is becoming more prevalent due to its ability to work in combination with photovoltaics in order to increase consumption of energy generated from integrated PV [48]. This is otherwise known as increasing self-consumption, where, if all electricity generated from PV was consumed locally, self-consumption = 100%. Additionally, integrated battery storage allows domestic loads to be shifted throughout the day, which can allow a household to significantly cut its peak demand on the grid [48]. Domestic battery storage has also gained additional publicity in recent years after the release of the Tesla Powerwall in 2015, with several other automotive manufacturers such as BMW and Mercedes expanding into the domestic battery market. This is due to companies within in the automotive industry already having established their position as commercial battery manufacturers.

Two properties of a battery which are crucial to its performance are its battery capacity (kWh) and its power rating (kW). These properties determine the quantity of energy a battery can store and the level of power it can provide respectively. Additionally, a battery's depth of discharge (DoD) and its round trip efficiency impact its performance in providing and storing power [49]. The DoD of a battery is the percentage of stored energy which has been discharged, for example, if 9 kWh has been discharged from a 10 kWh battery, then its depth of charge is 90%. DoD is important to a battery's performance as discharging to 100% can cause the chemical composition of a battery to degrade, which in turn will limit the lifetime and cycle performance of a battery [49]. Therefore, a specific battery model will have a recommended DoD which users should avoid exceeding in order to maintain the longevity of their battery.

Typical estimations of the lifespan for domestic batteries, in combination with PV, vary from in the range of 5 – 10 years [49], up to 20 years when using them for low DoD with infrequent deep discharges [50]. Additionally, the performance and lifetime of a battery is dependent on its temperature. The lifespan of a battery can suffer as a result of its exposure to extreme temperatures. For lithium-Ion batteries, temperatures below -20 ºC and above 60 ºC can cause irreversible damage to battery composition [51]. However, such extremes in temperature are not likely in the domestic environment in the UK.

The two most common types of battery for usage with domestic PV are lead acid batteries and lithium ion. However, this thesis will focus on lithium ion due to their higher round trip efficiency [49]. The electrification of heat will result in electrical loads from houses increasing, however domestic battery systems present the possibility of halving this peak grid demand [51].

Domestic battery storage can also be utilised with previously mentioned Economy 7 tariffs, in which batteries can be charged overnight, utilising cheaper electricity and further allowing peak domestic loads to be shifted, even without PV generation. This has the potential to mitigate costs to households by charging at times with cheaper grid electricity.

4. Methodology Overview

The experimental methodology for this thesis can be summarised in the following steps:

1. Modelling domestic space heating and DHW demands for a "Typical" and "Modern" standard UK home, using ESP-r and DHWCalc respectively.

2. Using Excel to calculate the grid demands from a 99% efficient direct electric boiler, as well as calculating the gas demand for a 95% efficient gas condensing boiler. This forms the "Base Case" by which more advanced heating systems can be compared.

3. Calculate the resultant demands from an air source heat pump working to provide the space heating requirements from ESP-r.

4. Creating a Visual Basic code within Excel in order to simulate the usage of a PV-battery system working with a heat pump and direct electric boiler. This allows for an hour by hour simulation of this heating system supplying the generated heating demands from ESP-r and DHWCalc, as well as calculating the hourly grid demands from the system.

5. Use the outputs from the Excel modelling to quantify grid demands, grid associated carbon footprints (using 2019 grid carbon intensity data from the National Grid Carbon API [52]), and a financial analysis based on consumed grid electricity and heating system prices.

This thesis is focused on modelling the performance of a domestic heating system operating in Scotland, and will therefore perform building simulations with Scottish weather files and supporting data for Scotland. The heating systems modelled will be applied to an archetype detached housing model of two standards, "Typical" representative of the average standards of the current housing stock, and "Modern", representative of a future housing stock with advanced insulation standards and lower energy usage.

4.1. Domestic Hot Water Demand – DHWCalc

To generate the domestic hot water demand for each dwelling, the open source tool DHWCalc is utilised. This tool was developed by the Institute of Thermal Engineering at the University of Kassel. This tool was initially developed to generate DHW demands for solar heat pumps, however the DHW demands generated are representative of typical DHW usages. DHWCalc generates flow rates and "draw-offs" of DHW over a user defined time period, generating various categories of draw off according to predefined probability distributions. These categories of draw off are dependent on use, i.e. DHW draw off from a tap (represented by a constant probability from 5am – 11pm), or draw offs from showers and baths (represented by gaussian distributions in the morning and night, representative of typical household behaviour) [53].

The DHW demand was generated in 1 hour time steps, in accordance with the timesteps from the building simulations described in the following section. DHWCalc allows for simulations down to 1 minute resolution, which would allow for a model with finer details. However, for simplicity, 1 hour time steps were deemed to be of high enough resolution and allowed for significantly smaller datasets, whilst matching ESP-r modelling timesteps.

DHWCalc generates volumes of water drawn off in a given time period as its output, so in order to calculate the power required to produce this hot water, some calculations must be performed. To determine the quantity of heat required to raise the temperature of given mass of water, the following equation is used:

$$Q = C_p m \Delta T$$

Where Q is the required heat input in Joules, Cp is the specific heat capacity of water ($Cp = 4.186\ JK^{-1}kg^{-1}$), m is the mass of water (where 1l of water = 1kg), and ΔT is the increase in temperature (K).

To determine this heat requirement, the mains water inlet temperature is required to determine the ΔT from inlet temperature to 60 degrees. As the inlet temperature is affected seasonally, an inlet mains water temperature is used for each month of the year, according to a report from the Energy Saving Trust [54]. This is then used with a mass of water drawn, provided by DHWCalc, to calculate the heat requirement to generate the domestic hot water supply.

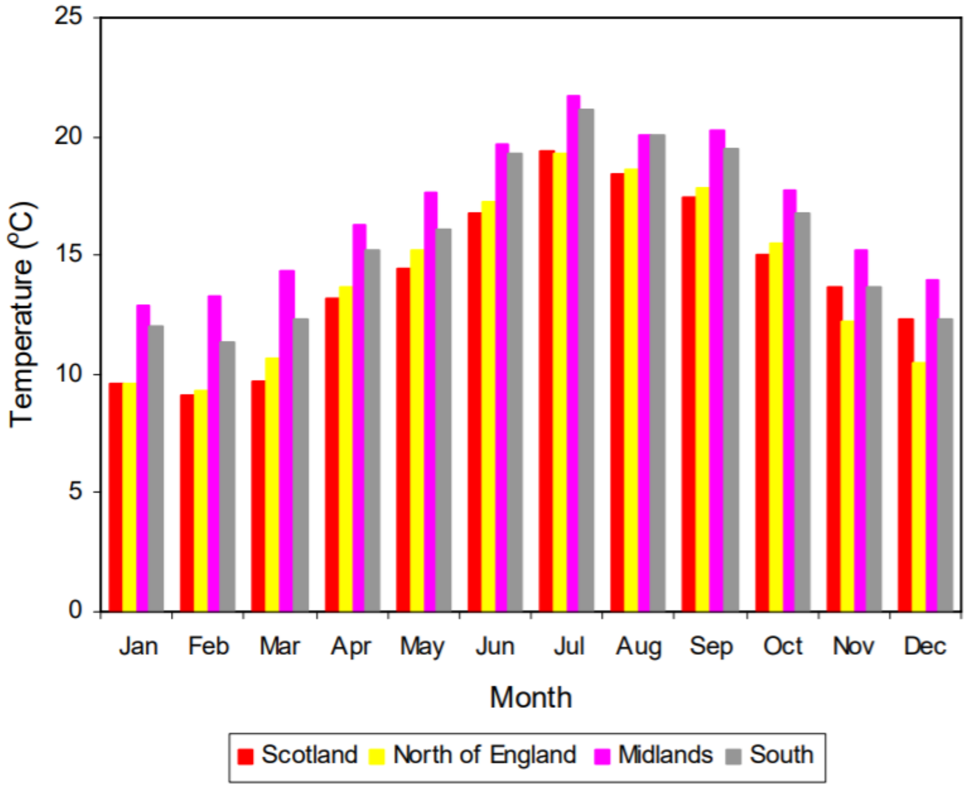

Figure 5, Regional Variation of cold water mains inlet temperature in the UK (Figure source: Energy Saving Trust [54]).

Figure 5 displays the variation of mains water inlet temperature across the UK. The inlet values for Scotland were selected for this investigation, with the inlet temperatures used in calculations displayed in a table in the appendix.

The inputs to DHWCalc were for a single household with four categories for different draw types, small, medium, bath and shower. The assumptions for daily mean draw of DHW vary between the "Typical" and "Modern" detached houses. For the "Typical" home, it is assumed that the mean daily draw off is 200 l/day for a family of 4 [55]. Whereas, for the "Modern" home, more efficient DHW usage is assumed with a lower mean DHW draw of 145 l/day, based upon draw rates within low carbon homes [56]. This assumption is also made due to the potential usage of low flow rate taps and appliances which may utilise aeration, which are used in low energy houses, such as passive houses [57].

DHW	Typical	Modern
Mean Draw (l/day)	200	145
Annual Heating Load (kWh)	4484	3250

Table 2, mean daily draw rates for the "Typical" and "Modern" dwellings, displaying the annual heating load (kWh) to generate the DHW.

Table 2 displays the mean daily draw rates used alongside the annual heating load required to generate the DHW for both modelled dwellings. The heating loads required to generate the DHW were calculated in Excel using the above equations and cold water mains inlet temperatures.

4.2. Housing Model Description

To generate heating demands for houses in the UK, the building modelling software ESP-r was utilised. ESP-r is an open source modelling software produced by the Energy Systems Research Unit (ESRU) at the University of Strathclyde. It has been extensively used and validated in the field of building performance research [58]. The models utilised in this thesis are archetype housing models representative of typical housing types within the UK, specifically detached homes. These archetype models were provided by the ESRU, giving the basic geometry of the builds, with all construction materials and operational details (such as heating loads and causal gains) then being added manually for this thesis.

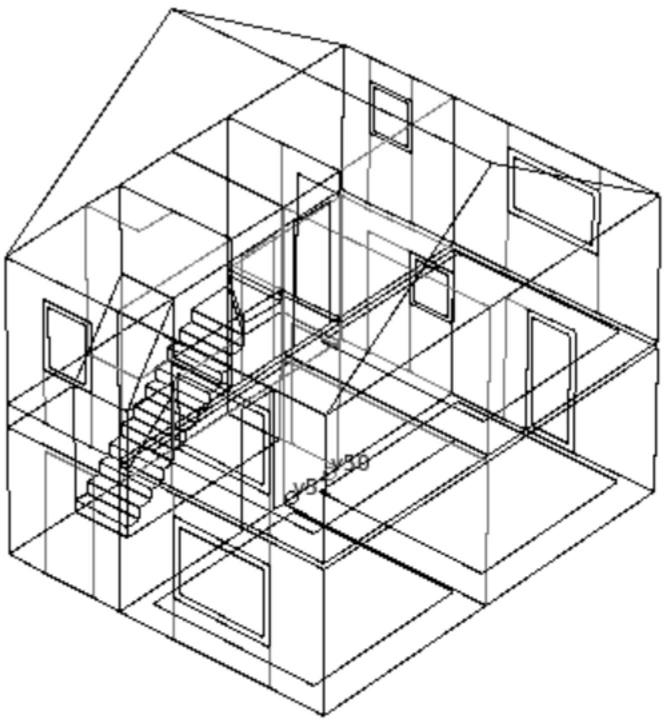

Figure 6, Wireframe model of a detached archetype housing model as presented in ESP-r.

Figure 6 displays the geometry of the detached archetype housing model provided by the ESRU. In order to generate heating results from this model, all constructions such as walls must be manually added within the software, including physical details of the constructions, such as their U-values. Additionally, details such as heating controls, heating power, occupancy, casual gains and infiltration must be added in order to produce a functional model representative of typical UK housing.

For the archetype housing models, two levels of insulation and infiltration are simulated in order to present a "typical" UK housing standard representative of the performance of the current housing stock, and a "modern" level of insulation and infiltration representative of new, higher standards for homes as modelled in a previous study [59]. The houses were simulated using a test reference year weather file for Oban 1994 available within the ESP-r weather database. Although 1994 is not a recent year, it was the most recent functional weather file for the West coast of Scotland, which is within the same Climatic region of the UK as Glasgow. As a result, this was deemed an appropriate weather file for the simulations.

Construction	"Typical" Value	"Modern" Value
External Wall U-Value ($Wm^{-2}K^{-1}$)	0.45	0.11
Floor U-Value ($Wm^{-2}K^{-1}$)	0.6	0.1
Ceiling U-Value ($Wm^{-2}K^{-1}$)	0.25	0.13
Glazing U-Value ($Wm^{-2}K^{-1}$)	2.94	0.7
Infiltration Rate (Ac/h)	0.5	0.06
Annual Space Heating Demand (kWh)	3410	1784

Adjusted Constructions	"Typical" Value	"Modern" Value
External Wall U-Value ($Wm^{-2}K^{-1}$)	0.952	0.09
Adjusted Annual Space Heating Demand (kWh)	5612	1580

Table 3, U-Values and Infiltration rates based on current typical properties and new build properties within the UK with corresponding space heating demands, with a secondary table displaying adjusted material properties required to tune the heating demands [13, 35].

The U-values and infiltration rates displayed in table 3 are based upon the standard insulation and air tightness of the current UK housing stock (under "typical"), plus the approximate standards of newbuilds, displayed as close to the passive house standard. These values have been utilised to match and compare with previous research [35] in order to validate the results from the ESP-r models. This is also achieved by comparing heating requirements with those provided by Ofgem for a typical domestic home in the UK [59].

The tables display the space heating power demand required to maintain a temperature of 20 degrees during times of occupancy, with the secondary table displaying updated U-values for the walls. These updated construction values were altered in order to increase the space heating requirement from the model, as seen in "Adjusted Space heating demand". This adjustment was made to the "typical" home in order to tune the heating demand from the building models, in order to represent heating demand from real world houses, matching data from Ofgem and previous research for detached houses [35, 59]. The adjustments made to the "modern" home were to reduce the heat requirement, in order to bring the annual kWh m^{-2} for space heating within passive house standards (<15 kWh m^{-2}) [13].

A simplification in the modelling process (when compared to the referenced study, [35]) has been to simply use a very low infiltration rate for modern builds, rather than modelling any form of mechanical heat recovery. This infiltration rate is simply 0.06 AC/h to all living zones within the "Modern" model. It is assumed here that utilising a very low infiltration rate will provide similar thermal performance to a mechanical heat recovery system, giving an adequate heating demand for modelling purposes. In reality, a building with no other ventilation to the environment other than an infiltration rate of 0.06 AC/h could quickly create a stuffy and uncomfortable space with little fresh air for the occupants.

Additionally, the roof space of the detached building models were integrated with 10 LG NeON2 400W PV panels within ESP-r. ESP-r allows for the simulation of generated electricity from PV panels, using the weather file loaded into the simulation. The LG NeON2 panel was selected as it appears to be one of the highest performing PV panels on the market at the moment, with an efficiency of 21%. 10 panels were added to the models, as this is the maximum number that would fit on the South facing section of the roof of the detached house. The LG NeON2 PV specifications are presented in the Appendix.

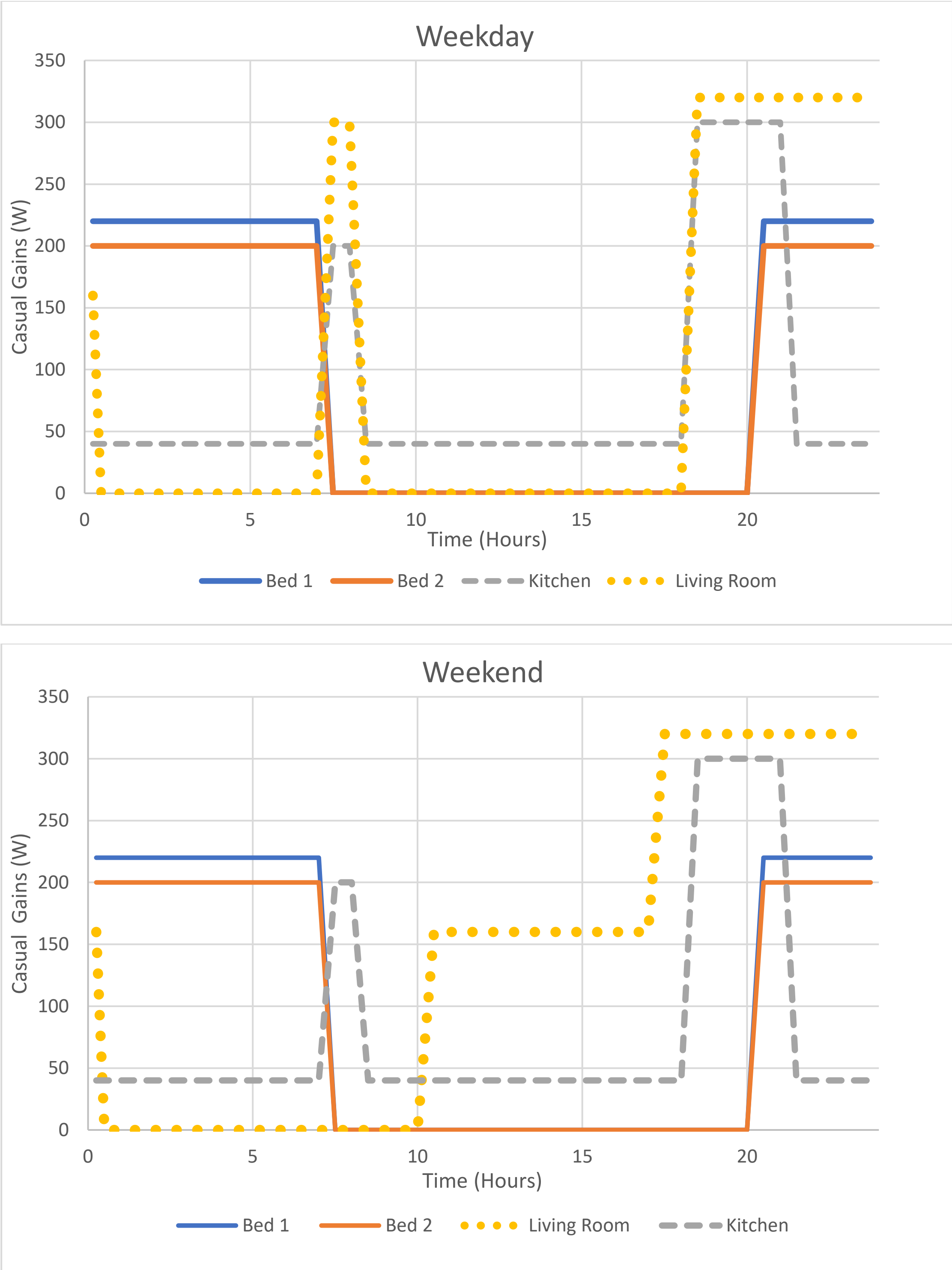

Figure 7, Graphs of casual gains to bedrooms 1 and 2, the living room and kitchen. Occupancy behaviour and gains are based on modelling performed in previous research [22]

Figure 7 displays the casual gains to the detached housing model on weekdays and weekends. The weekend gains profile is also used for holiday periods during the year. These gains profiles are based both on previous research and the SAP standard gains methodology [22, 60]. The assumptions on which these gains profiles are produced are that this is a family home with 4 occupants, two adults and two children. The sensible heat gains from these occupants can be observed by examining the gains profiles to the bedrooms, which display gains or approximately 220 W in bedroom 1, based on two adults sleeping, and a reduced gain of 200W based on children at rest. Additionally, assumptions were made based on user activity – the kitchen and living rooms observe a gains increase according to typical occupant behaviour, for example increased gains to the living room in the evenings after a work day, and throughout the day on weekends, and spikes in the kitchen at morning and night representing appliance usage. Additionally, the kitchen includes constant equipment gains based on casual sensible gains from a refrigerator, estimated at 40 W.

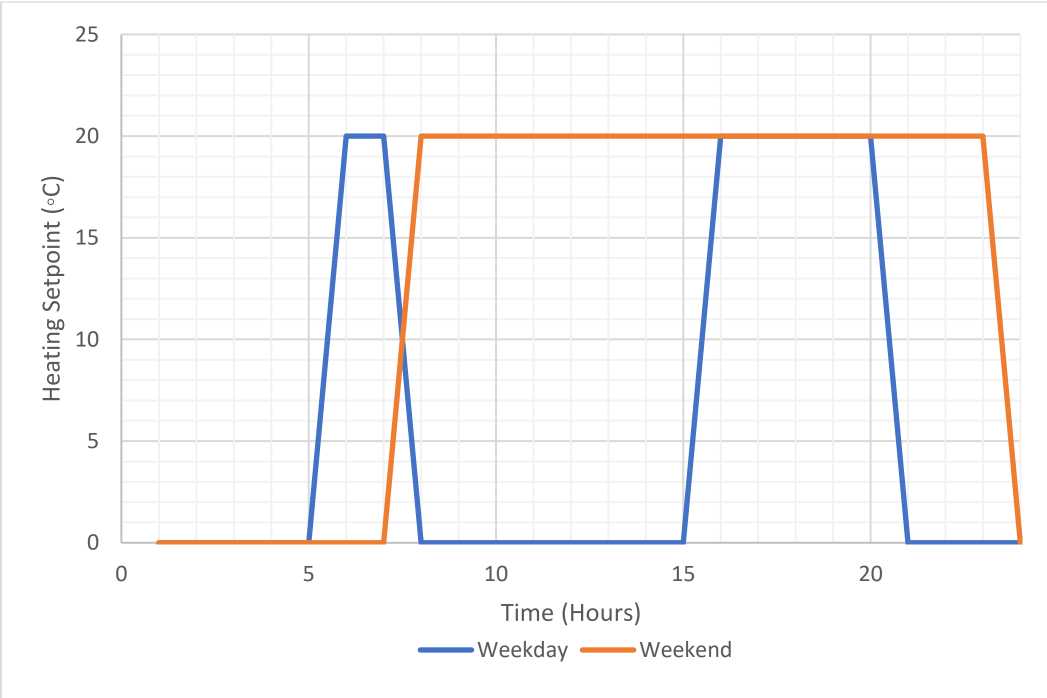

Figure 8, Heating setpoints for all living zones for weekdays and weekends.

Figure 8 represents the heating setpoints within the dwelling, where all "living" zones are any zones in which occupancy may occur – i.e. every zone except the roof. Each zone in ESP-r was set to a heating set point of 20 ºC, providing a typical comfortable environment standard for domestic settings [8]. Each zone in ESP-r was set with a maximum heat input of 1000 W. This means that a heating system will not be able to provide more than 1000 W at any given time to a zone during simulation. Once the heating set point is reached within a simulation, the supply power is backed off to maintain thermal conditions. Within the simulation, this is measured by zone "dry bulb" temperature, the temperature which would be measured by a thermometer exposed to dry air and shielded from any environmental radiation. In this regard, the temperature range typically aimed for within a dwelling is from 18 – 22, which is deemed as a pleasant living temperature [61]. To simplify the results gained from modelling in ESP-r, dry bulb temperature is the desired metric to track as it gives a reasonable indicator of thermal comfort, and is more straightforward than PPD or PMV. Dry bulb temperature is also a more universal measurement which can be utilised in the modelling stage.

4.3. ESP-r Modelling Results

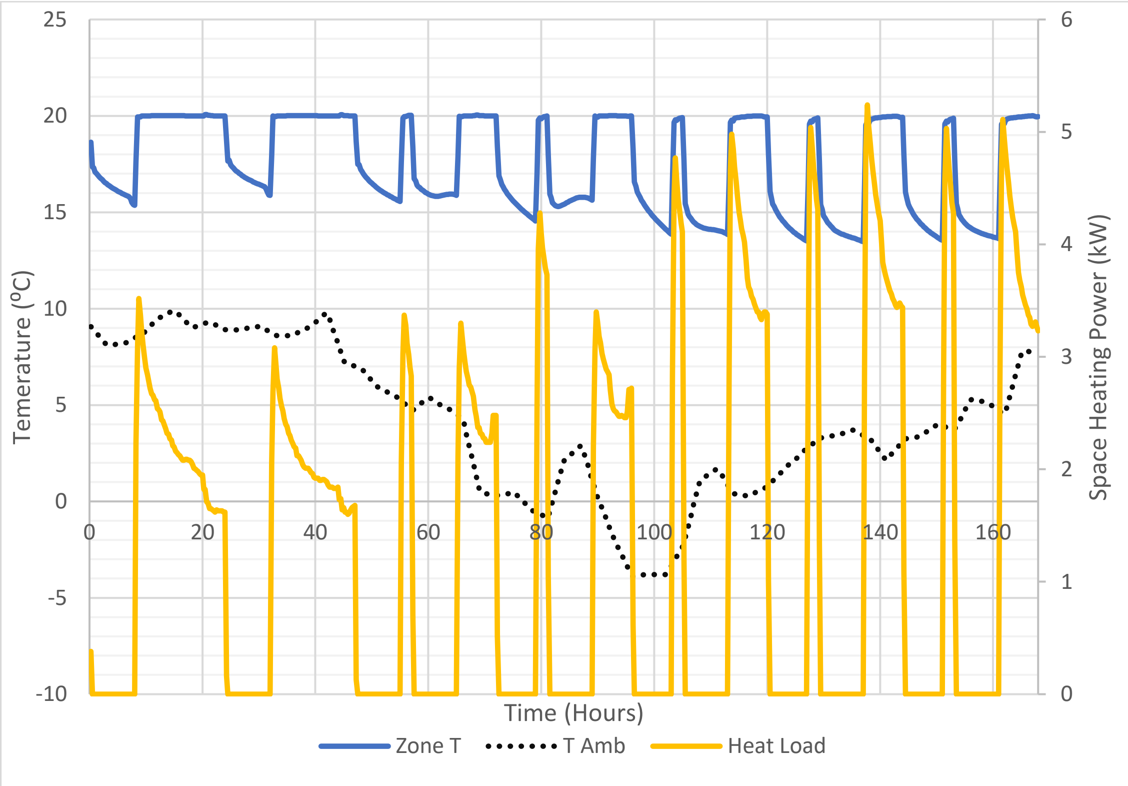

Figure 9, Averaged Indoor temperature (blue) across all "living" zones within the "Typical" detached house. With Ambient outdoor temperature in ºC (black dotted) and space heating demand in kW (Solid Yellow).

Figure 9 displays the zone and ambient outdoor temperatures for the "typical" detached home, with supply heating load during the coldest week of the year. This graph displays the indoor zones at an adequate dry bulb temperature during periods of heating load. This graph also displays the sharp drop off of indoor temperature as a result of low thermal insulation and the rates of infiltration from the environment. During this week, the indoor temperature drops off to 13 ºC as the heating system cycles off. However, during any periods of active occupancy, the heating load is capable of providing thermal comfort. During periods of active heating the load maximises at over 5 kW of total space heating load within the dwelling. As can be observed, as soon as the heating load cycles off, the indoor temperature immediately drops several degrees within an hour. Figure 9 also displays as the ambient temperature drops throughout the displayed week, there is a greater demand on the heating system to maintain adequate thermal conditions, as expected. This lack of thermal performance will result in excess energy consumption required to provide adequate thermal conditions, when compared to an equivalent housing model with better insulation.

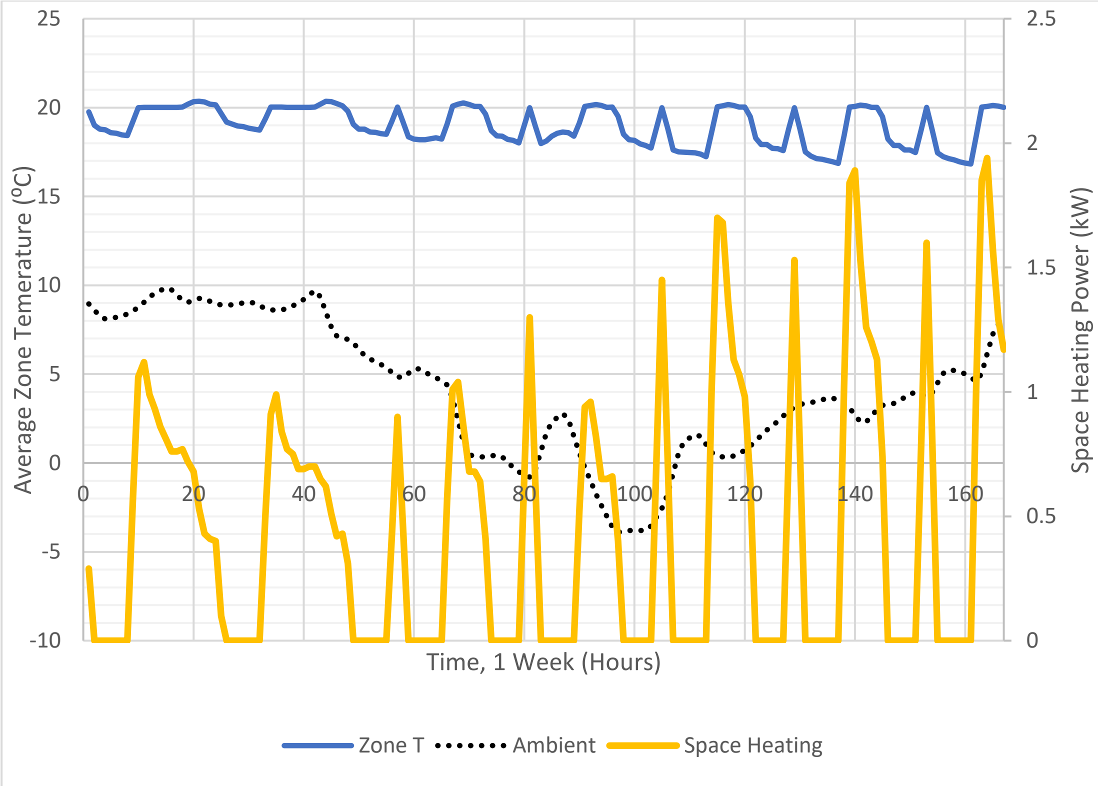

Figure 10, Averaged Indoor temperature (blue) across all "living" zones within the "Modern" detached house. With Ambient outdoor temperature in °C (black dotted) and space heating demand in kW (Solid Yellow).

Figure 10 displays the week with the coldest ambient temperatures during the simulated year. This graph displays the temperature averaged across all indoor zones of the building, as well as the total heating load provided to the property. The first 48 hours displayed on the x-axis are a Saturday and Sunday, during which the weekend heating controls can be observed as previously described. Additionally, the heating controls can be observed during weekdays with a sharp spike from 7-9am (spike in demand occurring just before x = 60) and a longer duration spike in the evening. Notably, this graph displays the significant increase of thermal performance provided to the model via improved insulation of the construction materials and reduced infiltration to the interior. This can be observed in the zone temperature which gradually dips below the 20 °C setpoint once the heating cycles off. During this week the lowest temperature is observed to be 17 °C, during a working day when there is no active occupancy.

Additionally, the improved thermal performance results in a reduced space heating load requirement.

4.4. Heat Pump Modelling:

To model the performance of a realistic air source heat pump providing the domestic heat requirement, the results of two previous pieces of research are utilised [22, 62]. The equation of a realistic heat pump based on data from a previous study is given. From these studies, an equation for realistic COP of an actual installed domestic heat pump is used:

$$HP\ Power\ Demand = \frac{Space\ Heating\ Demand}{(6.7e^{(-0.022(T_{OUT}-T_{AMB}))})}$$

Heat Pump power demand (W), Space Heating Demand (W), T_{OUT} = HP output temperature (ºC), T_{AMB} = Ambient Outdoor Temperature (ºC).

The above equation utilises the external ambient air temperature as the "cold" reservoir for the air source heat pump, with Tout = the water output temperature to the home (45 ºC). Here the denominator of the equation is the realistic COP of a real air source heat pump. This COP was derived from empirical data (in a previous thesis [62]) from an air source heat pump retrofit, and therefore presents a more accurate means of generating the power requirement for a heat pump than using theoretical or idealised equations [22]. The COP using the above equation can be examined for various output temperatures in figure 2.

4.5. Battery Modelling

The battery model implemented in Visual Basic uses the "energy bucket" model, which simulates the battery as a storage device like a bucket which can be filled and emptied [63]. The constraints to this are the input and output power flows and the battery capacity. The power flows will be set at 5.5 kW, based on the maximum power output from the Powervault 8 kWh model [64]. Additionally, two efficiencies will be applied to any power output from the battery, 90% for the batteries round trip efficiency and

90% for the inverter through which the battery would transmit its power to the domestic heating system [42, 64].

4.6. Modelling Algorithm:

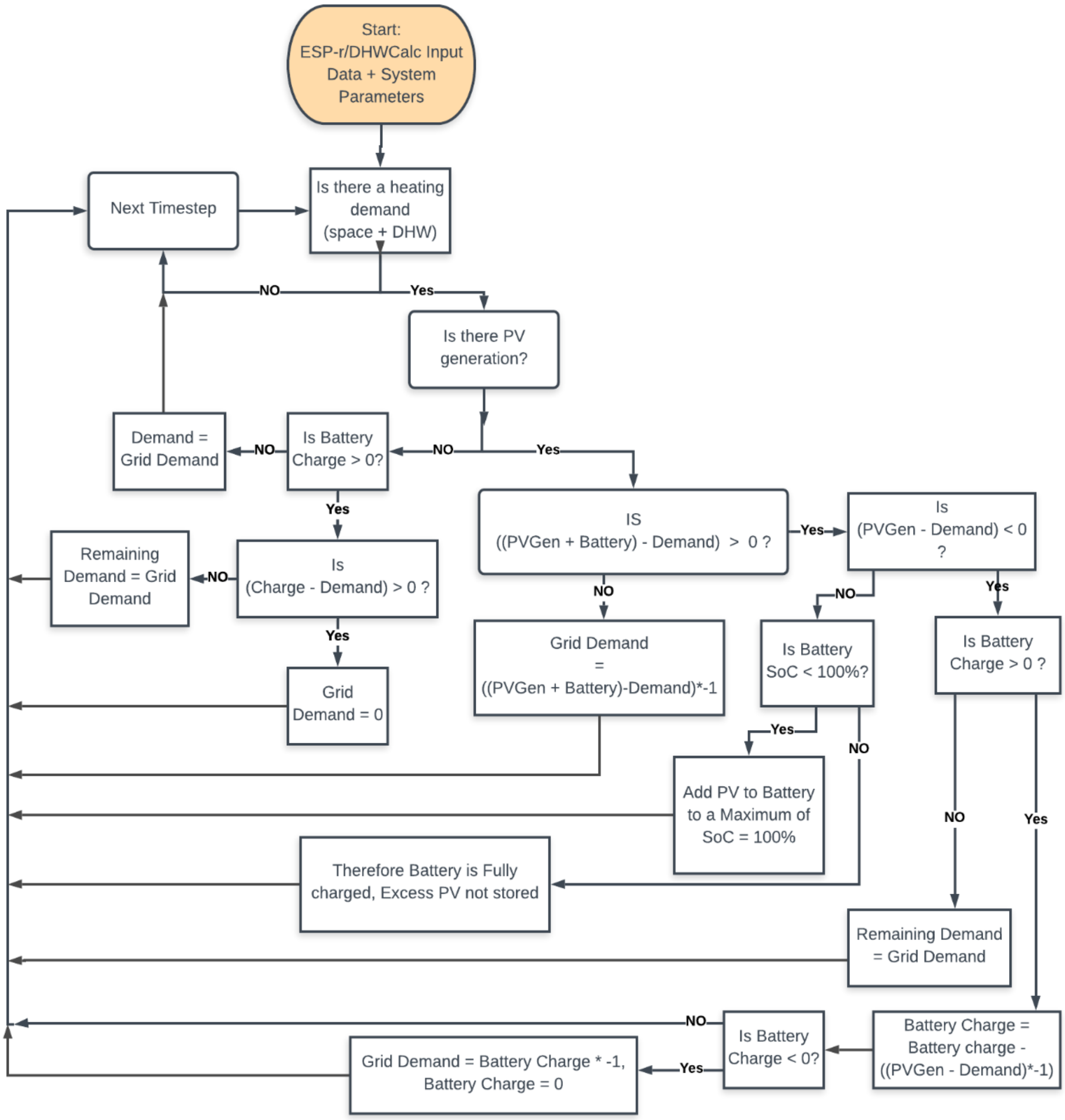

Figure 11, Flow Diagram displaying all procedures executed within the visual basic code to simulate a battery/PV system working to provide electrical demand for domestic heat.

An algorithm was produced in Visual Basic which acts as a control function for the solar panels and domestic batteries. This allows for the performance of such a system installed in a home to be simulated for each timestep of the input data. The inputs to this algorithm are the space heating demands and PV power generation produced in

ESP-r, as well as the DHW demands from DHWCalc. To determine the effectiveness of different heating systems, such as heat pumps or direct electric boilers, calculations were performed in Excel prior to running the code.

For any system being simulated using the code produced, the input demand data must be in hourly timesteps. The input demand data must then be added to a column within an Excel sheet. The code will then cycle through that column checking whether or not there is an electrical demand for the heating system for each timestep. If there is no demand, then the code will print “0” in a “Grid Demand” column, and will not subtract any charge stored in the battery. Additionally, if there is no demand, but PV generation is occurring, then the battery will charge, and any excess PV is recorded as grid export. Otherwise, if there is a demand, the code will execute the above procedure to determine whether the PV generation or stored energy in the battery can cover the domestic demand. If the energy from the PV/battery can cover this demand, then the code will again print “0” in the “Grid Demand” column. Otherwise, the code will determine how much energy is required from the grid to support the demand for heat generation within the house.

The input system parameters for the code are the maximum battery capacity, initial state of charge (SOC), the DC-AC inverter efficiency and the round trip efficiency for the battery, as well as battery capacity. The initial state of charge for the battery was set to 0 kWh for all simulations. This assumption was made as the simulation begins in winter, on the first of January, and during each winter day the battery fully discharges due to high heating demand and low solar generation. Both the inverter efficiency and the battery round trip efficiency are assumed to be 90%, based on the typical efficiency of inverters and Lithium-ion batteries currently on the market [42]. The inverter efficiency is multiplied by the PV power generation whenever PV generation is utilised to meet a domestic demand. When the battery is discharged to meet demands, both the battery round trip efficiency and the inverter efficiency are applied, reducing the energy provided to a more realistic quantity.

5. Results

5.1. Section 1, Base Case Gas and Direct Electric Boilers

This results section examines the emissions and energy demand of both modelled housing types when all space heating and DHW is supplied with either a modern gas condensing boiler or direct electric boiler. This creates a base level of performance by which more advanced heating systems can be compared.

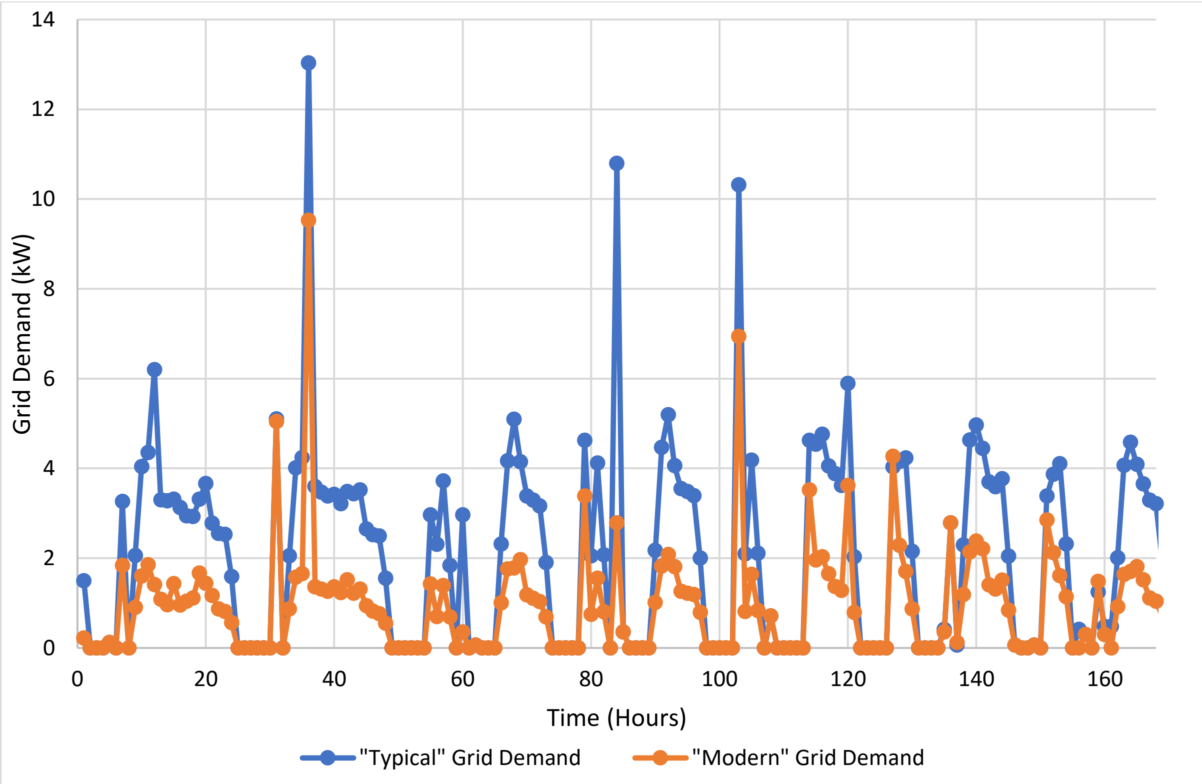

Figure 12, Electrical Demand on the grid from a direct electric heating system for a "typical" UK home (Blue) and a "Modern" home (orange) for the first week of the year.

Figure 12 displays the grid demands for the base case direct electric boiler system modelled for both the "Typical" and "Modern" home space heating and DHW demands, for the first week of the simulated year. This graph does not display any gas boiler demands as the gas boiler has no impact on the electrical grid. Figure 12 clearly displays the positive impact that increased thermal performance provides to reducing grid demand when using a purely electric heating system, as the total heat requirement, and therefore electrical load in the "Modern" home is less than half that of the "Typical" home. This figure also displays the issue posed by the electrification of DHW, as seen in the sharp spikes in demand throughout the week. This is largely dependent on occupancy behaviour and habits, i.e. running a bath or taking a long shower. These are factors which are less easily addressed than simply improving the insulation of a house to improve space heating performance.

	Condensing Boiler Emissions (kg CO2)	Condensing Boiler Grid Demand (kWh)	Direct Electric Boiler Emissions (kg CO2)	Direct Electric Grid Demand (kWh)
Typical House	1987	0	426	10207
Modern House	944	0	207	4847

Table 4, Emissions (kg CO2) and Grid Demand (kWh) for a gas condensing boiler and direct electric boiler.

Table 4 displays the carbon footprint of gas and electric boiler systems providing all space heating and DHW demand to both the typical and modern homes. The gas condensing boiler emissions have been calculated assuming the boiler has a 95% efficiency, with an emissions level of 0.195 kg of CO2 / kWh of gas burned [65].

The direct electric boiler is assumed to be 99% efficient, with emissions calculated from hourly grid carbon data for the South of Scotland from 2019, provided by the National Grid Carbon API [52]. Due to the highly decarbonised electrical grid in Scotland, the carbon footprint associated with grid electricity is extremely low, and far lower than utilising a gas heating system. However, using a direct electric system does result in a high power requirement from the grid. At this stage, the carbon footprints displayed are purely from running the heating systems, i.e. fuel and electricity usage, and does not consider the embodied carbon of the technology. This is expanded upon in the carbon results section.

In the "Typical" housing case, the total requirement for heat was 60% for space heating and 40% for DHW, whereas in the "Modern" housing case, space heating made up 35% of the heat demand and DHW made up 65%.

5.2. Section 2 Heat Pump and D.E. Boiler

At this stage, a heat pump is modelled to provide the space heating to the dwelling, whilst the D.E. boiler provides all DHW demand.

	Total Grid Demand (kWh)	Total Grid Emissions (kg CO2)	Heat Pump Emissions (kg CO2)	Heat Pump Grid Demand (kWh)	Direct Electric Boiler Emissions (kg CO2)	Direct Electric Grid Demand (kWh)
Typical House	6664	273	99	2291	174	4373
Modern House	3826	158	31	656	127	3170

Table 5, Emissions (kg CO2) and Grid Demand (kWh) for both a direct electric boiler and air source heat pump providing heating demands to each dwelling.

Table 5 displays the resultant grid demands and associated carbon footprint of the two dwellings once their space heating demand is provided by an air source heat pump modelled in Excel, with all DHW demand provided from the direct electric boiler system. The emissions displayed are again associated with the grid carbon footprint from the South of Scotland hourly grid carbon data.

The inclusion of an air source heat pump to provide space heating to the dwelling results in a significant drop in energy demand from the two dwellings. Notably, this drop is more significant in the “Typical” house due to its space heating requirement being a larger percentage of its overall energy demand when compared to the “Modern” house which has significantly better thermal performance. This can also be observed in the energy demands from the heat pump, which are a significantly lower percentage of the total heat demand when compared to the base cases. By installing the air source heat pump, the electrical demand from the “Typical” home for space heating is reduced from 60% of total heat demand (when only using a direct electric heating system), to 34% with the use of a heat pump. In the “Modern” home, the electrical demand for space heating is reduced from 35% to 17%.

5.3. Section 3, Heat Pump, D.E. and PV

This section displays the resultant energy demands once the PV panels are installed on both homes.

	Total Grid Demand (kWh)	Total Grid Emissions (kg CO2)	Heat Pump Emissions (kg CO2)	Heat Pump Grid Demand (kWh)	Direct Electric Boiler Emissions (kg CO2)	Direct Electric Grid Demand (kWh)
Typical House	5706	240	82	1940	158	3766
Modern House	3171	136	23	539	113	2632

Table 6, Emissions (kg CO2) and Grid Demand (kWh) for the direct electric boiler, air source heat pump and PV system.

Table 6 displays the resultant domestic energy demands and associated emissions and carbon footprints once the dwellings are installed with 10 LG NeON2 400W solar panels. These panels, modelled in ESP-r, generate 3775 kWh of electricity annually. However, due to the mismatch between PV supply and domestic heating demand, much of this energy is not consumed by the heating system, resulting in a relatively low drop in total heating demand of 958 kWh for the “typical” home and 655 kWh for the “modern” home.

These results also display a reduction in emissions from running the electrified heating system, as less electricity is being drawn from the grid. While PV panels do have a considerable embodied carbon footprint, this will be explored later in the carbon results section. Considering the reduction in electricity drawn from the grid when compared to the previous results section, and the annual quantity of electricity generated from the PV, this gives a self-consumption value of 28% for the “Typical” home, and 18% for the “Modern” home. The higher rate of self-consumption in the “Typical” house is due to the greater electrical load to provide space heating and DHW, when compare to the “Modern” house. If this was a real-world system including electrical loads for appliances within the household, then the self-consumption values would be higher, due to greater domestic load, however the model only considers domestic loads associated with an electrified heating system.

5.4. Section 4, Heat Pump, PV and Battery Storage

In this section, the performance of the domestic energy system is analysed over a range of battery capacities to determine the impact of increasing battery capacity on the system. The results of a focused analysis on a system with an 8 kWh battery capacity is displayed in 7.

	Total Grid Demand (kWh)	Total Grid Emissions (kg CO2)	Heat Pump Emissions (kg CO2)	Heat Pump Grid Demand (kWh)	Direct Electric Boiler Emissions (kg CO2)	Direct Electric Grid Demand (kWh)
Typical House	4578	160	55	1575	105	3003
Modern House	2044	72	13	350	59	1694

Table 7, Total Domestic Grid Demand (kWh) and associated emissions (kg CO2) for the "Typical" and "Modern" homes, with demand and emission breakdowns for heating systems.

Table 7 displays the resultant grid demands and associated carbon footprints after the installation of the 8 kWh lithium-ion battery system, modelled in Excel. This addition to the domestic energy system results in lower grid demands by allowing for excess energy generated from the PV panels to be used at a later time.

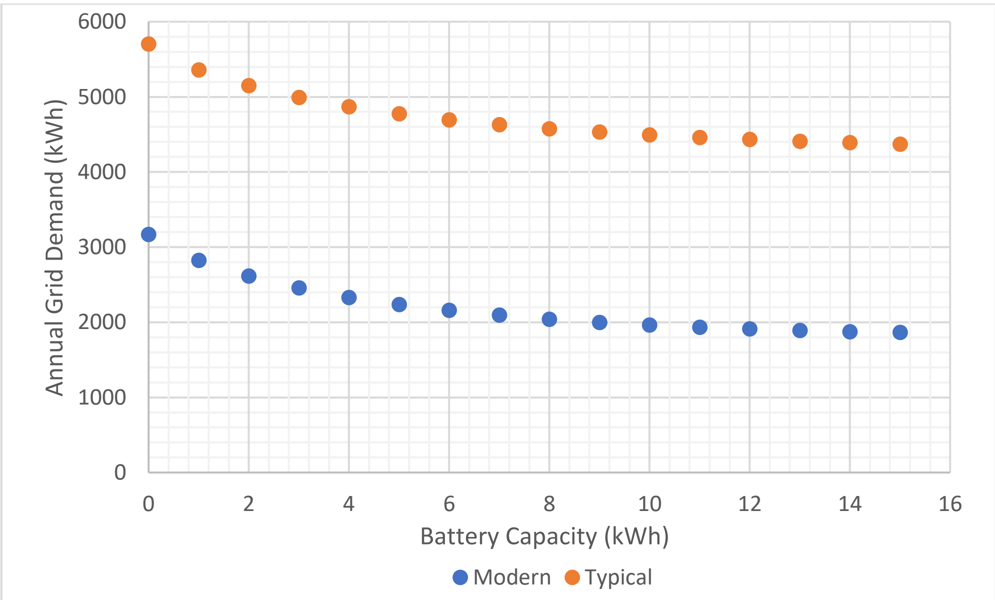

Figure 13, Annual electrical grid demand (kWh) vs installed battery capacity (kWh) for both the "Typical" UK detached home and the "Modern" UK home. Demands generated in this figure are from models utilising PV, Heat pumps and direct electric boilers.

To understand the relationship between installed domestic battery capacity and the mitigation of grid demand, the Excel model was run multiple times for a range of battery capacities for both dwellings, with the results displayed in figure 13. This displays that a small increase in kWh of battery capacity has a significant impact on the grid demand reduction, but the significance of this demand reduction decays asymptotically as the battery capacity is increased. This is due to the mismatch between when there is the greatest demand for heat within the course of a year, and when there is the greatest PV production. For example, during the winter, the total percentage of energy produced from the PV is well utilised, as there is a high energy demand and low PV generation. Conversely, in summer there is a comparatively low energy demand but high PV generation.

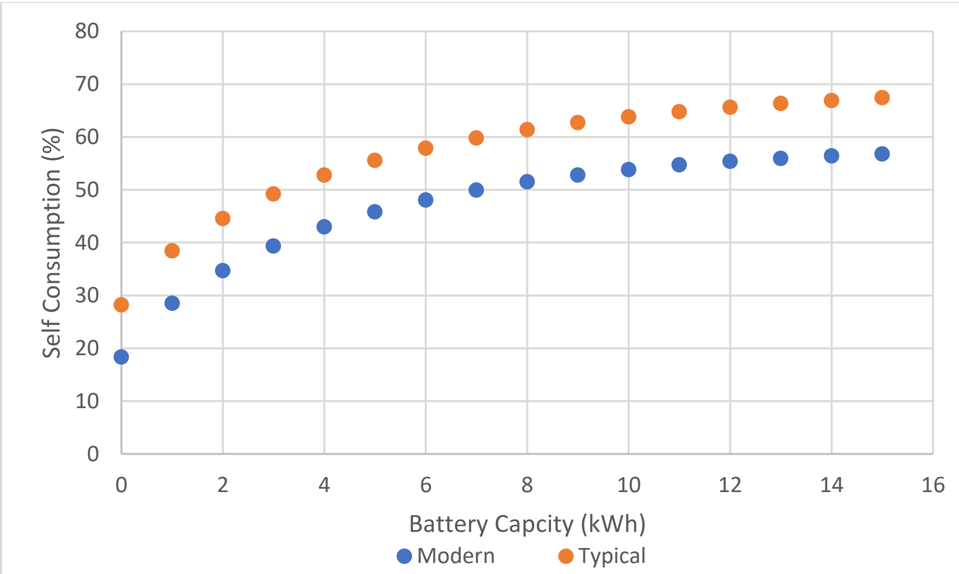

Figure 14, Self-consumption (%) vs Installed Domestic Battery Capacity (kWh) for both dwellings.

Figure 14 displays the relation between the rate of self-consumption of energy, and the installed battery capacity. This is linked to figure 13, as increased rates of self-consumption ultimately result in reduced rates of grid electricity consumption. Given the high price of installed battery storage systems, this also displays the potential benefits of spending a smaller sum of money on a lower capacity battery, as lower capacity batteries will be more fully used to their potential and result in reduced demand on the grid.

5.5. Results Summary:

Here, the resulting annual grid demands of each system, along with the emissions produced from running the systems are compared and summarised.

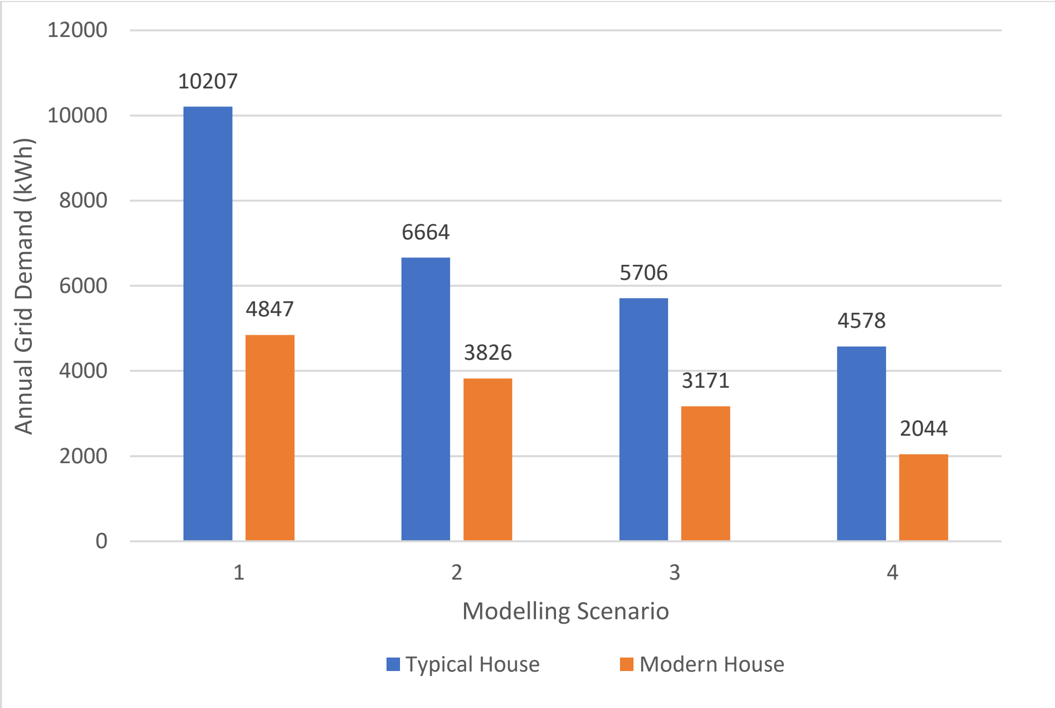

Figure 15, Annual grid demand (kWh) for all electrified heating systems from case 1 to 4 for both dwellings.

Figure 15 displays the annual grid demand associated with each electrified heating system for both dwellings. A significant result from these values is the importance of a well insulated and airtight dwelling, as in scenario 1, in which all space heating and DHW is provided by a direct electric heating system. Here, the "Modern" home has less than half the electrical demand compared to the "Typical" home. The "Typical" home is only able to undercut the demand of the scenario 1 "Modern" home when it has a heat pump, PV panels and lithium-ion batteries installed. Therefore, in terms of making efficiency improvement to the domestic sector, this displays the immediate need to make the "simple", or comparatively low-tech, changes to a property, such as increased insulation, glazing and reduced infiltration.

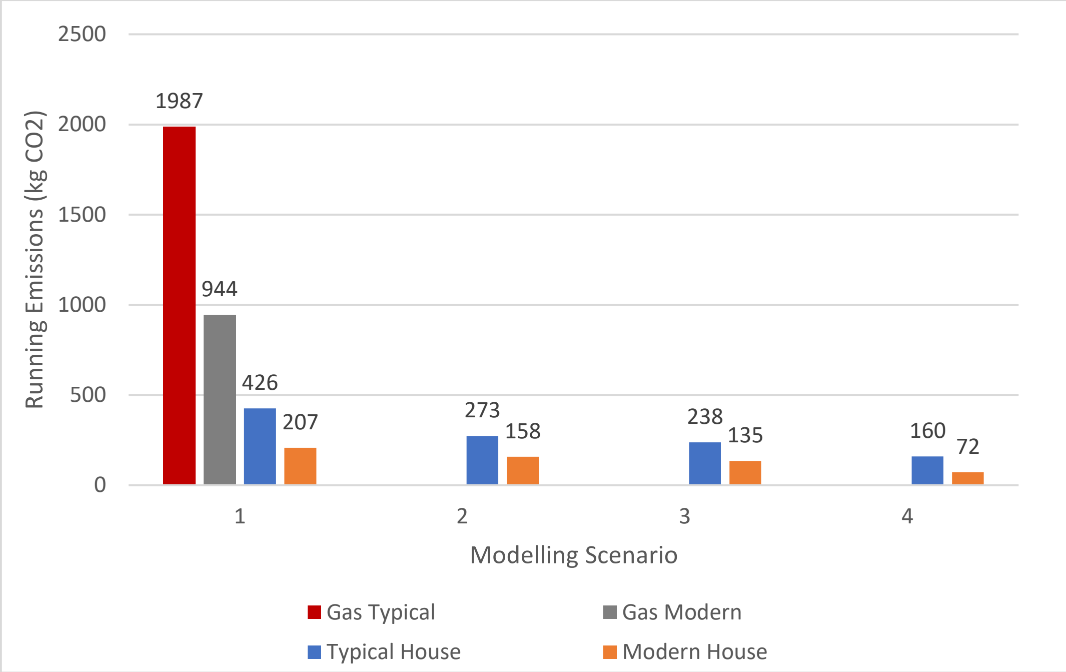

Figure 16, Annual Emissions (kg CO2) for each modelled heating system.

Figure 16 displays the annual emissions, in kg of CO2, produced as a result of using each of the modelled heating systems. This figure clearly illustrates the necessity to transition from fossil fuel burning heating systems to low carbon and electrified systems, when comparing the scenario 1 gas boilers to all other electrified heating cases. The results of this figure are highly dependent on the region in which these systems are installed, as all grid electricity emissions have been calculated using Southern Scotland grid carbon data, which is the region of the UK with the lowest grid carbon intensity. Therefore, in other regions of the UK, or in other countries around the world, the annual emissions savings will be highly variable both due to the grid carbon intensity, but also the environmental conditions which will impact the space heating requirements and PV generation.

5.6. Carbon Footprint:

Here the embodied carbon footprints of the modelled systems are factored into the lifetime carbon footprint of the entire domestic energy system.

Technology	Embodied Carbon Footprint (kg CO2e)
ASHP	1500 [66, 67]
Battery (8 kWh)	1568 [68]
PV (20 m2)	6000 [67, 69]
Boilers	200 [70]

Table 8, Embodied carbon of modelled heating equipment, with sources in square brackets.

The embodied carbon footprints of the heating system components are listed in table 8, with values estimated based on available literature referenced. As the embodied carbon footprint of products are not calculated and published by manufacturers, the listed values are ballpark figures and should be broadly representative of the technologies modelled. The above values were taken from various LCAs performed on the stated technologies, with some stating units such as m^2 per kg CO_2e, such as for PV panels, or per kWh in the case of batteries.

To estimate the carbon footprint across the system lifetime, a 25 year period has been selected as this is the lifetime of the modelled PV panels, which are the longest lasting components. To gain an initial embodied carbon footprint for each heating system architecture, the above components' footprints are added together for each scenario. Then for each year of the system lifetime, the footprint from running the system is added on to this initial embodied carbon footprint value. During the 25 year system lifetime period, components will require replacement, such as the ASHP, battery bank, and boilers. As each of these components require one replacement within the system lifetime, it is assumed that these items are all replaced on the 15th year of use, with the above embodied carbon footprints listed in table 8 being added on again.

In the 15th year, when the boilers, heat pumps and batteries are replaced, the embodied carbon of the heat pump replacement is assumed to 260 kg CO_2e. This is due to the stated value in the table 8 being calculated as the combined embodied carbon values for refrigerant production (approximately 630 kg CO_2e), domestic heat distribution system such as piping, radiators and materials (approximately 610 kg CO_2e) then finally the heat pump itself (approximately 260 kg CO_2e) [66, 67]. The uncertainty on all figures within table 8 is ±20%, therefore these are approximate estimates based on available literature [66].

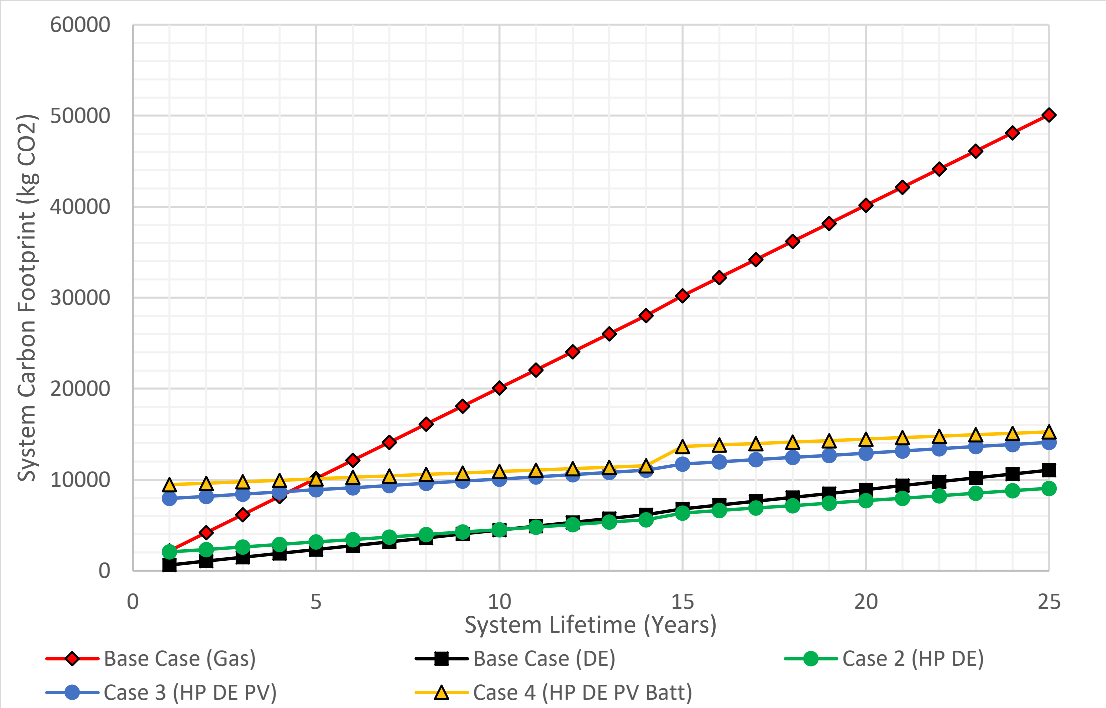

Figure 17, Heating System Carbon Footprint (kg CO2) vs Time (Years) for the "Typical" house.

Figure 17 displays the system carbon footprint for the "Typical" dwelling as the system ages through its 25 year lifetime. The carbon footprints of the first year shown are the summation of the previously stated embodied carbon footprints plus the annual emissions from fuel and electricity consumption. This clearly displays the significant carbon footprint associated with a fossil fuel system, as the condensing gas boiler quickly overtakes the carbon footprint of the other heating systems, ending with a final system carbon footprint of approximately 50 tonnes of CO2. This also displays the gas boiler overtaking the carbon footprints of both the base case direct electric system, and the case 2 heat pump and direct electric system after one year of usage. Additionally, the case 3 and 4 systems, which begin with a high embodied carbon footprint, due to the inclusion of PV and lithium-ion batteries, are overtaken by the gas condensing boiler during their 6th year of usage.

Here, the case 2, heat pump and direct electric, system are seen to be the lowest carbon heating system for the "Typical" dwelling, although its carbon footprint is not significantly lower than the direct electric case. This is largely due to the system running emissions being calculated using Southern Scotland hourly grid carbon values for 2019 [52], which have an extremely low carbon value per kWh (averaging 35 gCO2/kWh). As a result, due to the "Typical" dwellings relatively high space heating requirement, the heat pump allows for a lower usage of grid electricity to provide the same quantity of heat. However, due to the high global warming potential (GWP) of refrigerants used within heat pumps, the final lifetime carbon footprint of the ASHP is not significantly lower than the direct electric case. The ASHP would show a greater carbon saving in a region with a higher grid carbon intensity. Additionally, if the system had been designed to utilise the heat pump with a DHW preheat, the grid electricity requirement for the case 2 direct electric system could be reduced.

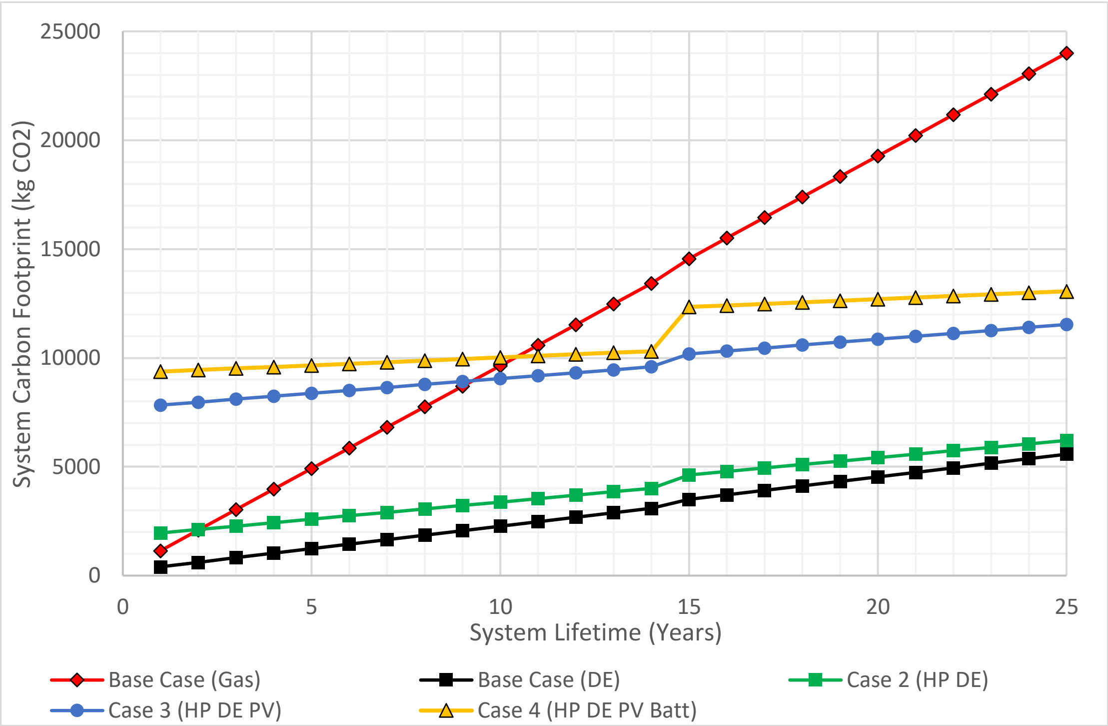

Figure 18, Heating System Carbon Footprint (kg CO2) vs Time (Years) for the "Modern" house.

Figure 18 displays the carbon footprints across the heating system lifetime for the “Modern” dwelling. Here, the carbon footprint for every modelled case is reduced due to the significantly lower space heating requirement, and reduced DHW demand from the assumptions on low energy taps and showers. This reduced heat demand results in less fuel burned, and less grid electricity consumed, reducing system running emissions.

This, again, displays the gas condensing boiler as being the system with the highest carbon footprint over the system lifetime, ending with approximately 23 tonnes of carbon after 25 years. However, due to the significant reduction in heating demands due to the improved thermal conditions of the dwelling, the required time period for the gas boiler system to overtake the systems from cases 3 and 4 is significantly longer than in the “Typical” dwelling. Here, the gas boiler overtakes cases 3 and 4 in their 11th and 12th years of use respectively. This is due to the high embodied carbon associated with PV and batteries, which accounts for the spike in carbon in the 15th year for cases 3 and 4. Ultimately, this also presents the “Modern” home as having a significantly lower carbon footprint when compared to the “Typical” home.

5.7. Financial Analysis

In this section, the financial aspect of this project is examined through multiple means, determining the NPV of each system, as well as LCOH, and plotting the lifetime running costs of each system for both housing types, including capital investments and O&M. In this financial analysis, the modelled systems will receive RHI payments at a rate of 10.85 pence / kWh of heat delivered, and PV grid export payments at a rate of 5.5 pence / kWh exported []. The PV export rate is an ideal case, as this is the highest payment currently available for export. Additionally, bills are calculated with gas prices assumed at 4.13 pence / kWh and electricity at 16.36 pence / kWh [26, 47].

Equipment	Model	Cost
ASHP	Mitsubishi Ecodan W85	£5,000 [71]
Boiler	Elektra C 12 kW Electric	£1,500 [15]
	Viessman Vitoden 100-w	£1,000 [72]
PV	LG NeON2 400 W	£2,250 [73]
Battery	PowerVault 8 kWh	£7,020 [74]

Table 9, Equipment Costs for all modelled technologies.

Table 9 displays the approximate cost of components required to create the cases which have been previously modelled. The above costs are ballpark figures typical for the technologies listed, however this does not include any costs for labour, which significantly increases the price of installation and is explored in the discussion.

$$NPV = -E_{IC} + \sum_{t=1}^{T} \frac{I_T}{(1+r)^T}$$

Net Present Value (NPV, £). E_{IC} = initial investment (£), I_T = net cash inflow during Tth year (£), T = year, r = Discount Rate (%)

NPV is used to determine the cost benefit of a given project based on return on initial investment, E_{IC}. It has been used to determine the cost benefit of installed domestic heat pump systems to determine return on investment [45]. To determine the financial benefit of a project using NPV, a project with an NPV value > 0 indicates the project returning profits on an initial investment, with NPV = 0 predicting to break even, and NPV < 0 losing value on an initial investment. The larger the NPV value, the greater the return on investment. In the case of all systems in this project, the discount rate r is assumed to be 0, as in domestic scenarios the assumption is made that payment is made up front [75].

Scenario	Typical NPV £	Modern NPV £
Case 1 (Gas)	-13293.31299	-7468.0215
Case 1 (DE)	-45167.9924	-23025.049
Case 2 (HP DE)	-25827.17136	-23025.049
Case 3 (HP DE PV)	-23073.67257	-16690.424
Case 4 (HP DE PV Batt.)	-33803.63117	-27421.505

Table 10, calculated NPV values for each system.

Table 10 presents the NPV values for all systems modelled. As is apparent, all systems will cost the user over the entire lifetime, and will not generate a return on investment. However, the NPV values do provide indication as to what systems will lose the most money for a household. As is apparent, gas provides the minimal expenditure over the system lifetime, with cases 1 (DE) and 4 (HP DE PV Battery) being the most expensive. The NPV for case 1 is higher in the "Typical" standard home due to the high running costs from electrical bills. Whereas the "Modern" home has lower running costs, resulting in the high capital cost of case 4 giving the lowest NPV for the "Modern" standard home.

$$LCOH = \frac{I_o - S_o + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_T}{(1+r)^t}}$$

Levelised Cost of Heating (LCOH, £/kWh). Io = Capital Investment (£), So = Subsidies/earnings (£), T = year (Years), Ct = O&M running costs (£),Et = Heat produced in given year (kWh), r = Discount Rate (%) [45, 75]

LCOH is a metric utilised to gauge the cost associated with a heating system. In energy generation systems, LCOE (levelised cost of energy) is frequently used to determine the price at which electricity can be sold from a given generator. LCOH follows the same process applied to any useful heat generating system to determine a cost of heat per kWh provided by a given system. This is useful for examining the cost a household will pay per kWh for heat over the entire lifetime of the system.

Scenario LCOH	Typical (£/kWh)	Modern (£/kWh)
Case 1 (Gas)	0.0478	0.0531
Case 1 (DE)	0.1711	0.1794
Case 2 (HP DE)	0.0953	0.1616
Case 3 (HP DE PV)	0.0846	0.1266
Case 4 (HP DE PV Batt.)	0.0991	0.1576

Table 11, LCOH for all modelled heating systems.

Table 11 present the LCOH of each heating system applied to both modelled dwellings. This reinforces the fact that, at present, gas heating is by far the most cost-effective heating system due to the low price of gas per kWh and its relative simplicity as a technology when compared to the alternatives. This reduces capital costs. Excluding case 1 (DE), all other systems in the "Typical" dwelling display a significantly lower LCOH when compared to the "Modern" dwelling. This is due to the higher demand for heat in the "Typical" home driving down the LCOH values, as the total heat provided by the system is the denominator within the LCOH equation. In both housing standards, case 3 appears to be the second most financially viable option after gas. In this case, the exclusion of the cost of batteries, alongside PV export and RHI payments, results in a lower cost per kWh over the system lifetime.

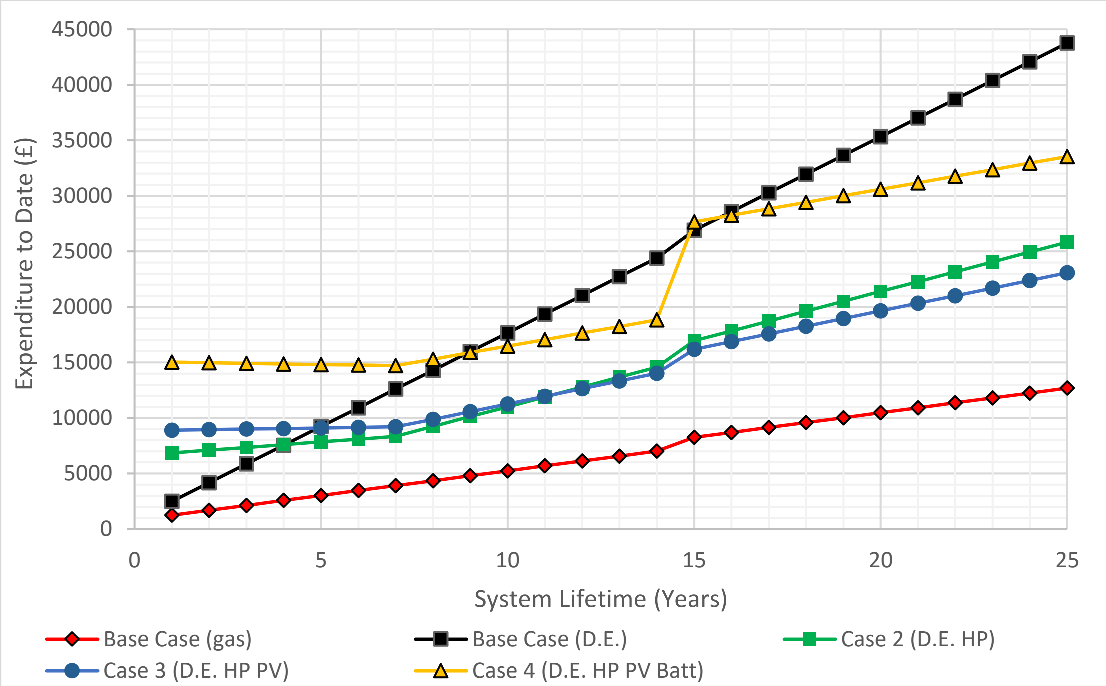

Figure 19, Lifetime Running Costs for each scenario shown for the "Typical" modelled house. This displays the running costs for each system including initial expenditure, equipment replacement, RHI subsidies and PV payments, and gas and electricity bills.

Figure 19 displays how the expenditure to date for each modelled scenario evolves over time for the "Typical" dwelling. Here, the y-axis displays how much money has been spent by the xth year as a result of capital expenditure, fuel and energy bills and any maintenance costs, with PV export and RHI payments being factored in. This illustrates the high expense of electricity as presented by the base case direct electric heating system. This case overtakes all other systems by the 9th year, finishing with a total expense of almost £44,000 over 25 years, well above the total cost of the other systems.

This figure also illustrates the high capital costs associated with installing heat pumps, PV panels and batteries. Cases 2, 3 and 4 are seen to have relatively frozen expenditures for the first 7 years, with case 4 making a small amount of income during this period. This is predominantly the result of the RHI payments received by the households. During this time period, the cashflows are supported by the PV export payments for cases 3 and 4, with these cases also requiring reduced quantities of expensive grid electricity. Additionally, due to the inefficiency of the "Typical" dwelling, cases 2, 3 and 4 all receive £637.5790 annually for the heat they deliver to the dwelling from their heat pump. An interesting result presented here is the positive impact the installed PV has on the expenditure for case 3, as here it is presented as having a lower final cost when compared to the HP and DE only scenario. With cases 2 and 3 being approximately twice as expensive as the scenario with a 95% efficient gas boiler, this presents the clear cost issue the electrification of heat will impose on households within the UK.

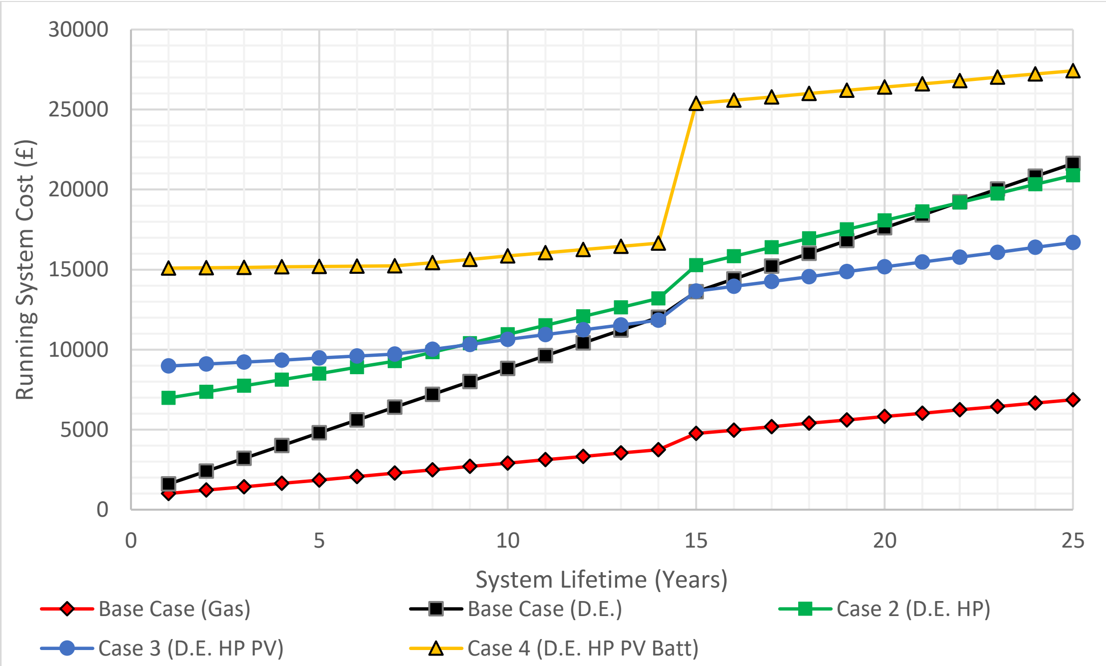

Figure 20, Lifetime Running Costs for each scenario shown for the "Modern" modelled house. This displays the running costs for each system including initial expenditure, equipment replacement, RHI subsidies and PV payments, and gas and electricity bills.

Figure 20 displays the lifetime costs associated with each heating system applied to the "Modern" standard home. In this scenario, the most expensive system over the 25 year period is case 4. This is a consequence of the higher thermal efficiency of the "Modern" standard home, resulting in a significantly reduced space heating load for the direct electric boiler scenario, therefore mitigating the consumption of costly grid electricity.

While the scenarios in figure 20 which utilise heat pumps all have stable low expenditures over the initial 7 year period, these scenarios experience slightly higher bills than the "Typical" case due to the lower RHI payment received by the household. From the space heating provided by the ASHP, the "Modern" standard home receives an annual payment of £180.1300 due to heat delivered (at a rate of £0.1085 / kWh [26]).

However, ultimately this is not a disadvantage to the “Modern” standard home due to its overall increased efficiency, which acts to significantly reduce energy bills. If the system had been modelled to utilise the heat pump to aid with DHW generation then the RHI payments would be significantly higher, and additionally this would cut the grid demand from all cases with a heat pump. This is expanded upon in the discussion.

Figure 20 also presents case 2 (DE and heat pump) as being marginally cheaper than the case 1 DE scenario over the 25 year period. This is again due to the high capital costs associated with heat pump adoption. This marginal cost saving could also be increased with the heat pump being utilised in DHW production.

6. Discussion

6.1. Results Overview

At the initial stage of planning for this project, one of the lines of investigation was to compare the performance between a purely electric heating system utilising battery storage and another system using thermal storage in the form of a hot water tank, instead of battery. As the project progressed, given the number of heating systems being modelled, the decision was made to narrow the scope of the investigation and remove the comparison to a thermal storage heating system. This resulted in the heat pump not being utilised in any form of DHW preheating, which can significantly cut the heat requirement for hot water production. While this could still be performed with some form of smaller buffer tank, it was not included in the modelling, and as a result, the DHW demands are higher than would be seen in a domestic setting utilising a heat pump for DHW. The scenarios explored, with a direct electric heating system providing the heat output to a detached house is unusual, with a detached house normally utilising a thermal storage tank to meet high instantaneous demands. However, the direct electric boiler system selected is capable of providing the maximum flow rates generated from the modelling results. In reality, this would probably result in lower flow rates and potential temperature fluctuations from outlets such as taps and showers, due to the dwelling size and occupancy. Obviously, this isn't ideal, and in reality some form of water storage tank should be implemented for a detached home.

However, despite this, this thesis has effectively quantified the grid demands from various systems, alongside their carbon footprints and financial costs. Any shortcomings in these particular areas are explored in the following sections.

6.2. DHWCALC:

The modelled results from DHWCalc are purely representative of typical hot water usage. DHW usage is highly dependant on occupant behaviour, number of occupants and their habits. This means that as DHW contributes to the majority of the heat requirement in a modern standard home, a households energy consumption for heat can vary significantly from house to house dependent on occupant behaviours.

6.3. ESP-r Data

The test reference year used for the building model simulation was out of date, being from 1994. The decision to use this file was made due to it being the most recent functional weather file for the West of Scotland available within the ESP-r database. Due to climate change, a more recent test reference year will likely display higher temperatures with milder winters, and therefore a reduced heating load throughout the year.

In performing detailed modelling of the systems presented in this thesis, a compromise was not using data from the same year. For example, the test reference year from 1994, and the grid carbon intensity from 2019. Ideally, a 2019 test reference year would be utilised, with the weather impacting the thermal performance of the dwellings, and in turn, the weather would be directly linked to the grid carbon intensity in Scotland due to high renewables penetration.

The casual gains used in the ESP-r modelling were a rough approximation assuming four occupants with two adults and two children, and additional gains based on equipment power emission assumptions and behaviours. The assumption of 220 W for two adults sleeping and 200 W for two children are likely higher than the real sensible gains that would be emitted from these occupants. In reality, these gains would be lower, as a study revealed the average male adult emits approximately 90 W whilst sleeping, with the average female adult emitting approximately 75 W [76]. This would result in even lower gains from children. However, this overestimation in the gains profile would likely not result in more than 100 W excess sensible gains to the entire house, and therefore would not result in a significant increase in heating demand if more accurate gains were implemented.

6.4. Visual Basic Modelling:

The modelling performed on Excel and coded with Visual Basic was an extremely simplistic modelling approach. This approach utilised efficiencies for different technologies, such as inverters, batteries, and the COP of an ASHP and simply applied these to the space heating and DHW demands. This simplification does not reflect any complexities of the modelled technologies, for example potential lags in ASHP effectiveness due to frosting of the outside heat exchanger, or decays in the battery capacity or PV. The method utilised would be adequate to predict the approximate power demand for the heating system, however in reality this system will consume more grid electricity over time. For a more accurate model, system decay factors could be applied to the technologies modelled as they progress through their life cycle until replacement. This would result in a lower usable battery capacity and PV generation over time. This would ultimately return a higher grid demand, carbon footprint, and increased cost to the system.

A potential issue with the battery modelling within this investigation was the simplicity of the battery model used. While the "energy bucket" battery modelling approach is an established method for modelling the performance of a simplified battery [63], it neglects nuances of battery charging and discharging, as both processes are limited by power curves. This is a result of the voltage across a battery changing as it is charged and discharged, which impacts its power output and input. However, with Li-ion batteries, the discharge curve is quite stable. The impact this would have on the modelling however is minor due to the length of the timesteps (1 hour) and would likely result in a drop in PV self-consumption due to reduced battery effectiveness, and an increase in grid energy consumption.

6.5. Carbon Footprints:

The method for calculating the operational emissions of the system was performed by matching when grid demand occurred, which was simulated from the Visual Basic code, to the grid carbon intensity during the simulated year. This gives a very precise carbon footprint from the consumed grid electricity, as whenever grid electricity is consumed (output from model), the exact grid carbon intensity for that time is known, therefore associated emissions can be calculated. Unfortunately, the grid carbon intensity data from the National Grid Carbon API does not issue any uncertainty in their data, however this would not likely have a major impact on the results of this investigation.

However, the uncertainty in the embodied carbon footprints are stated by the LCAs used as being at ±20%. Due to the overall difference in the final carbon footprints of the cases presented, this will only impact the difference between case 2 and the direct electric case 1. Therefore, within the South of Scotland, both of these cases will have practically the same carbon footprint when applied to the houses modelled.

The carbon savings of the electrified heating systems presented previously are sensitive to the grid carbon intensity. This thesis has investigated these emissions using grid carbon data for the South of Scotland, which has the lowest annual carbon intensity in the UK, averaging approximately 35 gCO_2/kWh in 2019. When the modelled grid demands simulated for the "Modern" standard house are applied to the region of the UK with the highest grid carbon intensity in 2019, the East Midlands (averaging 359.7 gCO_2/kWh in 2019), the electrified heating systems do not reduce the households carbon footprints:

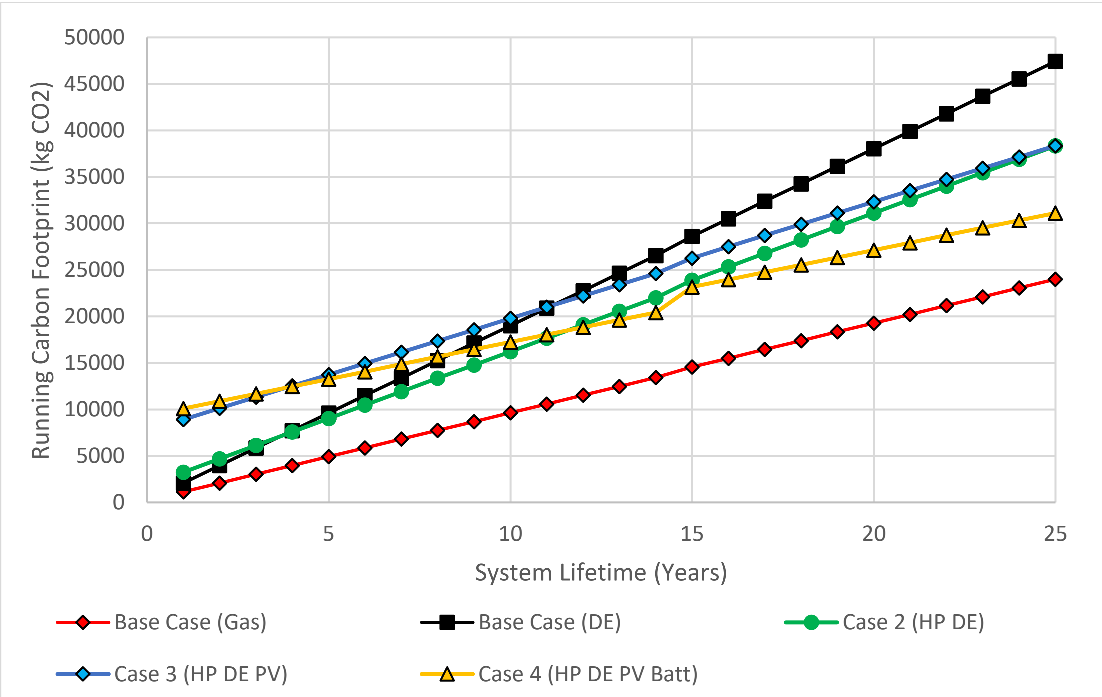

Figure 21, Carbon Footprint (kg CO_2) for all heating systems for the "Modern" house using grid carbon data from the East Midlands.

Figure 21 displays that depending on the region of the UK, a household may reduce its emissions when compared to the "low-carbon" heating systems such as heat pumps, if they were to install high efficiency condensing boilers. In this scenario, with high carbon grid electricity, the case 4 heating system is the lowest electrified system after 25 years, due to its low grid electricity usage. This offsets its embodied carbon when compared to the other electrified cases. However, given that the UK is currently in a transition to low carbon energy systems, the grid intensity in this region should decrease in line with net zero 2050 targets. With a reduction to grid carbon intensity over the coming years, this will result in the electrified heating system providing reduced carbon footprints when compared to gas.

6.6. Financial Results

The financial analysis of the heating systems in this thesis clearly illustrate the dichotomy of the electrification of heat. This transition is an absolutely necessary step towards decarbonisation and climate change mitigation, however the costs of electricity and high capital costs present a serious barrier for the uptake of the technology. As is presented in the financial analysis, gas is by far the cheapest source of heat, but in Scotland is by far the most polluting. Conversely, heat pumps present a significantly higher capital and higher running costs, but far lower emissions over the system lifetime. RHI payments do aid households in the uptake of these technologies, and will likely continue to encourage uptake. However, the cost of electricity may require some form of government intervention to prevent poorer households on purely electric heating systems from experiencing fuel poverty.

A shortcoming of the financial analysis was that it did not include labour costs, only the cost of components. According to a government report, in 2014, the component costs of an air source heat pump installation accounted for approximately 60% of the installation costs, with labour costing approximately 21% of expenditure [77]. Considering the component costs stated in table 9, this could set the price of labour at approximately £1050 for an air source heat pump installation. Additionally, the labour cost for the PV panels would likely be in excess of £1000, with additional costs for inverter replacements [78]. This presents a significant added cost to the inclusion of these domestic renewable technologies.

Coming into effect in the Autumn of 2020, the new government Green Homes Grant will be allowing households to apply for grants up to £5000, with low income households eligible for grants up to £10000 [79]. These grants are to be spent on home improvements such as increased insulation, draught reduction and heat pump installation. Schemes such as these could result in a reduction in the capital costs facing households with the adoption of heat pumps.

Additionally, while the inclusion of PV and batteries presents additional financial costs, this thesis demonstrates their ability to reduce the burden on a renewable grid by mitigating the domestic heating load to some extent.

7. Conclusion:

This project achieved its goal of quantifying the approximate grid demands representative of future electrified heating systems in two standards of detached UK home, one with insulation standards typical of the UK housing stock, and another with insulation standards approximately equivalent to the passive house building standard. The most obvious result from modelling the heating systems for both standards of housing, was that higher levels of insulation have a significant impact on the heating demands, and therefore grid demands in a dwelling with electrified heat. As the "Modern" standard home had a heat requirement 52.5% lower than the "Typical" home. Additionally, it was demonstrated that heat pumps combined with PV and batteries can more than half the grid demand associated with a passive house standard dwelling.

For the analysis of the "Modern" new build standard home, it was shown that when the heating system was modelled consuming grid electricity from the South of Scotland for 2019, the direct electric base case resulted in the lowest carbon footprint for the home. This was due to the extremely low grid carbon intensity at present in the central belt of Scotland. However, the inclusion of heat pumps allows for heat production with a minimised grid demand. While the embodied carbon associated with batteries and PV significantly increases the footprint of the heating system they support, they present the opportunity to cut grid demands. On a national level this technology would aid a highly renewable grid, by cutting peak demands.

In the financial analysis of the modelled systems it was demonstrated that even with RHI payments, the high capital costs combined with the high price per kWh of electricity presents a major hurdle for the electrification of heat. Given that fuel poverty is already an issue in the UK, the transition to electrified heat poses a serious threat to the ability for households to pay significantly higher energy bills and maintain thermal comfort. This will likely result in the continuation of the RHI scheme, as well as the potential for other government incentives or support for poorer households during this transition.

8. Future Work

- **<u>Battery Decay Modelling:</u>**

The battery system modelled in the previously described Visual Basic code was a static "energy bucket" model. The model was an idealised case with simplifications neglecting battery decay, which over the system lifetime would have a significant reduction in the domestic battery effectiveness. This could be improved by implementing a battery decay factor which degrades the capacity of the battery over time after each charge/discharge cycle [63]. This would allow for the investigation of a more realistic system performance over time, as the modelling in this thesis presented a static, non-decaying performance over the entire system lifetime. This change would likely result in a decrease of self-consumption of PV over time, with increased grid demands, bills and associated carbon footprints.

- **<u>PV Decay Modelling:</u>**

Similar to the battery simplifications, the PV system modelled also experienced no decay over time, as in the real world. This could also be implemented in future modelling to give a more accurate simulation of the domestic energy system performance over its lifetime.

- **<u>Tariff Based Battery Charging:</u>**

With the cost of electricity being a major challenge in the electrification of heat, there is scope for an investigation on using the battery systems modelled in this thesis to participate in tariffs such as Economy 7. Throughout the winter months, the modelled battery systems fully discharge daily due to the high domestic heating loads and low PV. This presents untapped potential to shift the domestic heating demand when it is at its highest – Winter. This would involve charging the battery overnight, when electricity is cheaper, then discharging the battery when high domestic heating loads occur, to mitigate the impact that the electrification of heat will have on the grid. This could have the joint benefit of minimising peak grid demand and household bills

- **Comparison with Thermal Storage Scenarios:**

A productive line of investigation for future work would be to examine the relative performance of a thermal storage tank in place of the battery storage presented in this thesis. As this was initially a line of investigation before the thesis scope was narrowed, the work performed in this thesis could form the basis for a comparison with thermal storage. This could compare the grid demands, heating system effectiveness and user costs.

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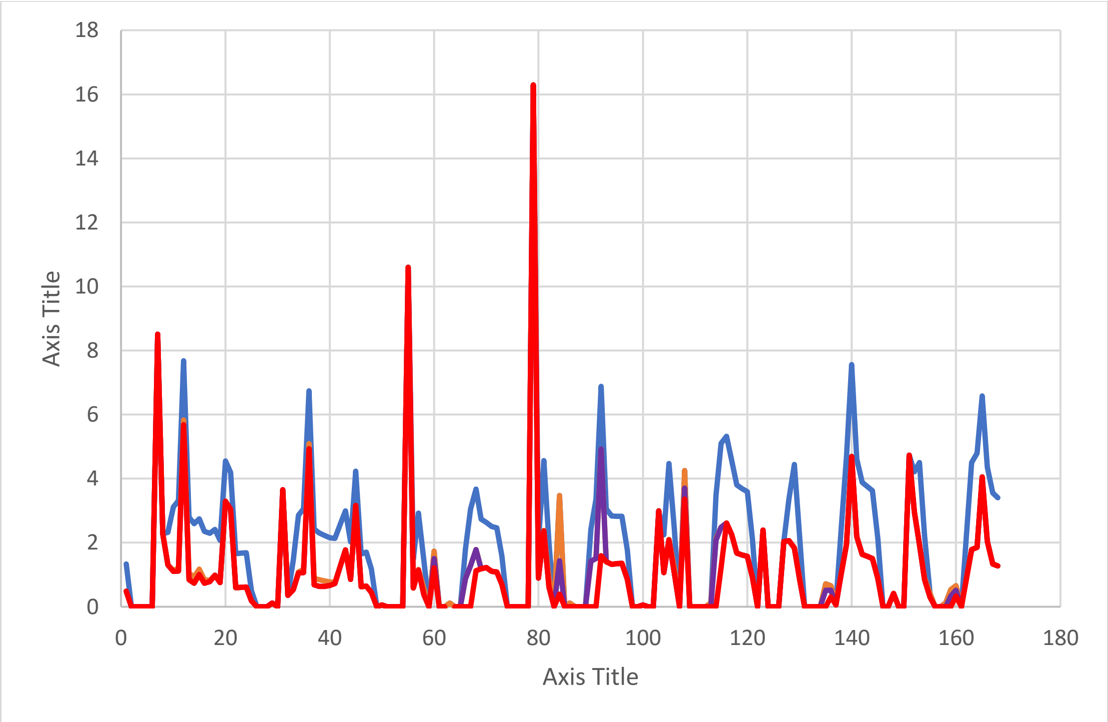
10. Appendix

Appendix A, Inlet water temperatures in Scotland:

Month	Seasonal Inlet T (C)
January	9
February	8
March	9
April	13
May	14
June	15
July	16
August	18
September	17
October	16
November	14
December	13

Appendix B, Typical Home, coldest week of the year, comparative grid demand vs time for each modelled system:



Appendix C, Typical LCOH input data for calculation:

Typical LCOH	Case 1 (Gas)		Gas LCOH	
	Io	1100	0.047784	£/kWh
	So	0		
	Ct	443.7325		
	Et	10206.92		
	Case 1 (DE)		**DE LCOH**	
	Io	1500	0.171131	£/kWh
	So	0		
	Ct	1686.72		
	Et	10206.92		
	Case 2 (DE HP)		**LCOH**	
	Io	6600	0.095336	£/kWh
	So	4464.311		
	Ct	887.6593		
	Et	10206.92		
	Case 3 (DE HP PV)		**LCOH**	
	Io	8850	0.084545	£/kWh
	So	7819.163		
	Ct	821.7134		
	Et	10206.92		
	Case 4 (DE HP BATT)		**LCOH**	
	Io	15070	0.099084	£/kWh
	So	6268.014		
	Ct	659.2658		
	Et	10206.92		

Appendix D, Modern LCOH input data for calculation:

Modern LCOH	**Case 1 (Gas)**		**Gas LCOH**	
	Io	1100	0.053082	**£/kWh**
	So	0		
	Ct	210.7209		
	Et	4798.622		
	Case 1 (DE)		**DE LCOH**	
	Io	1500	0.179427	**£/kWh**
	So	0		
	Ct	801.002		
	Et	4798.622		
	Case 2 (DE HP)		**LCOH**	
	Io	6600	0.161571	**£/kWh**
	So	1260.922		
	Ct	561.7546		
	Et	4798.622		
	Case 3		**LCOH**	
	Io	8850	0.126623	**£/kWh**
	So	5075.672		
	Ct	456.6438		
	Et	4798.622		
	Case 4		**LCOH**	
	Io	15070	0.157558	**£/kWh**
	So	3525.422		
	Ct	294.2771		
	Et	4798.622		

Appendix E, Typical NPV input data for calculation:

Typical NPV	**Case 1 (Gas)**		**Gas NPV**
	Eic	1100	-13293.3
	En	-12193.3	
	Case 1 (DE)		
	Eic	1500	-45168
	En	-43668	
	Case 2 (DE HP)		
	Eic	6600	-25827.2
	En	-19227.2	
	Case 3 (DE HP PV)		
	Eic	8850	-23073.7
	En	-14223.7	
	Case 4 (DE HP PV Batt)		
	Eic	15070	-33803.6
	En	-18733.6	

Appendix F, Modern NPV input data for calculation:

Modern NPV	**Case 1 (Gas)**		**Gas NPV**
	Eic	1100	-7468.022
	En	-6368.02	
	Case 1 (DE)		
	Eic	1500	-23025.05
	En	-21525	
	Case 2 (DE HP)		
	Eic	6600	-20882.94
	En	-14282.9	
	Case 3 (DE HP PV)		
	Eic	8850	-16690.42
	En	-7840.42	
	Case 4 (DE HP PV Batt)		
	Eic	15070	-27421.5
	En	-12351.5	

Appendix G, LG NeON2 400W Specifications (Used in ESP-r):

LG NeON®2

LG395N2W-V5 | LG400N2W-V5

General Data

Cell Properties (Material / Type)	Monocrystalline / N-type
Cell Maker	LG
Cell Configuration	72 Cells (6 x 12)
Number of Busbars	12EA
Module Dimensions (L x W x H)	2,024mm x 1,024mm x 40 mm
Weight	20.3 kg
Glass (Material)	Tempered Glass with AR Coating
Backsheet (Color)	White
Frame (Material)	Anodized Aluminium
Junction Box (Protection Degree)	IP 68
Cables (Length)	1,200mm x 2EA
Connector (Type / Maker)	MC 4 / MC

Certifications and Warranty

Certifications	IEC 61215-1/-1-1/2:2016, IEC 61730-1/2:2016, UL 1703
	ISO 9001, ISO 14001, ISO 50001
	OHSAS 18001
Salt Mist Corrosion Test	IEC 61701:2012 Severity 6
Ammonia Corrosion Test	IEC 62716:2013
Module Fire Performance	Type 1 (UL 1703)
Fire Rating	Class C (UL 790, ULC/ORD C 1703)
Solar Module Product Warranty	25 Years
Solar Module Output Warranty	Linear Warranty*

* 1) 1st year: 98%, 2) After 1st year: 0.35% annual degradation, 3) 89.6% for 25 years

Temperature Characteristics

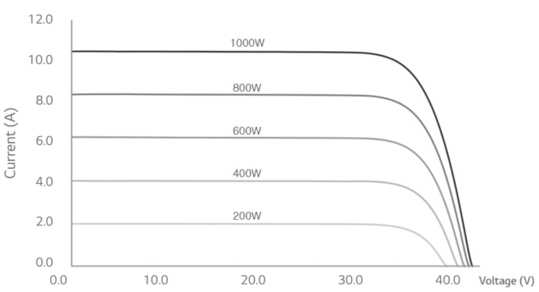
NMOT*	[°C]	42 ± 3
Pmax	[%/°C]	-0.36
Voc	[%/°C]	-0.26
Isc	[%/°C]	0.02

* NMOT (Nominal Module Operating Temperature): Irradiance 800 W/m2, Ambient temperature 20 °C, Wind speed 1 m/s, Spectrum AM 1.5

Electrical Properties (NMOT)

Model		LG395N2W-V5	LG400N2W-V5
Maximum Power (Pmax)	[W]	296	300
MPP Voltage (Vmpp)	[V]	37.7	38.0
MPP Current (Impp)	[A]	7.86	7.88
Open Circuit Voltage (Voc)	[V]	46.4	46.5
Short Circuit Current (Isc)	[A]	8.37	8.40

I-V Curves



Electrical Properties (STC*)

Model		LG395N2W-V5	LG400N2W-V5
Maximum Power (Pmax)	[W]	395	400
MPP Voltage (Vmpp)	[V]	40.2	40.6
MPP Current (Impp)	[A]	9.83	9.86
Open Circuit Voltage (Voc, ± 5%)	[V]	49.2	49.3
Short Circuit Current (Isc, ± 5%)	[A]	10.43	10.47
Module Efficiency	[%]	19.1	19.3
Power Tolerance	[%]	0 ~ +3	

* STC (Standard Test Condition): Irradiance 1000 W/m², cell temperature 25 °C, AM 1.5

Operating Conditions

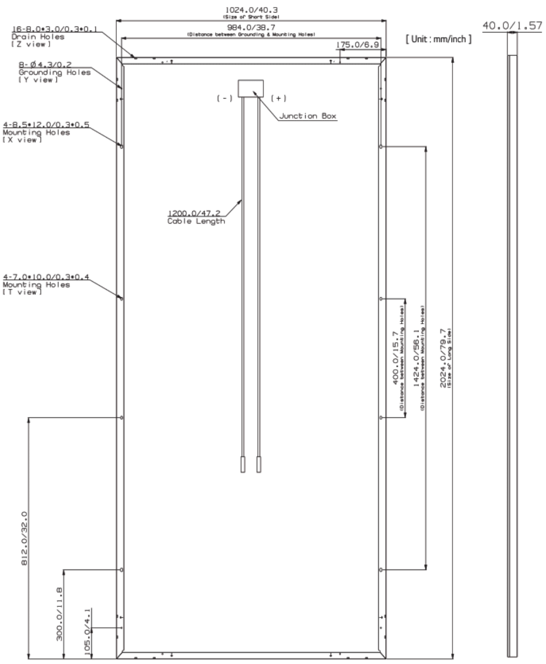
Operating Temperature	[°C]	-40 ~ +90
Maximum System Voltage	[V]	1,500(UL), 1000(IEC)
Maximum Series Fuse Rating	[A]	20
Mechanical Test Load (Front)	[Pa/psf]	5,400 / 113
Mechanical Test Load (Rear)	[Pa/psf]	3,000 / 63

* Test Load = Design load x Safety Factor (1.5)

Packaging Configuration

Number of Modules per Pallet	[EA]	25
Number of Modules per 40ft HQ Container	[EA]	550
Packaging Box Dimensions (L x W x H)	[mm]	2,080 x 1,120 x 1,226
Packaging Box Gross Weight	[kg]	551

Dimensions (mm / inch)



LG Life's Good

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Product specifications are subject to change without notice.
LG395-400N2W-V5.pdf