DEVELOPMENT OF ADVANCED HEAT PUMP AND THERMAL STORAGE SYSTEMS CAPABLE OF COST EFFECTIVE DEMAND SIDE MANAGEMENT

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ABSTRACT

The EU renewable energy directive (2009/28/EC) has set a range of national targets to collectively raise the average renewable share across Europe to 20% by 2020. Northern Ireland and Ireland have set their own ambitions on 40% electricity consumption from renewables by 2020 and 10% and 12% renewable heat by 2020 respectively for Northern Ireland and Ireland. Air source heat pumps have been identified as a major contributor towards reaching renewable heat targets and decarbonisation of heat. In order to maintain a working grid however system constraints result in limitations on wind generation often resulting in curtailment overnight in low demand hours with high wind. Full electrification of heat also gives rise to the necessity to increase generation and reinforce the electricity grid. A more cost-effective solution would be a more sophisticated method which would balance energy production and demand through energy storage. Using high temperature heat pumps domestic retrofit application is possible and when combined with energy storage, demand side management (DSM) control strategies, and user incentives it could be possible to provide a deployable means of balancing non-dispatchable wind generation with heating demand.

The research presents operational performance of a retrofit high temperature cascade air-source heat pump (ASHP) and thermal store which uses publicly available real-time and forecast electricity grid data for Northern Ireland using a low cost network connected Raspberry Pi computer to automate dynamic charging and discharging of a thermal store based on the state of the grid demand in real-time. The ASHP can reach a flow temperature of 80°C at 11kW nominal output, thus avoiding replacement of radiators in the occupied test house. The ASHP impact on peak grid demand is minimised by shifting thermal energy stored at low grid demand. Operational data shows the system is capable of providing 8.7% of the daily demand from storage but the overall system COP drops to 1.91 compared to a COP of 2.27 when heating the house directly. The impact is an increase of on average 1.2p/kWh thermal delivered to the house compared to direct only heating. However, the CO2e intensity of the combined system was 30 gCO2e/kWh thermal less intensive than a gas boiler tested in the same house.

The ASHP was also run as a hybrid coupled with the test house existing gas boiler in parallel mode (one heat source active at any one time only). In this situation the gas boiler effectively replaced the thermal store to provide DSM avoiding the HP impacting on peak grid demand. In addition, the hybrid was run using a real-time electricity market price signal as an

alternative to a real-time grid demand signal. A small test was also run with the HP in series with the gas boiler. Due to the lack of a combined control, this mode resulted in reduced operating efficiency, however this could be removed with simple control optimisation.

The Raspberry Pi enabled low cost robust fully automated smart grid capability for relatively little cost. The occupants of the test house were unaware of the source of the heat and maintained the existing heat controls. Occupant thermal comfort was never compromised, and occupants were never encouraged or discouraged to use their heating system any differently to the gas boiler installation. The research shows that carbon intensity of domestic heating can be lowered when using an ASHP. Coupled with well-designed thermal storage the impact of electrified heating on the grid network can also be managed with simple and cheap technology without compromising on user thermal comfort. This will come with an efficiency compromise due to storage losses however if storage coincides with otherwise curtailed wind energy overall grid efficiency will increase.

ABBREVIATIONS

3-PV	Three port valve
AC	Alternating current
AGU	Aggregated generator unit
ASHP	Air source heat pump
BR	Boiler room
CO_2e	Carbon dioxide equivalent
COP	Coefficient of performance
CSV	Comma separated value
DC	Direct current
Delta T (Δt)	Temperature difference
DHW	Domestic hot water
DNO	Distributor network operator
DPDT	Double-pole double-throw
DSM	Demand side management
DSR	Demand side response
DSU	Demand side unit
GHG	Greenhouse gas
GPIO	General purpose input and output
GSHP	Ground source heat pump
HP	Heat pump
IQR	Inter-quartile range
IOT	Internet of things
I-SEM	Integrated-Single Electricity Market
KPI	Key performance indicator
kW	Kilo-Watt
kWh	Kilo-Watt hour
LPHW	Low pressure hot water
ltr	Litre
mA	Milli-Amp
Micro-CHP	Micro combined heat and power
Ø	Diameter
PCB	Printed circuit board
PCM	Phase change material
PSU	Power supply unit
PWM	Pulse wave modulation
RHI	Renewable heat incentive
s	Seconds
SCOP	Seasonal coefficient of performance
SEM	Single Electricity Market
SEMO	Single Electricity Market Operator
SH	Space heating
SMP	System marginal price
SNSP	System non-synchronous penetration
SPDT	Single-pole double-throw
SPF	Seasonal performance factor
TRV	Thermostatic radiator valve
V	Volt
Wh	Watt hour

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1 INTRODUCTION

1.1 Introduction

A revolution of UK heating supply will be necessary to meet the carbon reduction targets set out in the Climate Change Act (2008). The act is a commitment by the UK government to significantly reduce greenhouse gas emissions by at least 80% of 1990 levels by 2050. In addition the UK has made pledges to the global effort, The Paris Agreement (2015), to reduce emissions in order to prevent global average temperatures exceeding 2°C above pre-industrial levels and to pursue a warming limit of 1.5°C. As a current member of the European Union, The EU renewable energy directive (2009/28/EC) applies which has set a range of national targets to collectively raise the average renewable share across Europe to 20% by 2020. Northern Ireland and Ireland have set their own ambitions on 40% electricity consumption from renewables by 2020 and 10% (DETNI, 2011) and 12% (Eirgrid, 2014) renewable heat by 2020 respectively for Northern Ireland and Ireland. The implications of the UK vote to leave the EU has not changed the UK's 2050 climate change goals and legislated carbon budgets remain as a means of achieving global climate change targets (Committee on Climate Change, 2018).

Air source heat pumps have been identified as a major contributor towards reaching renewable heat targets and decarbonisation of heat (Department of Energy & Climate Change, 2013; Arteconi, et al., 2013). In order to maintain a working grid however system constraints result in limitations on wind generation often resulting in generation curtailment overnight in low demand hours with high wind. Full electrification of heat also gives rise to the necessity to increase generation and reinforce the electricity grid. A more cost-effective solution would be a more sophisticated method which would balance energy production and demand through energy storage. Using high temperature heat pumps domestic retrofit application is possible and when combined with energy storage, demand side management (DSM) control strategies, and user incentives it could be possible to provide a deployable means of balancing non-dispatchable wind generation with heating demand.

1.2 Domestic Energy Consumption & Fuel Poverty

Across all sectors in the UK approximately 46% of total final energy consumption was for heating (approximately 80% of which is produced from fossil fuels), of this total 63% and 14% is for space and water heating respectively (Eames, et al., 2014). In the UK in 2015 the domestic sector was responsible for 29% of the total final energy consumption of which approximately 80% is for space heating and hot water demand (BEIS, 2017c).

In Great Britain the dominant fuel used for heating is mains gas accounting for 20,141,801 households or 78.3% according to the 2011 UK Census which is summarised in Table 1-1. The table shows heating type breakdown of fuels used in the provision of heating for households, with at least one usual resident, in each of the four countries in the UK. In comparison Northern Ireland domestic heating is dominated by heating derived from heating oil. Oil central heating in Northern Ireland accounts for 437,269 households or 62.2% compared to 120,956 or 17.2% for gas central heating although this has increased to 237,199 as of quarter 4 2017 (UREGNI, 2018). What is striking from the figures in Table 1-1 is the level of households in the UK reporting no installed central heating, 682,826 or 2.6% of UK households. Although Northern Ireland has by far the smallest proportion across the UK with 3,766 households or 0.5% reporting to have no central heating in 2011, fuel poverty is a major issue in Northern Ireland.

Fuel poverty is defined as a household which spends more than 10% of its income on fuel in order to maintain a satisfactory level of heating of 20°C in the living room and 18°C in other occupied rooms. Official figures for Northern Ireland put the level of fuel poverty at a staggering 42% in 2011, higher than households in Great Britain and the Republic of Ireland and one of the highest in Western Europe (The Consumer Council NI, 2018). Figures for Great Britain stand at: England 11% in 2015 (BEIS, 2017a); Scotland 34% in 2016 (Scottish Government, 2018); and Wales 23% in 2016 (Beaumont, et al., 2016). Fuel poverty is generally a result of multiple factors including: energy inefficient housing stock; low household income; high fuel costs; and under occupancy (those most vulnerable to fuel poverty tend to live in larger homes) (The Consumer Council NI, 2018). The consequences of fuel poverty can have severe impacts on society. The result of having to limit heating due to poverty can be cold and damp homes or trying to maintain a satisfactory level of thermal comfort can lead to debt or restriction of expenditure on other essential items. Fuel poverty and cold homes are associated with a wide range of direct health impacts including increased mortality (excess winter deaths) and morbidity (Geddes, et al., 2011). It has been estimated by Geddes, et al. (2011) that excess winter deaths in the colder quarter of housing is almost

three times higher than the warmest quarter of housing, due to it being cold. Healy (2003) analysed excess winter deaths across Europe and found that there was a common misconception that countries with milder climates were less susceptible to excess winter deaths from cold strain, in fact colder countries with higher building standards than the UK, had much lower rates of excess winter deaths. Morbidity (health conditions) associated with cold housing include respiratory, circulatory and mental health conditions as well as those conditions which can be exacerbated by cold homes including common colds and flu, arthritis and rheumatisms (Geddes, et al., 2011). The reasons for the higher rates of fuel poverty in Northern Ireland has been attributed to a combination of climate, low incomes, high fuel prices and in particular the dependence on oil, an unregulated fuel, for home heating.

The dominance of oil heating in Northern Ireland is due to the relatively late arrival of gas supply to the country which was only introduced in 1996 via the Scotland to Northern Ireland gas pipeline initially supplying the Greater Belfast and Larne areas (Northern Ireland Executive, 2017). The network was extended to the "10 towns" between 2004 and 2006 which has 36,100 connections as of Q4 2017 (UREGNI, 2018). Further work to extend the network, "Gas to the West" was awarded full planning permission in mid-2017 which aims to connect a further 40,000 customers over the next 40 years with an investment of £250 million (Gas to the West, 2017). If the scheme achieves these figures it would represent an investment of £6,250 per customer for 5.7% of households in Northern Ireland (using number of households in NI from Table 1-1 and basic assumption that all new connections would be domestic and number of households remains unchanged). Given these figures and timeframes it is clear that oil heating will remain the dominant form of home heating fuel in Northern Ireland unless there is a momentum shift toward alternative heating methods that can at least offer convenience and affordability on a par with gas central heating. The best solution for home heating will be the most sustainable option which can meet the needs of the present without compromising the ability of future generations to meet their own needs by finding the optimum balance between the three main aspects of sustainability: the environmental aspect; the social aspect; and the economic aspect.

Table 1-1 Number and proportion of households in the UK, with at least one usual resident, by type of main space heating fuel. The data is from the 2011 UK Census. Figures for England and Wales sourced from Office for National Statistics (2018); Scotland sourced from National Records of Scotland (2014); and Northern Ireland sourced from NIRSA (2012).

Central Heating	England	%	Scotland	%	Wales	%	Northern Ireland	%	UK Total	%
All categories: Type of central heating in household	22,063,368	100.0	2,372,777	100.0	1,302,676	100.0	703,275	100.0	26,442,096	100.0
No central heating	594,561	2.7	54,965	2.3	29,534	2.3	3,766	0.5	682,826	2.6
Gas central heating	17,386,813	78.8	1,761,431	74.2	993,557	76.3	120,956	17.2	20,262,757	76.6
Electric (including storage heaters) central heating	1,828,589	8.3	317,831	13.4	72,176	5.5	24,671	3.5	2,243,267	8.5
Oil central heating	848,145	3.8	135,223	5.7	113,984	8.7	437,269	62.2	1,534,621	5.8
Solid fuel (for example wood, coal) central heating	149,694	0.7	26,209	1.1	24,987	1.9	18,120	2.6	219,010	0.8
Other central heating	357,916	1.6	16,608	0.7	11,618	0.9	4,083	0.6	390,225	1.5
Two or more types of central heating	897,650	4.1	60,510	2.6	56,820	4.4	94,410	13.4	1,109,390	4.2

1.3   UK Domestic Typical Heating System

1.3.1   Wet Central Heating

The most common form of domestic heating in the UK is hydronic central heating systems in which heat is produced at a central source, typically from a gas or oil boiler, and distributed around the whole building, typically via pipes and room radiators. From Table 1-1 we can see that 2.6% of households in the UK have no central heating systems and in Northern Ireland specifically the proportion is much lower at 0.5%. The system is designed so that normally habitable or used rooms and spaces are heated to achieve guaranteed temperatures under certain conditions. In all hydronic domestic central heating systems water is chosen as the medium used to transfer heat from the central generation point, commonly referred to as the boiler, to the heat emitters from which it is returned to the boiler to repeat the cycle. Water is chosen as it is low cost and readily available however the disadvantages of water are its low boiling point and high freezing point, and corrosiveness to metallic materials (Watkins, 2011).

Hydronic domestic central heating systems are classified as low pressure hot water (LPHW) which in the UK equates to systems with temperatures less than 100°C and static operating pressures in the range of $1 - 3$ bar absolute (Watkins, 2011). LPHW systems are considered a suitable design for domestic properties were temperatures are below 100°C avoiding potential hazards of flash steam in the event of pipe or valve failures. Traditional design used flow temperature of 82°C and delta T (Δt) of 11-12°C, resulting in a return temperature of 71°C (Watkins, 2011). The introduction of condensing boilers has resulted in an increase in the design Δt to lower the return temperatures which is needed to condense flue gases and thereby optimise boiler efficiency. This has a knock-on effect of requiring larger heat emitters.

Low temperature heating systems can be further categorised as open or sealed systems. In an open system an open feed and expansion cistern are incorporated with the systems operating at atmospheric pressure plus the static head created by the feed and expansion cistern and flow temperatures not exceeding 82°C. In a sealed system the feed and expansion cistern is replaced by a sealed expansion vessel allowing the heating system to operate at a slightly higher pressure above atmospheric and a slightly higher flow temperature is also achievable, in the region of 85-95 °C (Watkins, 2011). Flow temperatures above 82°C however require additional consideration to be given to heat emitters to avoid scald risk and

therefore it is unlikely domestic systems will be designed with flow temperatures exceeding 82°C.

The circulation of the heat transfer medium is typically either by gravity (thermo-siphon) or by pumped circulation. Full gravity heating systems are no longer installed as fully forced water circulation for heating and hot water is the most efficient arrangement in most instances.

There are numerous piping arrangements for UK domestic heating systems namely: one-pipe systems; two-pipe systems; two-pipe reverse return systems; two-pipe radial systems; and micro-bore systems. Each arrangement has their own advantages and disadvantages but the most commonly used method, the two pipe system, illustrated in Figure 1-1 (Watkins, 2011), will be discussed here. The arrangement offers good versatility and is suitable for large commercial buildings down to small domestic residential systems. The two-pipe system consists of a run of two parallel pipes, one pipe delivers heated water to each heat emitter and the other pipe is dedicated to returning the water from each heat emitter. The main advantage of this system over the one-pipe system is that each heat emitter receives water at the temperature it leaves the boiler (not counting pipe heat losses) and the return temperature is the same from each heat emitter that is returned to the boiler. Whereas in a single pipe system were water flows in a single circuit from one heat emitter to the next heat emitter, the entering temperature will get progressively lower. The disadvantage of the two-pipe system is the cost of the additional pipe work. The system can also suffer from a flow imbalance due to differing lengths of flow and return pipework which can result in increased flow rates in emitters closest to the boiler. To alleviate this the system should be balanced using the lockshield return valves on the heat emitters or using regulating valves.

Figure 1-1 shows an open-vented heating system which was historically favoured by installers in the UK. More recently sealed systems have become more common in the UK which involves replacing the feed and expansion tank with a sealed expansion vessel and using a direct connection to the water mains for filling the heating system and regulating the sealed system pressure. The piping arrangement shown in Figure 1-1 would otherwise be the same. The illustration in Figure 1-1 also incorporates a domestic hot water cylinder (DHW) into the system. If a combi boiler is used, which can provide instantaneous hot water, the cylinder is omitted, and mains water is heated directly (and separately from the main space heating system) at the boiler and fresh heated mains water is delivered to the point of demand.
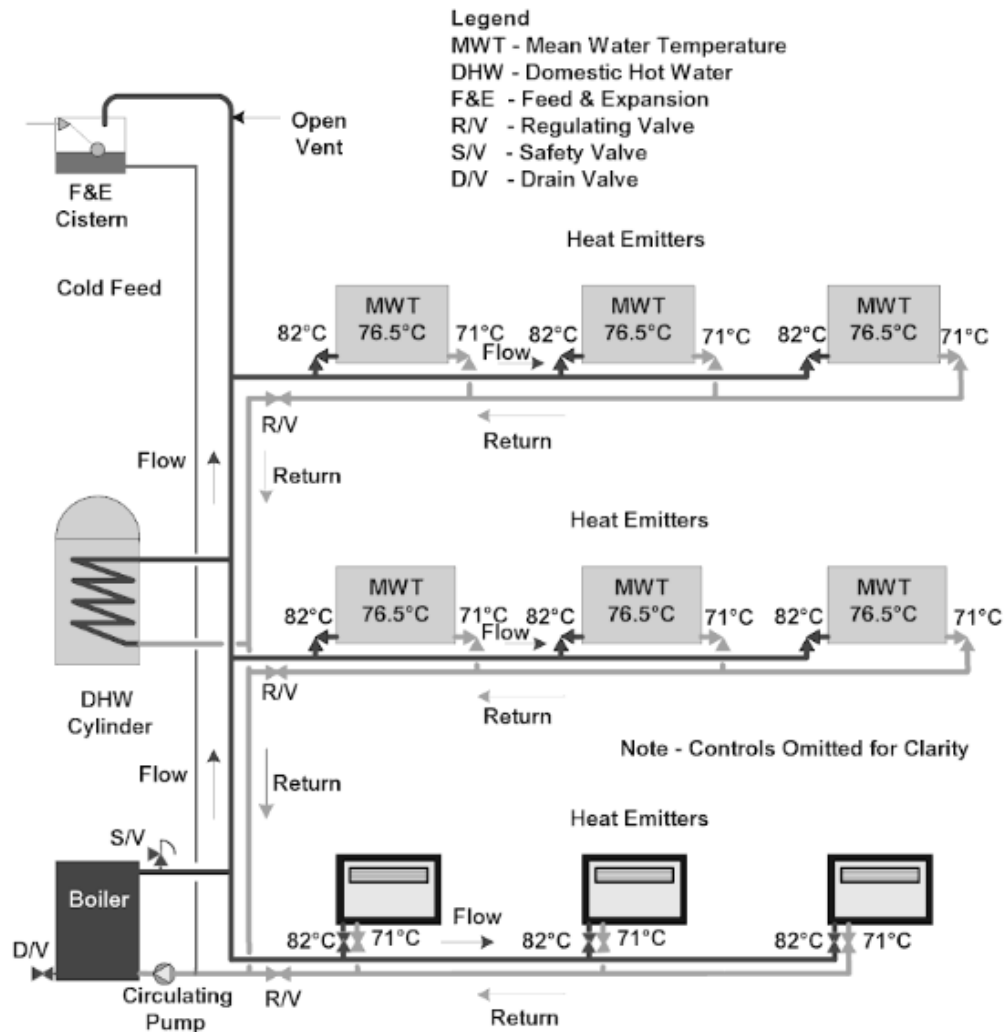
Figure 1-1 Operating principles of a direct return two pipe heating system – non-condensing (condensing systems would employ different flow and return temperatures). Taken from Watkins (2011).

1.3.2 Basic Heating Controls

There are 2 main categories in which heating system controls may fall into: (1) Controls for safety; (2) Controls for comfort and energy efficiency. Controls for safety are incorporated in heating system design to provide a critical function in order to prevent serious or fatal injury occurring in the event of a malfunctioning component within the system. Generally, most of the safety devices are integrated into the heating appliance (including burner safety controls) with the exception of the safety relief valve. The safety relief valve automatically prevents high pressures in the system from developing by exhausting excessive pressures which may develop above the safe operating pressure. It should be located at the boiler or on the boiler flow pipe as close as practically possible. It should be set so that the maximum design pressure is not exceeded.

Controls for comfort and energy efficiency have developed greatly since the installation of the first domestic central heating systems. There is now a minimum standard of system control required by building regulations. The drivers for control advances has been lifestyle changes were flexibility and automation provide greater convenience, the desire to have greater control over the thermal comfort conditions within the home, advancements in electronic controls and subsequent reducing costs, and the increasing awareness of the need to reduce energy consumption and improve energy efficiency. The control capabilities have developed from simple on/off, through to timed controls, room thermostats controlling single or multiple zones within the house, basic hot water storage control to separate space heating and hot water control, right through to fully digital wireless controls which can control individual radiators, room temperatures, and hot water storage requirements remotely via mobile phone apps. However, the basic premise of what good systems controls should do has remained fundamentally unchanged since the installation of the first domestic central heating systems. The main objectives of the control system should seek to provide an automated method of maintaining thermal comfort throughout the heating season, regulate the system so that it operates as designed, ensure the heating system operates at maximum efficiency thereby reducing running costs, conserving energy, and reducing the carbon footprint of the home.

The most basic controls in dwellings up to 150m^2 which include a domestic hot water cylinder consist of a boiler interlock, space heating control via a single room thermostat, generally located in the most occupied room, and a hot water cylinder thermostat. Both the space heating and hot water control should be independent and programmable via a timer. It is generally good practise to install thermostatic radiator valves (TRVs) in all rooms apart from the one with the room thermostat. For heating systems without hot water storage were hot water is produced instantaneously via a combination boiler the same applies excluding the need for the hot water control.

In England the upgrading and new installation of heating appliances is covered by The Building Regulations 2010: Conservation of Heat and Power in existing Dwellings Part L1B (HM Government, 2018) which includes the most recent set of amendments which came into force in April 2018. The document corresponds to the Northern Ireland building regulations: Part F (Conservation of fuel and power) of the Building Regulations (Northern Ireland) 2012 (The Department of Finance and Personnel, 2012). The most recent amendment adds the requirement of the control system, described in the prior paragraph, to include one of the

following: flue gas heat recovery; weather compensation; load compensation; smart thermostat with automation and optimisation.

In order to ensure compliance with the regulations Figure 1-2, adapted from (BEAMA Limited, 2018), illustrates several control systems for dwellings up to 150m^2 for new or replacement boilers with a hot water cylinder and without (combination boiler). For systems with a hot water storage there are two common methods of circuit control (see Figure 1-2, images 1-4). This is either by using two 2-port motorised valves, commonly known as a "S-Plan" arrangement, or by using a single 3-port motorised mid position valve, commonly known as a "Y-Plan" arrangement. Both techniques use a specific wiring configuration and a programmer so that space heating and domestic hot water can be independently controlled. The control user can manually or pre-programme either or both circuits to switch on, with regulation, in turn, via dedicated thermostats. The wiring configuration is designed so that if both thermostats are satisfied the boiler will switch off and avoid cycling or running when motorised valves are closed. This is known as a boiler interlock. Comfort is maintained in rooms without electronic thermostats via TRVs which shut off radiators once a pre-set comfort level is reached. For combination boilers water is heated instantaneously at the boiler so the control for hot water storage is not required and therefore excluded. In practise this simplifies the installation and wiring required for a combination boiler which at its simplest will have a single thermostat connected via a wired or wireless connection directly to the boiler circuit board. Dwellings with a floor area greater than 150m^2 may use the same control techniques but with the inclusion of a second independently thermostatically controlled space heating circuit (normally one per floor). This normally requires the addition of another motorised 2-port valve and thermostat.

Generally speaking, the described methods of heating system control will be by far the most commonly encountered for the most common types of conventional heating (gas and oil boiler central heating systems), especially were the boiler has been replaced or the home was built in the last 10-15 years. The main difference which may be encountered is the level of sophistication of programmer and thermostat used. More recently this is moving towards digital smart controls which have become cheaper in price, have much greater functionality and flexibility, are simple to install or retrofit due to wireless communication ability, and provide greater opportunity for energy savings through automation and machine learning.

	2 port valve control (S Plan)	3 port valve control (Y Plan)
BOILER WITH HOT WATER CYLINDER	1 Programmer, room thermostat and TRVs	2 Programmer, room thermostat and TRVs
	3 Programmable room thermostat and TRVs	4 Programmable room thermostat and TRVs
COMBINATION BOILER	5 Time switch, room thermostat and TRVs	6 Programmable room thermostat and TRVs

KEY TO SYMBOLS

Boiler	2 port valve	3 port valve	Auto by-pass valve	Wheel head valve	Lock shield valve	TRV	Room thermostat (RT)	Programmable room thermostat (PRT)	2 channel programmer (P2)	Timeswitch (single channel) (T1)	Cylinder thermostat (CT)	Junction box	Wireless or wired connection

Figure 1-2 Example layouts for new heating systems in dwellings up to 150m² and for replacement boilers in all dwellings to ensure building regulation compliance. Adapted from (BEAMA Limited, 2018).

As mentioned previously the 2018 amendment to building regulations requires the inclusion of one of: flue gas heat recovery; weather compensation; load compensation; smart thermostat with automation and optimisation. Flue gas heat recovery pre-heats the incoming mains water used for hot water to reduce the gas required to reach the desired hot water temperature. Weather and load compensation adjust the flow temperature of the water circulating through the radiators depending on the outdoor temperature or heating load respectively. Lower flow temperatures complement condensing boilers which work more efficiently with returning water temperatures of 55°C or under as greater heat can be recovered from the flue gases. Smart thermostats as mentioned are becoming increasingly popular. Their function can vary dependant on the brand of device but the main functions include remote control via smart phone app, the ability to learn how long your house takes to heat up and therefore the ability to optimise the time your heat is switched on thus removing the guessing inherent of fixed timers, and also occupancy sensing so that the heat is switched off or turned down when the home is unoccupied. Another major benefit of these devices is that the operating firmware can be remotely updated allowing software changes that can further enhance system efficiency without having to update the boiler for example. The devices, in some cases, can also be used as a central controller to control wireless TRV valves allowing rooms to be heated at different times meaning for example bedrooms could be heated before bedtime only rather than all day when they are less likely to be occupied.

As mentioned, smart controllers can offer great benefits for the occupant in terms of improving thermal comfort and increasing heating efficiency through much greater flexibility and remote system control. There is however a further potential with these devices and that is combining heating control with time-of-use tariffs and energy storage to provide a grid balancing service. This is most attractive when we consider the case of electrified heating with a heat pump. Heat pumps are seen as having a major role in efforts to decarbonise the domestic energy sector (Department of Energy & Climate Change, 2013; Arteconi, et al., 2013) however there is a resultant increase in electricity demand as gas and oil begin to be displaced and as such, heat pumps will need to be "smart-grid-ready". The problem is there is no current clear government policy or clear market incentive to realise the potential of domestic heating flexibility aside from the traditional Economy 7 style of thinking. This results in reluctance or delayed response by heat pump manufactures in investing and designing smart enabled heat pumps, put simply, because it is unclear what they would be designing for. Smart controllers can therefore fill a vacuum, as they serve a primary function orientated around user functionality and comfort. Software on these controllers can easily be updated

to provide the required demand-side-response (DSR) functionality by switching heat pumps on and off, charging/discharging thermal stores at the most appropriate times, or rather than on/off control there could be a setback function which reduces the thermostat temperature or reduces flow temperature depending on the level of DSR required. In addition, by allowing third party controls and software (i.e. not that of the heat pump manufacturer or energy suppliers) there may be the potential for greater innovation and competition in the technology and software, the potential for greater returns for the home owner, and therefore likely greater uptake of such technology. The grid side is then managed by the system operator sending out a simple signal to indicate the desired demand side response, and the energy supplier supplies electric on an incentive based tariff. This simple method means all participants in the smart grid get rewarded.

1.4 Alternative Domestic Heating Methods

1.4.1 Heat Pumps

A heat pump is a thermodynamic device which uses a refrigeration cycle to extract low grade heat from a source and eject a higher temperature heat to a sink. In its simplest terms heat is moved (pumped) from one place to another by being absorbed by a substance and conveyed to the point of delivery by that substance, where it is released (Watkins, 2011). The substance used is known as a refrigerant. This definition is applicable to all pieces of refrigeration equipment, air conditioners and chillers using a refrigeration cycle, so they all are effectively heat pumps. However, the term "heat pump" is generally reserved for units which supply heat as the primary end product rather than air conditioning or refrigeration which removes heat to provide cooling as its primary function. Some heat pumps can be reversed to provide heating in winter and cooling in summer but for domestic houses in the UK which most commonly use radiators the function would neither be suitable or normally necessary.

For UK domestic heating applications, a heat pump replaces a conventional oil or gas boiler and provides thermal energy using radiators or underfloor heating. Heat pumps are better suited to underfloor heating applications due to the lower flow temperatures required but they may be retrofitted to the existing radiator system. This may require replacing the radiators with larger ones or high temperature units do exist which can achieve flow temperatures equivalent to oil or gas boilers. Conventional heat pumps are electrically driven and because they move low grade heat from a source and concentrate it as a high-grade heat at a sink, they can produce a greater amount of heat energy than the electrical energy consumed to power the compressor, fans or pump. Therefore, for heat pumps that can achieve a coefficient of performance (COP), which is defined as useful heat out divided by total electricity in, greater than a variable threshold value, will produce heat cheaper than a conventional fossil fuel powered boiler, even though electricity is more expensive than oil or gas. The COP threshold value is described as variable because it is dependent on the relative price of domestic oil or gas, the COP of the fossil fuel boiler (efficiency), and the respective price of domestic electricity. In addition, the carbon dioxide footprint of an electrical heat pump producing an equivalent amount of heat as an oil or gas boiler will be less carbon intensive, above a certain COP threshold, even though the electricity is derived from a national power station which uses fossil fuel with transmission and distribution losses of the electricity also considered. The COP threshold value of the heat pump gets consistently lower as the carbon intensity of the source electricity reduces i.e. as greater volumes of renewable

energy make up the national electricity. Therefore, heat pumps have good potential for reducing the carbon intensity of heating homes and will only get better as reliance on fossil fuels for electricity production reduces.

Generally, heat pumps that will be installed in a domestic home will use a vapour compression refrigeration cycle which utilises an electrically driven compressor. The thermodynamic cycle, taken from Watkins (2011), is illustrated in Figure 1-3.
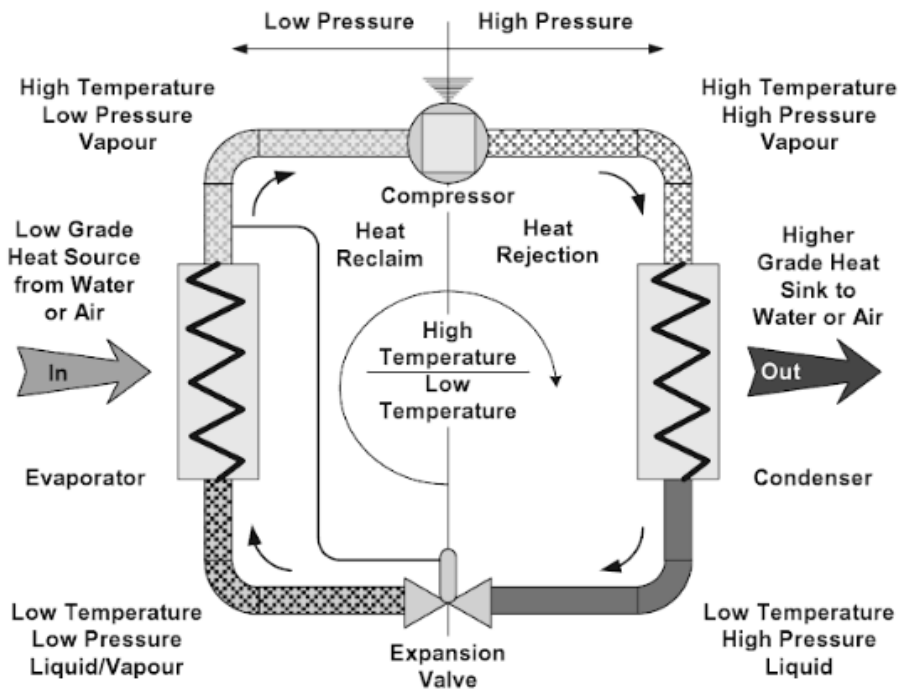
Figure 1-3 Heat pump vapour compression cycle (Watkins, 2011)

The cycle has four basic components comprising a compressor, condenser, expansion valve and evaporator. Superheated refrigerant vapour at low pressure enters the compressor where it is compressed to a high temperature high pressure vapour. It then enters a condenser which is either an air or water heat exchanger which sinks heat from the refrigerant (as it is lower temperature) cooling the vapour refrigerant and causing it to condense to a sub-cooled liquid which is still at high pressure. From the condenser it enters an expansion valve which causes a pressure and further temperature drop. The refrigerant then enters the evaporator as a low pressure low temperature mixture of liquid and vapour. In the evaporator the refrigerant absorbs heat from a low grade heat source (typically air or water) causing the refrigerant to evaporate before returning to the compressor as a superheated low pressure vapour to repeat the cycle.

Heat pumps are generally categorised by the type of heat source and heat sink they use. For domestic applications the heat source is normally air source or ground source however any form of low grade or waste heat is suitable as a source. The heat sink refers to the method of delivery of heat to the house. For retrofits the heat sink would be water source using a heat exchanger as the condenser to transfer heat from the refrigeration cycle to the house hydronic central heating system. The heat sink could also be via air where air is blown over the condenser warming the air which is then delivered to the rooms to be heated via ducting. However, air heating is not a common method of home heating in the UK. Therefore, only a description of an air-to-water heat pump and a ground source heat pump will be detailed.

Figure 1-4, taken from Watkins (2011), illustrates a typical air-to-water heat pump configuration with an external evaporator and internal condenser. Flow temperatures for an air source heat pump (ASHP) are typically 35-45°C as indicated on the figure. This flow temperature is particularly well suited to underfloor heating systems which have a large surface area for heat emission. However, for radiator systems the flow temperature is not high enough and generally flow temperatures in excess of 65°C are required with traditional radiator systems designed for a max flow temperature of 82°C.

Figure 1-5, taken from Watkins (2011), illustrates a typical ground source heat pump (GSHP) which is ideal for domestic properties. In this configuration a continuous loop of high-density polyethylene pipe is laid in a shallow trench in which a brine solution is circulated absorbing low grade heat from the ground. The horizontal shallow trench method is much less expensive than vertical borehole ground source heat pumps which require a specialist drilling company to drill and commission a well, however the horizontal method requires a large area for the pipes. The attractiveness of a GSHP over an ASHP is the higher COP achievable, and therefore despite the higher upfront installation cost, the GSHP may be cheaper over its lifespan due to lower running costs. Typical installation costs are in the region of £6,000-£8,000 for an ASHP, and £10,000-£18,000 for a GSHP (Energy Saving Trust, 2018). GSHPs can achieve a higher COP than an ASHP because of a more stable source temperature. Down to 15m in depth the temperature is approximately equal to the mean annual air-temperature of 8-11°C fluctuating in this range seasonally and below this depth the temperature increases on average by 2.60°C per 100m (BGS, 2017). In contrast the air temperature varies across the day with the minimum temperature likely to be the point of greatest heat demand. For example, the winter average minimum and maximum air temperature for the UK in 2017 was 2.2°C and 7.9°C respectively. As an example of real-world comparable COP values for ASHPs and GSHPs, a large scale field study emanating from the UK Renewable Heat Premium

Payment (RHPP) policy showed seasonal performance factors of 2.65 and 2.81 respectively (Lowe, et al., 2017a). However, despite the higher efficiencies achievable, domestic GSHPs are often not practical in urban environments due to lack of sufficient space for horizontal configurations or lack of access for drilling machinery for vertical borehole configurations.

To circumvent the low flow temperatures typical of domestic HPs, a heat pump may be installed alongside a conventionally fuelled boiler as illustrated in Figure 1-6 (Watkins, 2011). This results in a hybrid system in which the heat pump serves as the lead boiler and the fossil fuel boiler is arranged to fire when the flow temperature needs boosting in order that the heating system will operate correctly. The return temperature should be designed to return as low as possible, around 25-30°C, in order to maximise heat pump efficiency (Watkins, 2011). The hybrid system can be designed to run in different ways with the priority generally being to meet the heat demand as efficiently as possible. Control strategies may look to optimise CO_2 intensity or cost of the heat produced dependant on the operating efficiency of the heat pump at an external temperature set-point. Having two heating sources using different fuels also opens potential for a demand side control strategy based on grid signals, as previously discussed in the controls section 1.3.2, in which, for example, the fossil fuel boiler could be relied upon at times of high grid electricity demand, high grid electricity price, or high grid electricity carbon intensity. However, without a method of thermal storage the heat pump is less able to take advantage of low electricity grid demand, price, or carbon intensity as the household heating demand would need to coincide with these events.

This type of hybrid system comes with the added disadvantage of increased system complexity with potential impact on the performance of the individual heat sources which may be dependent on an optimised control strategy to package the heat pump and boiler together so that they work in harmony. In particular the conventional boiler may cycle more frequently on low load conditions reducing its efficiency, and as such will need a control system which can prevent this occurrence. There will also be increased maintenance requirement and therefore cost. The main advantage being that the thermal comfort of the occupants is ensured, and a backup heat source is available in the event one might fail.

An alternative to the hybrid system for achieving conventional flow temperatures is the use of a cascade heat pump like the example illustrated in Figure 1-7 (Daikin, 2018). The Daikin Altherma air-to-water heat pump is a domestic cascade heat pump which uses two refrigeration cycles to extract thermal energy from ambient air source down to temperatures as low as -20°C. The unit can deliver flow temperatures on the central heating water side up

to 80°C and is available in 11, 14, and 16kW capacity. The manufacturer states a nominal COP of 2.50 for the 11kW version with a flow temperature of 80°C and return temperature of 70°C at an ambient dry bulb temperature of 7°C (Daikin, 2010). In order to put the COP value into context, in the UK a minimum seasonal performance factor (SPF) of 2.5 is required in order to be eligible for domestic renewable heat incentive payments (RHI) with higher payments for HPs with a higher SPF (OFGEM, 2018). The SPF is effectively the average COP measured across the year i.e. useful heat produced by the HP per annum divided by total electricity consumed by the HP per annum. For context, in the UK the average air temperature in 2017 was 9.6°C and the long-term average air temperature was 8.9°C between 1981 and 2010 (Met Office, 2018).

The advantage of a high temperature heat pump is the ability to retrofit into an existing central heating system which uses high temperature radiators and removes the need for a backup heater. Although lower temperature HPs will undoubtedly have higher SPFs, it is often neither practical nor financially feasible to retrofit wet underfloor heating unless major refurbishment of the property is taking place. Oversizing of radiators to accommodate lower flow temperatures is another solution however this is both expensive and disruptive and requires additional space within in the home. With useable wall space at ever greater premium, it is far from a perfect solution. The high temperature heat pump is therefore ideal for the boiler refurbishment market of which the UK has one of the largest in the world with domestic boiler sales of 1.7 million units in 2016 of a total of 26 million boilers installed throughout the country (BSRIA, 2017). It not only removes the need to disrupt or alter the current central heating system but it is a particularly attractive solution for off grid gas areas like Northern Ireland were domestic heating is predominately reliant on oil heating as detailed in section 1.2. In addition, when replacing an oil boiler, the oil tank can be removed, increasing useable space, whilst also removing a potential environmental or fire hazard. When replacing a gas boiler the risks associated with this fuel source are also removed. Replacing a fuel source which needs to be burned with an electric heating source also reduces the risk of carbon monoxide poisoning which is potentially fatal.

In summary when we consider domestic retrofit in a country like Northern Ireland with a high dependency on oil for heating, a high-temperature air source heat pump looks like an attractive option for upgrading ageing boilers with minimum disruption for householders. This is likely to be faster than extending the gas network with access possible to everyone with an electric connection. It is likely grid reinforcing would be required but this may be a

better investment strategy than investing in gas infrastructure given the need to decarbonise the heating sector across the country, not just in urban areas.
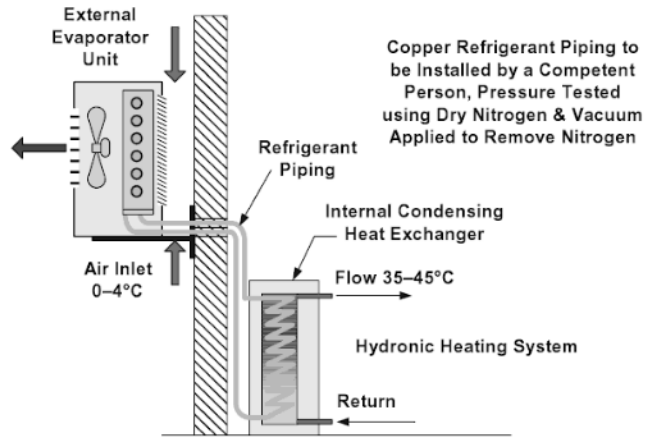
Figure 1-4 Split unit air-to-water heat pump (Watkins, 2011)
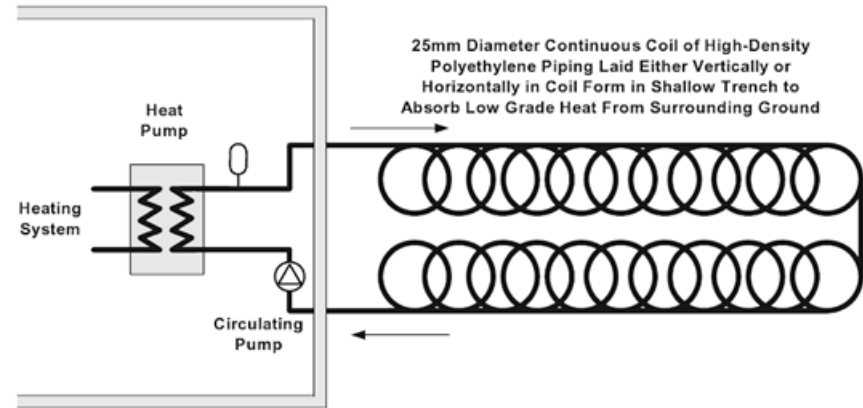
Figure 1-5 Shallow trench ground source heat pump, looped pattern (Watkins, 2011)
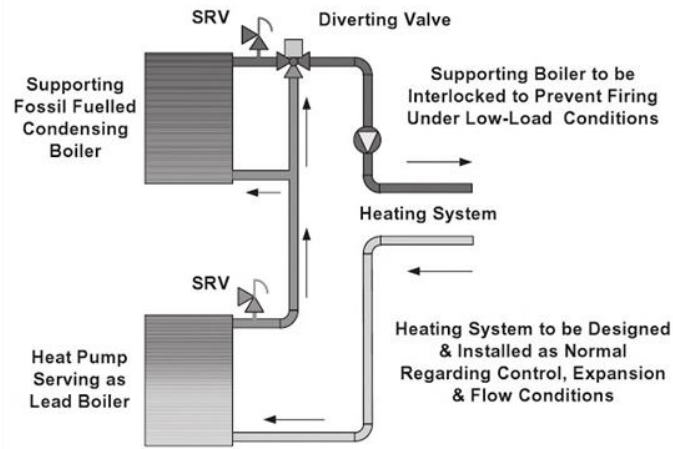
Figure 1-6 Heat pump with supporting conventionally fuelled boiler (Watkins, 2011)
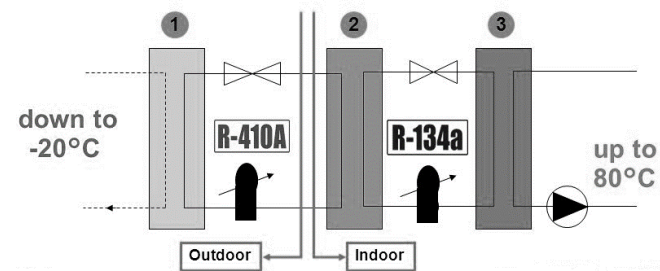
Figure 1-7 High temperature air-to-water cascade heat pump (Daikin, 2018)

1.4.2   Solar Thermal

Using solar thermal energy for heating water is not a new form of technology however it is alternative in the sense that it is not in widespread use as a form of domestic heating in the UK. The sun radiates substantial energy to the Earth and the attractiveness of being able to capture this energy in order to heat our homes is plain to see. In a UK domestic context, solar energy from the sun may be incorporated into central heating systems for space heating, raising DHW temperature, or as an energy source for heat pumps. The performance of such systems is highly dependent on the useful amount of solar irradiation available at the installation location.

Use of solar for direct space heating is not particularly practical in the UK due to its Northern latitude and therefore reduced solar irradiance in the winter months when space heating demand is greatest. However, it may be used to supplement a conventionally fuelled boiler in autumn or spring months when sufficient levels of solar irradiance exist as a means to reduce the quantity of fossil fuel required for space heating. Typically, in this arrangement, a solar collector panel would be coupled with a twin coiled thermal buffer store. Figure 1-8 (Viridian Solar, 2017) illustrates an example of such an arrangement. On the solar side, a pump activated by a temperature sensor circulates brine through the solar collector and the lower coil of the thermal store. The buffer tank is also heated by a conventional boiler which raises the temperature up to a level sufficient for the central heating system and for DHW purposes.
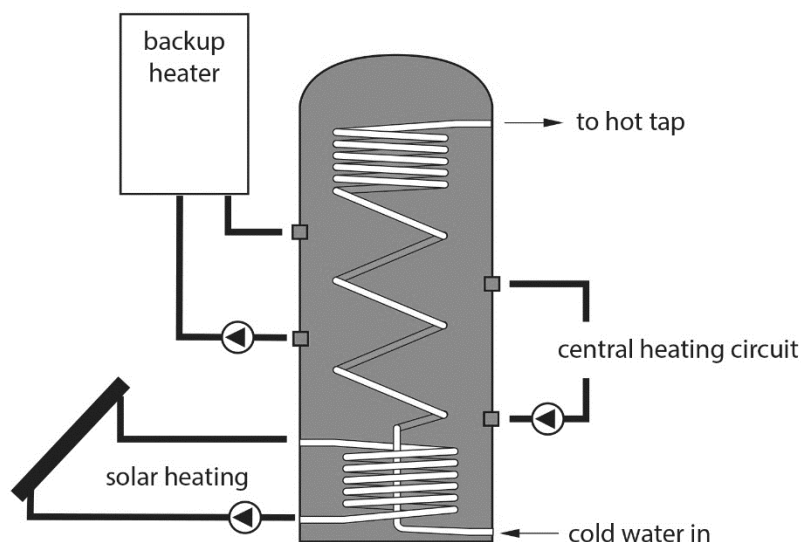
Figure 1-8 Solar collector with heat store (Viridian Solar, 2017)

Although the system has a positive environmental impact due to reduced fuel consumption and therefore carbon intensity, the low levels of solar energy available in the UK in the winter when space heating is at highest demand mean that the system may not make economic sense with long payback periods.

Combining solar energy with an air-source heat pump has the advantage of improving the low-grade heat sink available to the unit thereby improving the COP achievable for a standard heat pump. Solar heat pumps will normally be classified as either direct or indirect. For a direct system refrigerant is circulated through the solar panel which acts as the evaporator. Direct systems are a packaged unit and are limited by the distance that the solar panel evaporator can be from the condenser as well as the smaller size of the collector panel meaning they are generally only suitable for small applications. Indirect systems use a conventional solar collector which delivers heat to the heat pump evaporator. The number of panels can be increased so that larger heat loads can be served.

Solar energy is much more commonly used for raising DHW temperature in the UK due to reduced installation costs compared to those which incorporate a means of space heating. In summer peak solar energy can provide up to 100% of required DHW of an average home and reasonable proportions at other times of the year (Watkins, 2011). Generally solar heated DHW is either direct or indirect. The direct system heats water in a DHW cylinder directly by circulating water through a solar collector panel. There are number of disadvantages to this system including the risk of freezing in winter months, the possibility of the system reversing in winter thereby cooling the DHW cylinder, and the risk of excessively high DHW temperatures in summer months. An indirect system is more common in the UK which separates the solar heating circuit from the DHW circuit by means of a heat exchanger in the DHW storage tank. This alleviates most of the disadvantages associated with a direct system. An improvement on this is to use second storage cylinder to act as a thermal buffer store which preheats the main DHW storage cylinder. The addition means the solar collector can be used all year round providing a good proportion of the DHW requirements whilst alleviating potential issues such as reverse system operation resulting in the collectors emitting heat when solar irradiation is low. However, the main disadvantages are an increased installation cost and space requirement.

1.4.3 Biomass

Biomass heating is the practise of using a wood-fuelled boiler to provide heating for a single room or coupled with a central heating system to heat an entire home. Wood is generally from fast grown crops and burned as wood pellets, chips, or logs. It can be a low carbon form of heating so long as the wood burned is replaced by new trees and the carbon footprint of cultivation, manufacture, and transportation of the fuel is small. This can be done by using locally sourced fuel. The main disadvantage of biomass boilers are the space requirements, the boilers are larger than oil or gas boilers and space is required in order to store the fuel. This makes them less attractive for urban and built up environments.

1.4.4 Micro-Combined Heat and Power

Combined heat and power is typically the process of recovering waste heat generated when generating electricity which can then be used to provide a useful heat source. It is not a new concept and is more common in a commercial setting being generally applied in electrical power generating plants in conjunction with gas turbines, diesel engines, and coal fired steam turbine engines. Micro-combined heat and power (micro-CHP) is more recent and refers to production of both heat and electricity for use in a domestic or office-based setting. However, the primary goal is generally to produce heat with the ability to generate a small amount of electrical power.

Micro-CHP units typically employ a gas or oil driven internal combustion engine which drives an alternator thereby generating electricity. Waste heat is recovered from the engine and combined with a secondary conventional burner to produce the total heat requirement. The adoption of micro-CHP is normally limited by the size of units. Small wall hung units exist similar in size to a gas boiler however the power output is low, and a backup burner is often required to fulfil the total heat demand of a typical home. Different ratios of heat and electric production are achievable and excess electricity generated can be sold back to the grid if not required. Although micro-CHP still burns fossil fuels to produce energy, it is less carbon intensive than using a gas boiler and acquiring electricity from the grid separately.

1.5   Renewable Electricity Northern Ireland & Ireland

1.5.1   Wind Energy & Irish Electricity Grid

The electrical grids of Northern Ireland and Ireland are operated as an All-island power system with a single electricity market (SEM) operated by The Single Electricity Market Operator (SEMO) with SONI Limited and EirGrid plc as transmission system operators for Northern Ireland and Ireland respectively (SEMO, 2015). Both countries have set a target of 40% renewable electricity to be reached by 2020. The installed wind generating capacity as of November 2014 across the island was 2889 MW (IWEA, 2015) with an estimate of between 4400 and 4900 MW installed capacity required to meet the 2020 targets (EirGrid & SONI, 2014). As a percentage of system size this will lead to the island of Ireland having one of the highest penetrations of renewable generation in the world (EirGrid Group, 2014). However, it is not as simple as reaching these installed capacity volumes. The inflexible nature of wind generation means for a number of reasons curtailment or constraint is often required resulting in dispatch-down of wind generation across the system.

1.5.2   Wind Dispatch Down: Curtailment & Constraint

Renewable generation has priority dispatch, however there will be times when it is not always possible to accommodate all priority generation while maintaining the safe, secure operation of the power system. Therefore, security limits are imposed due to local and system-wide security issues, which when reached require renewable generators to reduce generation below their maximum available levels. This reduction is known as dispatch down and is classified into either curtailment or constraint (EirGrid & SONI, 2018).

Curtailment refers to the dispatch-down of wind for system-wide reasons (where the reduction of any or all wind generators would alleviate the problem). Curtailment is required for five main types of system security limits including (EirGrid & SONI, 2013):

1. System stability
2. Operating reserve requirements
3. Voltage control requirements
4. Morning load rise requirements
5. System non-synchronous penetration (SNSP)

The first four generally impose a minimum generation requirement on conventional (synchronous) generation and as such reduce the room for wind on the grid, whilst system non-synchronous generation (SNSP) is a limit on non-conventional generation (i.e. renewable generation). It is usually the first four which supersede SNSP.

Constraint refers to dispatch down of wind generation for more localised network reasons (where only a subset of wind generators can contribute to alleviating the problem). This is mainly for reasons of local network infrastructure, such as too much wind generation for the local network capacity or during outages for example maintenance, upgrade works, or faults.

The limit of system non-synchronous penetration (SNSP) was until recently 50% in Ireland, however this has been upgraded following successful completion of a 5 month trial after which EirGrid and SONI confirmed on 9th April 2018 that up to 65% variable renewable energy could be handled on the grid at any given time, a world first, made up of mainly wind power and contributions from solar and interconnector imports (EirGrid Group, 2018). The aim is to ultimately increase the non-synchronous penetration limit up to a maximum of 75%.

Across the all-island electricity market 29.7% of electricity demand was provided from renewables in 2017 of which 26.4% was from wind, 1.9% from hydro, and 1.4% from other. Wind energy generated 9,280 GWh of which an estimated 386 GWh was dispatched down, an increase of 159 GWh from 2016. The dispatch-down represents 4% of available wind energy resource across the island (EirGrid & SONI, 2018). Figure 1-9 illustrates the impact of curtailment and constraints summarised by hour of the day for the whole of 2017. It is generally curtailment which dominates during the night-time hours (23:00-09:00) over constraint which generally arises throughout the day (EirGrid & SONI, 2018). Curtailments (SNSP) refers to curtailment in order to reduce system non-synchronous penetration whereas curtailments (HiFreq/MinGen) refers to curtailment attempting to alleviate high frequency event or in order to facilitate a minimum level of generation on the system to satisfy reserve requirements, priority dispatch or to provide ramping capabilities. Curtailment is particularly pronounced over night when system demand is lower and there is reduced ability to accommodate wind generation due to the limits previously mentioned.

With respect to Figure 1-9 it is clear that there is potential for creating a demand during night time hours to reduce the high levels of curtailment between 23:00 and 09:00 in order to make use of this energy which is otherwise effectively lost. It would be logical if we could somehow harness this energy and store it until it can be effectively utilised, for example at peak system demand, thereby improving the installed wind capacity and reducing peak demand.
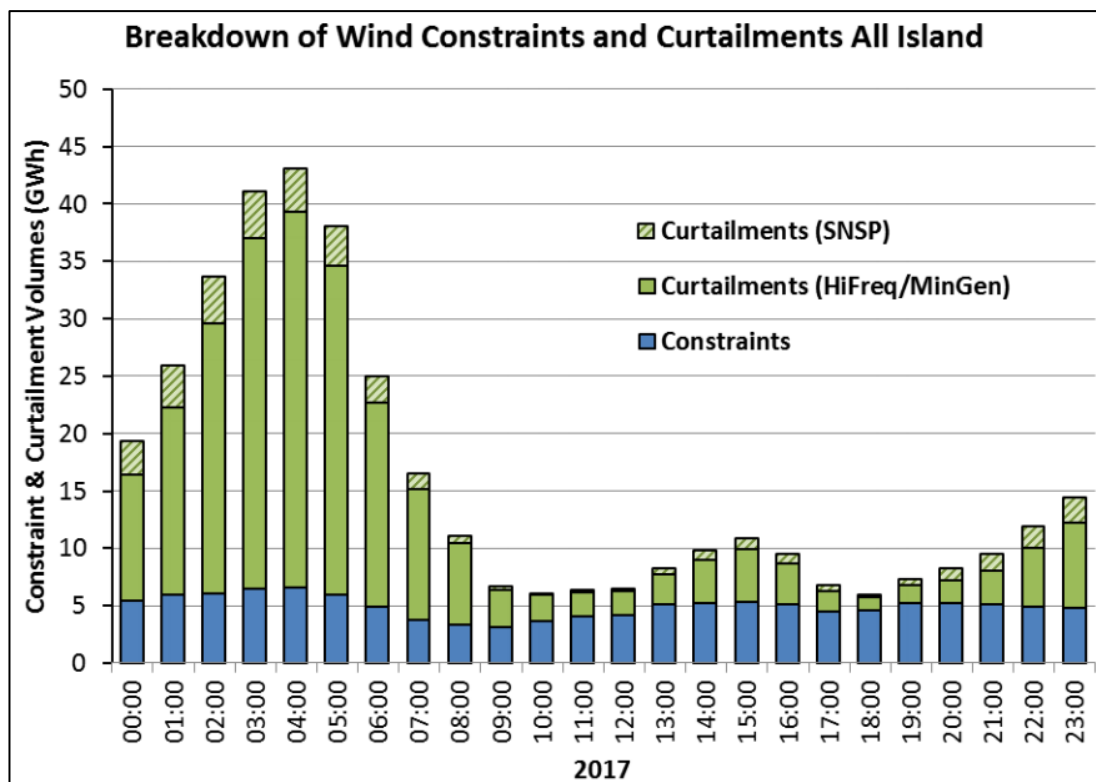
Figure 1-9 All-Island Irish wind total dispatch down volumes in 2017 summarised by hour of day. Curtailments (SNSP) refers to curtailment in order to reduce system non-synchronous penetration; Curtailments (HiFreq/MinGen) refers to curtailment attempting to alleviate a high frequency event or in order to facilitate minimum levels of generation on the system to satisfy reserve requirements, priority dispatch or to provide ramping capabilities. (EirGrid & SONI, 2018)

In order to alleviate as much as possible, the fundamental issues that give rise to curtailment EirGrid and SONI have produced an operational policy known as the DS3 programme: Delivering a Secure Sustainable Electricity System (EirGrid & SONI, 2015). Within this the need for facilities which can manage very high levels of instantaneous renewable penetration (demand side management facilities) has been outlined as an area requiring much work. As part of the program system operators have taken a number of steps to update and develop new system tools providing more accurate real-time information, greater control and monitoring facilities. One such tool used in control is the wind forecast tool. This tool provides an estimate of the wind generation which will be available in the coming hours and days ahead. The data is available publicly (EirGrid, 2015) and is illustrated in Figure 1-10 for the 16th February 2015 along with forecast market demand and system marginal price (SMP) for the same day. It is the readily available data such as this that will help research and innovation into development of demand side management capable technology.
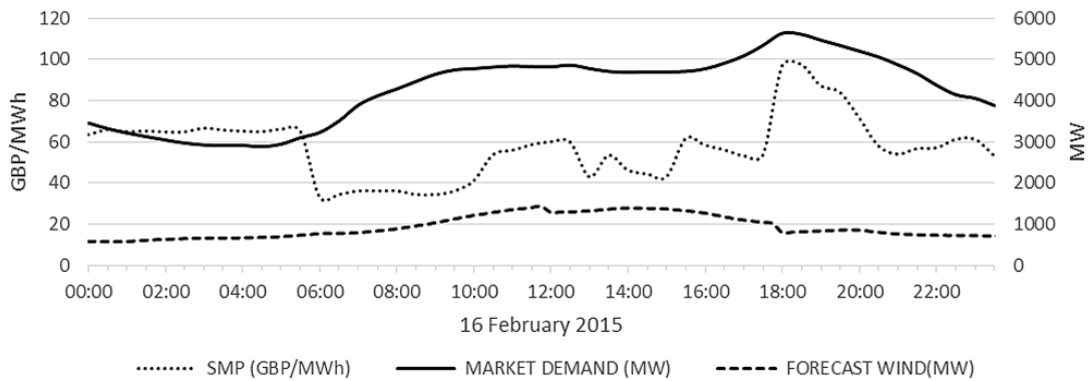
Figure 1-10 Forecast electricity energy market price (SMP), forecast market demand, and forecast wind generation for all Ireland electricity network. Data sourced from EirGrid (2015).

1.5.3   Single Electricity Market (SEM)

In Ireland and Northern Ireland, a Single Electricity Market (SEM) has operated from the 1st November 2007 combining what was two separate jurisdictional electricity markets into a single market operating across the island, a first of its kind (DCCAE, 2019). The goal of the SEM was to provide electricity generation at the least possible cost to meet customer demand whilst also maximising long-term sustainability and reliability (DCCAE, 2019). On 1st October 2018 the SEM transitioned to a reformed market known as the Integrated Single Electricity Market (I-SEM) in order to better harmonise markets across Europe.

The finer details of how the market operate are complex, however a general simplified overview is illustrated in Figure 1-11 (Mullany Engineering Consultancy, 2016). Electricity on the island is bought and sold via a single market pool which is facilitated by the Single Electricity Market Operator (SEMO) which is a joint venture by the Northern Ireland system operator, SONI, and the Republic of Ireland system operator, EirGrid Plc. SEMO, which is regulated by the Northern Ireland and Republic of Ireland independent utility regulators, facilitates market trading and co-ordination of financial dealing (UREGNI, 2019). Generators and suppliers participate in the market bilaterally buying and selling electricity to and from the pool either on-the-day trading markets or spanning several years ahead. Electricity can also be imported or exported via the island's two interconnectors (Moyle and East/West interconnectors) to Great Britain which is in turn connected to mainland Europe.

The main components of the SEM are energy and capacity. Energy consists of the supply of electricity with generators bidding into the pool a price for their generation for each half hour of the day ahead. SEMO in turn determines, based on these prices, a System Marginal Price (SMP) for each half hour trading window. The SMP is determined by ranking generators by price in a merit list with the highest price to meet demand (safely and securely) equating to

the SMP. Those generators that are not on the merit list (i.e. not required to meet demand) do not get paid the SMP, thus creating a competitive market were the most efficient generators tend to get utilised. There is also a payment, paid by supply companies, for generators providing capacity to the market which partially goes towards their fixed costs.
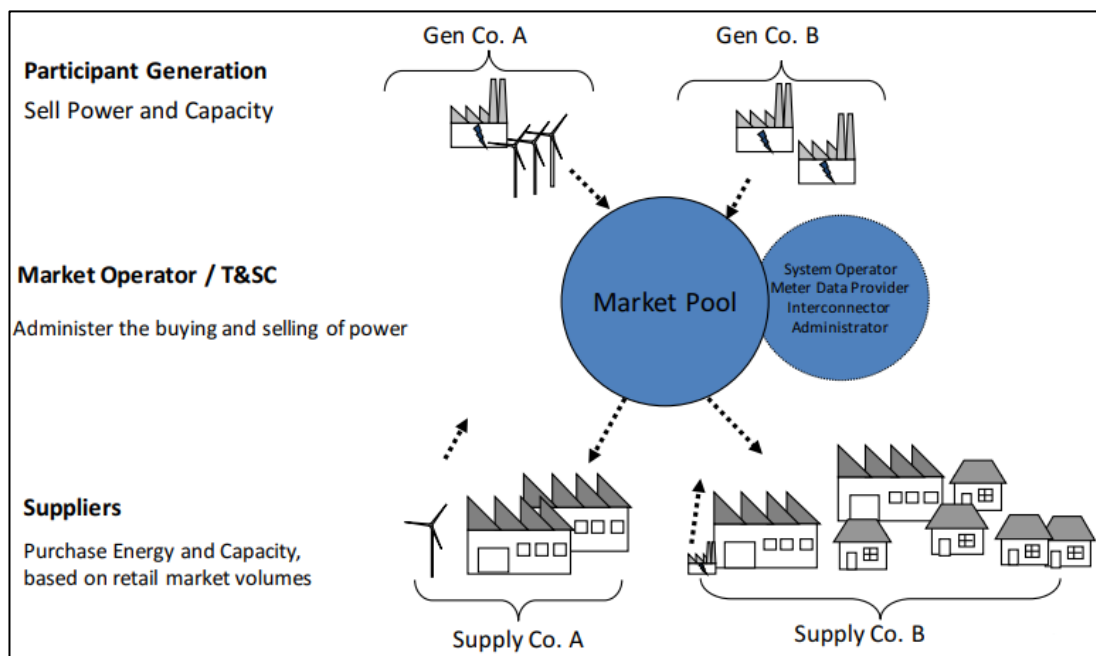
Figure 1-11 Ireland Single Electricity Market (SEM) overview (Mullany Engineering Consultancy, 2016).

1.5.4   Grid Services: Demand Side Management/Frequency Response

Grid services can be widely defined as built in flexibility on the grid in order to help manage system security or electricity price through efficiency. Grid services can encompass a wide range of different techniques which can operate over different time scales in order to achieve this flexibility for example:

- Static peak reduction such as behavioural changes in electric consumption over the course of a day from domestic through to industrial consumers in response to a variable price tariff;
- Flexible demand measures which allow dynamic load shifting within the day dependant on the system conditions on that day;
- Ancillary services offering a faster demand reduction capacity onto the market in response to a grid dispatch signal (similar to offering generation capacity) or offering a demand ramping capacity to make use of excess generation.

The normal operating frequency on the grid is between 49.8 Hz and 50.2 Hz, when generation and demand are equal the system frequency would be 50 Hz. Frequencies above 50 Hz are a

result of over generation for current demand and frequencies below 50 Hz are a result of under generation for the current demand. Sudden changes in demand or generation can result in frequencies outside the normal operating limits. Spinning and static reserve on the system are used to correct energy imbalances when they occur. Increased levels of variable renewable energy on the grid can be a problem for frequency control. Systems that can provide a dynamic frequency response or a static frequency response would be able to provide a grid service in order to maintain system stability. At a basic level, a dynamic frequency response is one that tracks the grid frequency and responds accordingly whereas a static frequency response does not track the grid frequency.

It is foreseen that demand side management will have a key role in facilitating the management of increased levels of renewables onto the grid (EirGrid & SONI, 2015). Demand side units (DSU) and aggregated generator units (AGU) can be an aggregation of a number of small loads or generators that can be managed via an intermediary actor in the market. The aggregated units can be centrally dispatched and can operate commercially within the single electricity market. Units like this can provide flexible system services to assist in the integration of renewables onto the grid. Within this scope is the potential to aggregate large numbers of heat pumps, electric cars, domestic energy storage and domestic appliances for example. DSUs that can provide demand reduction are eligible for a capacity payment in the SEM. To be eligible an aggregated DSU must have the capacity to reduce demand by a minimum of 4 MW with a maximum of 10 MW for a single site (otherwise it needs to be registered as a standalone DSU) (EirGrid Group, 2015). The DSU needs to be available 24 hours a day all year round and capable of real time communication with EirGrid electronic dispatch instruction logger (EDIL). The DSU must also demonstrate compliance with the grid code, which is achieved through testing, in order to become commercially operational.

A DSU can bid into the market a price for reducing a volume of demand they know they have available. This price could be lower than the price of a generator which has capacity to cover this demand. It can therefore be cheaper to reduce demand rather than pay a generator. The reduced demand is effectively displaced until generating capacity is greater, for example more wind is available or overall system demand is lower. This can theoretically put downward pressure on wholesale prices by reducing dependence on more expensive generators. It also means that the network capacity can be better managed i.e. peak system load and the ability of electrical infrastructure to serve that demand.

As the focus of the research is to investigate electrified domestic heating, grid services and demand side management applicable to heat pumps will be highlighted. This includes briefly both integration in terms of grid demand impact and possible opportunities in terms of offering ancillary services such as frequency response. Firstly, the uptake of heat pumps as a heating source for domestic houses will have the impact of adding to system demand. Without intervention it is likely that heat pump loads will correspond with daily peaks on the grid i.e. as people arrive home from work, they will switch on the heating or heating will be set to come on in the morning adding to the morning demand rise. In order to avoid these impacts behavioural changes can be adapted so that heat pump heating demand can be shifted from times of low system demand or limited at times of high system demand. This could be done for example in combination with dedicated thermal storage or using a building's thermal inertia. Secondly, heat pumps incorporating variable speed drives could be used to lower heat pump power output (rather than switching off) reducing electrical power consumption to provide a demand side response in relation to a frequency deviation on the grid for example. In order to do this suitable controls would be needed in order to respond to the grid signal whilst limiting the impact on the consumer. Ideally the domestic consumer would be unaffected in terms of thermal comfort experienced in their home. For reliability controls would need to be ideally automated and be able to respond in real-time to the grid. The overall aim would be to:

1. Decarbonise heating using heat pumps which in turn could further decarbonise the electricity grid by providing a demand for wind energy which might otherwise be curtailed.
2. Reduce the price of wholesale electricity by better utilising existing wind capacity and thereby increasing grid efficiency.
3. Improve grid security and stability by control of aggregated heat pumps for demand and frequency response.

1.6 Aim & Objectives

1.6.1 Aim

The primary aims of the research are to investigate an electrical heat pump as a renewable form of domestic heating that can replace a gas or oil boiler as a low disruption retrofit in order to reduce the carbon intensity of home heating whilst remaining cost competitive in terms of fuel cost. The heat pump when coupled with a form of thermal storage and autonomous demand side management control should also be able to limit the impact of electrified home heating on the electricity grid and open up possibilities which may be realised in future smart grids, for example, real time pricing tariffs. The system should be practically feasible and not be detrimental to occupant thermal comfort.

1.6.2 Objectives

The aim will be achieved by meeting the following objectives:

1. Analyse the operational performance of a retrofit high temperature air-source heat pump in the occupied terrace street houses at Ulster University Jordanstown campus.

2. Analyse the performance of the heat pump when coupled with thermal energy storage for providing central heating in terms of COP, cost, and CO_2e intensity

3. Development of a low-cost system which would allow the heat pump and energy storage system to provide autonomous demand side management requiring no interaction from the house occupants and without causing excessive detriment of occupant thermal comfort.

4. Investigate and implement a system capable of working on a future smart grid capable of receiving and responding to grid signals from the system operator in real-time.

5. Investigate and implement such grid signals with the aim of limiting the impact of heat pumps impacting on peak electricity system demand.

6. Investigate and implement such grid signals with the aim of limiting the impact of heat pumps impacting on electricity market price.

7. Investigate and implement such grid signals with the aim of increasing the capacity for renewable electricity penetration onto the grid.

8. Investigate and test alternate methods of providing low cost autonomous demand side response with increased reliability in the form a hybrid gas boiler and heat pump system.

2 LITERATURE REVIEW

2.1 High Temperature ASHP

In the introduction section 1.3 the most common types of heating systems found in typical UK domestic homes were detailed. The most common heating system was a hydronic central heating system powered predominately by gas boilers in England, Scotland, Wales and oil boilers in Northern Ireland. These boilers typically fall into 2 categories, system boiler (boiler with hot water storage) and combination boiler (instantaneous hot water). Combination boilers have a much simpler layout and are generally suitable for smaller households with a single bathroom whereas system boilers have a slightly more complex layout and are more suited to serving households with multiple bathrooms. Heat emission is via radiators located in each room of the house which were traditionally designed using a flow temperature of 82°C and delta T (Δt) of 11-12°C, resulting in a return temperature of 71°C (Watkins, 2011). Condensing boilers, which favour a lower return temperature (in order to condense flue gases), are typically designed for a Δt of 20°C and flow temperature of 80°C, therefore a larger radiator is required compared to the traditional design. A literature review was conducted looking at examples of high temperature electrical air-source heat pumps (75-80°C flow temperature) on the market which could replace a gas boiler in a typical UK domestic house i.e. a retrofit installation with limited disruption to the existing building fabric, central heating system, and control system. The priority of the literature review was to assess seasonal COP performance, carbon intensity, installation cost, and thermal power outputs limited by typical domestic household single phase electrical connection of 65/100 Amps.

2.1.1 Domestic High-Temperature ASHPs on the Market

High temperature heat pumps are defined as heat pumps that can achieve flow temperatures of 65°C and above (BSI, 2018). However in order to achieve high flow temperatures of up to 80°C using air as a source requires the use of a cascade heat pump system, illustrated in Figure 2-1 (DECC, 2016a), which incorporates two refrigeration cycles. To achieve this in one cycle would not be practical as reaching an outlet temperature of 80°C would require a theoretical compression ratio of approximately 7 and coolant temperature of 140°C using R134A (Amato, 2012). These conditions would be at the limit of most commercial components with additional effects such as high mechanical stress, compressor lubrication issues and low efficiency. Cascade heat pumps compared to single stage heat pumps have lower compressor discharge temperatures, lower evaporating temperature, lower

compression ratio and higher compressor volumetric efficiency (Hosoz, 2005). Cascade air source heat pumps for 80°C flow application typically use a low-pressure cycle with R410A, which performs well with low outdoor temperature, and high pressure cycle with R134A, which is suited to higher pressure and temperatures (Amato, 2012).

TO HEATING SYSTEM

CONDENSER

EXPANSION VALVE

COMPRESSOR

HEAT EXCHANGER

EXPANSION VALVE

COMPRESSOR

EVAPORATOR

AMBIENT HEAT IN
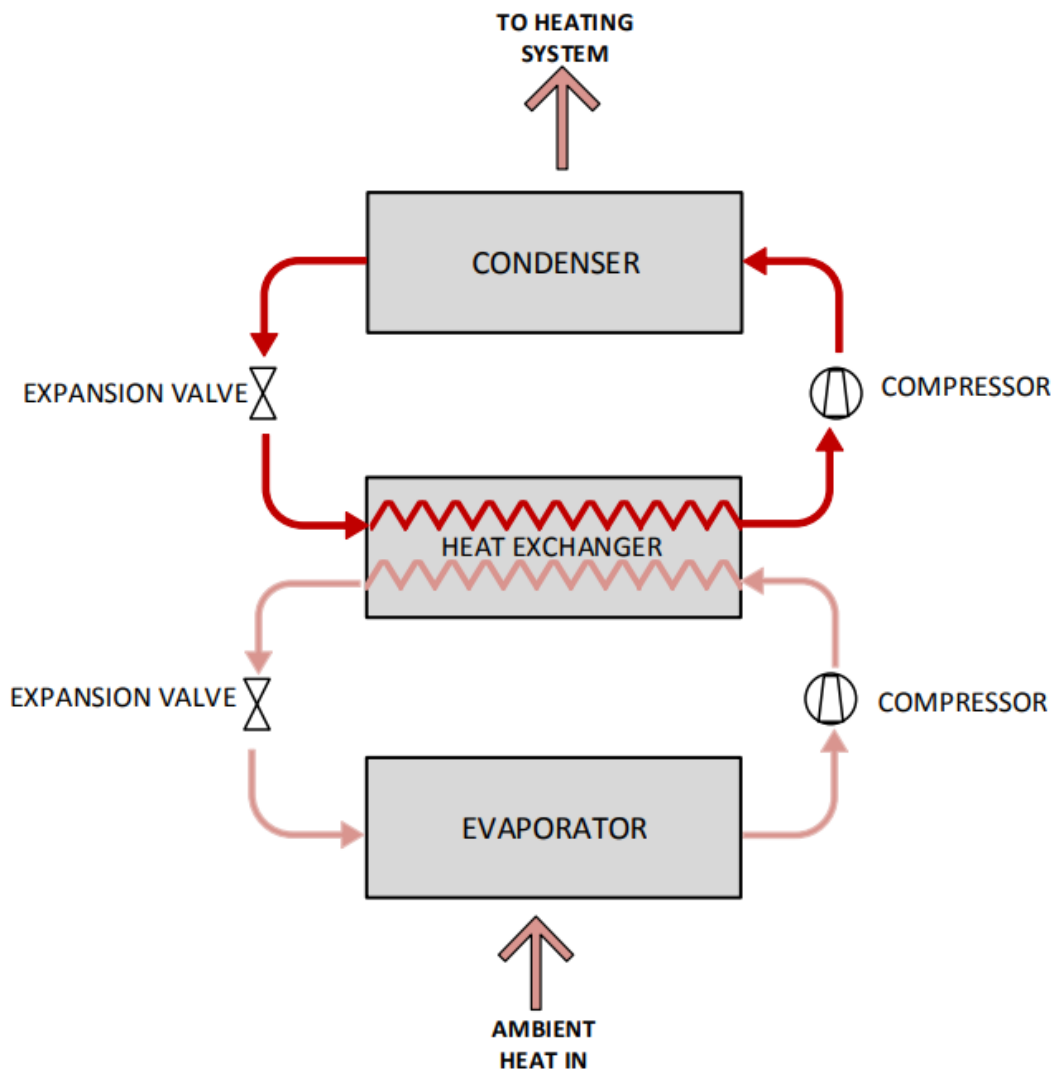
Figure 2-1 Cascade heat pump schematic (DECC, 2016a)

The current market for high temperature heat pumps tends to be a niche market generally including large, old, or listed properties with high heat loss which are off the gas grid and have high domestic hot water demand (DECC, 2016a). With cascade heat pumps the main advantages are the high temperature output and the ability to optimise the performance of each cycle however they are generally more complex, have higher space requirements, and are more expensive as a result compared to standard low temperature heat pumps. There are few examples on the market of domestic cascade heat pumps. A summary is presented in Table 2-1. Daikin makes one such unit namely the Daikin Altherma HT with heat outputs

of 11, 14, and 16kW using a single-phase supply. The product specification quotes COPs of 2.50, 2.48, and 2.41 respectively at 7°C outdoor temperature, 80°C flow temperature and 70°C return temperature (Daikin, 2010). Another Italian company makes a similar product the Thermocold DUO with claimed COP of 2.90 at a flow temperature of 65°C, however the operating ambient air temperature is unknown due to the lack of detail on the manufacturer's website (Thermocold, 2016). Hitachi's Yutaki S80 is another example working on the same principles and using the same refrigerants for the two cycles. It comes with heating capacities of 11, 14, and 16kW on a single-phase supply. The S80 is designed to use the second cycle only when required (i.e. for hot water production) and therefore quotes COP at 7°C outdoor temperature and 55°C flow temperature of 4.80, 4.60, and 4.35 for each heat capacity respectively (HITACHI, 2016). The S80 although capable of 80°C flow temperature is optimised for space heating flow temperatures of 55°C. The DECC (2016) quotes a COP for the S80 at comparable conditions to the Daikin Altherma, ambient 7°C and flow temperature 65°C, of 2.5-2.56.

Table 2-1 Summary of cascade heat pumps from literature. [1]7°C outdoor temperature, 65°C leaving water temperature, heat output in brackets. [2]7°C outdoor temperature, 80°C leaving water temperature, heat output in brackets.

Manufacturer	Product range	Refrigerant	Rated output (kW)	Max temp (°C)	COP (A7/LW65)[1]	COP (A7/LW80)[2]
Daikin	Altherma High Temp.	R410A & R134a	11, 14 or 16	80	3.08(11), 3.00(14), 2.88(16)	2.5(11), 2.48(14), 2.41(16)
Hitachi	Yutaki – S80	R410A & R134a	11, 14 or 16	80	2.5-2.56	----
Thermocold	DUO	R410A & R134a	----	80	Data not comparable	Data not comparable

2.1.2   State of the Market

As documented in the introduction sections the UK domestic heating market is dominated by fossil fuel boilers. Across Europe, heat pumps have seen greater levels of uptake. Heat pump sales figures for major markets in Europe in 2014 were: France, 193100; Sweden, 95500; Germany, 68400; UK, 18700 (Nowak, 2015). The 2014 estimated market size in the UK of high temperature air to water heat pumps (operating at 60°C or above) as a proportion of total sales (commercial and domestic) was approximately 2% or around 320 units (DECC, 2016a). Low oil prices in particular can have a negative impact on sales as the economics of the system struggle to compete. The DECC report on domestic high temperature heat pumps (2016a) found that manufactures were unsure about the market potential for high

temperature heat pumps and this is apparent in the low number of models on the market that can achieve flow temperatures of 80°C. Balancing the competitiveness of heat pumps versus the relative prices of oil, gas and electricity, and policy in the form of incentive schemes were some of the reasons stated for this. Markets with the greatest potential are seen as retrofit properties of the gas grid. Northern Ireland which as previously stated is dominated by oil boiler central heating, and even though investments are being made to extend the gas network, large proportions of properties in the country are unlikely to ever see a gas connection due to the sparse population of the country. As such high temperature heat pumps can be of particular interest for Northern Ireland. Even so retrofit properties on the gas grid are also seen as a potential market. The Committee on Climate Change suggested the uptake of heat pumps in the UK could reach 2.3 million by 2030 (Committee on Climate Change, 2015) so irrespective of the market potential for high temperature heat pumps, research into heat pump integration onto the market in terms of grid loading etc. has applicability across all types of electrically powered heat pumps.

Some the major barriers to heat pump deployment, particularly high temperature heat pump deployment in UK homes, have been identified as high upfront cost and uncertainty of payback period due to relative fuel prices. In the short term the ratio of oil/gas prices to electricity price mean that running cost is likely to be similar to an oil or gas fired boiler and therefore the increased upfront capital would be difficult to justify even if the boiler needs replacing (DECC, 2016a). This however is without consideration of any incentives that may be available for uptake of low carbon heating technology. High temperature heat pumps are not considered suitable for new build properties as low temperature heat distribution will realise higher COPs when running a heat pump.

The report by the DECC (2016a) estimates an annual market for high temperature heat pumps of 29,000-66,000 dwellings based on a number of factors such as the heat pump supply chain (compared to a mature boiler supply chain), annual replacement rates of heating systems, and the most likely target market i.e. off-gas grid retrofit properties. The estimate also assumes there is no connection restriction by the distributor network operator (DNO) which for heat pumps needs to be approved. This is an important point because the report also points out some customers have been asked to pay for grid improvements before installing a heat pump. This perhaps leads to a question of integration were heat pumps have methods of demand side management which can be implemented at time of stress on the grid by the network operator. In Germany, for example, heat pumps have an "EVU" input lock which can be used by the electric utility to send a discrete signal over the supply cable

instructing the heat pump to operate in one of four modes from fully off to fully on, offering both up and down regulation to the grid (Norregaard, et al., 2015). Implementation of something similar in UK might allow greater heat pump deployment onto the existing grid whilst reducing the need for grid reinforcement. Alternatives to using a high temperature heat on the gas grid were market potential is lower compared to off the gas grid is the use of a small standard HP in combination with a gas boiler existing at the property already or with a new boiler as a hybrid (DECC, 2016a). Although this may have a lower upfront capital cost, dual maintenance of what is effectively two separate appliances should be considered and due consideration would be required to optimise the efficiency of such a system i.e. a common control system would generally be required. Advantages of such a system would be that the heat pump could be sized for a lower or median household demand with peak/extreme heat demands provided by the gas boiler only and the system could be optimised based on running efficiency or relative cost of fuel for each appliance. A dual fuel system also has the advantage in terms of demand side management were the gas boiler could be activated at times of electricity network stress ensuring the house occupants are not negatively impacted in terms of thermal comfort.

2.1.3   System Performance

Electrical heat pumps use electrical energy to move heat from a source to a sink. Generally, the larger the difference between the source and sink the greater the amount of electricity will be required. The coefficient of performance (COP) of a heat pump is the ratio of useful thermal energy produced to the total electrically energy consumed for a given condition i.e. at a particular air temperature and flow temperature set-point. The seasonal COP (SCOP) is a measure of the system efficiency across a range of operating conditions i.e. varying air temperature across a period of operation. For air source heat pumps the daily and seasonal variation in air temperature effects the COP. Manufactures will typically quote in the product specification the COP when running at an air temperature of 7°C dry bulb/6°C wet bulb with an outlet temperature of 65°C and inlet temperature of 55°C for high temperature heat pumps based on testing to British Standard EN 14511 (BSI, 2018).

For high temperature heat pumps manufacturer quoted COPs, for air temperature of 7°C and flow temperature of 65°C, ranges from 2.2 to 3.1 (DECC, 2016a). It should be noted that this is based on laboratory testing. One of the key points that continues to appear in literature is the need for accurate system design and optimised control in order to achieve the best COPs (DECC, 2016; Delta Energy & Environment, 2011; Energy Saving Trust, 2010; Lowe, et al., 2017). This is true for all heat pump installations, from low to high temperature. When

comparing heat pump installations in the UK from the Energy Saving Trust Trial (Energy Saving Trust, 2010) to comparable heat pump installations in Germany (i.e. retrofit replacement of a high temperature boiler), German installations significantly outperformed those in the UK (Delta Energy & Environment, 2011). Median values of approximately 2.5 in the German trials compared unfavourably with median values of approximately 2 in the Energy saving trust trials. The main reasons were detailed as: under sizing heat pumps, incorrect controller setup, poor overall planning of the central heating system, and lack of end user education who tended to operate heat pumps in a manner similar to conventional boilers.

2.1.4 High-Temperature ASHP Case Studies

With the estimated number of high temperature heat pumps sales estimated at just 320 units in 2014, which includes all heat pumps capable of achieving flow temperatures above 60°C, it is difficult to find independent field trials (i.e. not those by manufacturer) for cascade heat pump application in domestic retrofit properties. Manufactures e.g. Daikin supply case studies on their website however this may not be the best source of information given their interest in selling the product. Previous published work at Ulster University covers initial performance trials for the proposed research using a high temperature cascade heat pump. Shah & Hewitt (2015) carried out performance trials with an 11 kW cascade air source heat pump manufactured by Daikin (Daikin Altherma HT) installed as a retrofit replacement for a condensing gas system boiler. The house was a typical 3 bed terrace house built on the University campus for testing, with early 20th century build specification, minimum thermal upgrades (double glazing, loft insulation, modern foam insulated DHW storage cylinder) and occupied by a family of three. The COP of the HP ranged from 1.82 to 2.38 with an average of 2.07 in winter conditions. Below 2°C air temperature frequent defrost cycles reduced the heat delivery to the house. In addition, the heat pump was coupled with a thermal store which when operational allowed for faster house heat up times and therefore thermal comfort to be achieved faster. An alternative study by Stiebel Eltron, a manufacturer, carried out field trials of 2 heat pumps with 75°C flow temperature which performed well when used to replace oil boilers. However low COP at high flow temperatures meant they did not plan to use them commercially (DECC, 2016a).

2.1.5 Cost

The cost of heat pump installation can be a major barrier with high temperature heat pumps 20-35% more than standard heat pumps (DECC, 2016a). Cascade systems are effectively two heat pumps therefore additional costs are apparent (2 compressors, extra heat exchangers

etc.). The low uptake of the product is exacerbated by the relatively low cost of gas fired condensing boilers and the cost savings that can be achieved as a result of the relative prices of oil/gas to electricity (Taylor, et al., 2016). High temperature heat pump cost ranges from £3000-£7000 with fully installed costs ranging from £6000-£14000 (DECC, 2016a). For heat pumps that can achieve 80°C flow temperatures the estimated product cost is £5000-£7000, with installation costs of £3000-£5000 and total overall costs of £9000-£13000 (DECC, 2016a). Costs for high temperature heat pumps should benefit from the ability to retrofit into the existing heating system (i.e. same radiators, DHW tank, and controls can be used), however this is not apparent in the literature. It is evident that installation costs can be high, and this is again likely to the immaturity of the heat pump market in the UK and lack of trained installers and thus the lack of competitiveness on the market. It is likely that costs would fall if the heat pump market matures similar to the gas boiler market (DECC, 2016b)

2.1.6 Carbon Saving Potential

The ability of heat pumps to provide a carbon saving in the domestic heat sector is dependent on the relative carbon intensity of electricity compared to the dominant heating fuels gas and oil and the efficiencies of the products that produce heat. A heat pump of COP 2.50 for example uses 1 unit of electricity to produce 2.5 units of heat whereas a gas boiler with an efficiency of 90% uses 1 unit of gas to produce 0.9 units of heat. The carbon intensity of electricity is higher however (as electricity needs to be generated and distributed) and is dependent on the fuel used to produce it which is variable across the day. The levels of renewable energy on the grid, fossil fuel, nuclear, all contribute to the carbon intensity of electricity and the proportions that make up the electrical generation are relative to price, demand and system security. The carbon intensity of the grid has been falling with the increased generation from renewable energy and the phasing out of coal fired generation. A drop of 11% in carbon dioxide emissions from the energy supply sector was realised between 2016 and 2017 in the UK with a drop of 57% from 1990 levels to 2017 (BEIS, 2018a). As such the required COP of an electrical heat pump to generate heat with a lower carbon intensity than modern condensing gas or oil boilers has reduced and further reduces as the electricity grid becomes less carbon intensive. The DECC report on high temperature heat pumps (2016a) estimates a high temperature heat pump providing 100% of domestic thermal energy demand has the potential for over 50% energy and carbon savings compared to an oil or gas boiler based on carbon conversion factors and energy prices for 2016 from the DECC Green Book guidance (BEIS, 2018b). The report also estimated an energy and carbon saving of between 5%-32% compared to a standard heat pump which was estimated at only being

able to provide 85% space heating and 80% DHW demand compared to 100% for a high temperature heat pump.

2.1.7   Summary

The advantages of using a high temperature heat pump capable of flow temperatures similar to gas or oil boilers are the ability to retrofit into existing homes without changing radiators, control systems or DHW water storage tank. Installations such as this are comparable to gas combi boiler retrofits that have become common place over the last decade. This type of installation is typically fast with minimum disruption and inconvenience for the occupants hence the attractiveness. High temperature heat pumps have a high potential for decarbonising the domestic heating sector and even have an advantage over standard heat pumps as they can be used to supply 100% of the heating demand whereas low temperature heat pumps would need to be supplemented with alternative heating sources for DHW demand. Heat pump deployment can further assist with decarbonisation of the electricity grid by creating a load for renewable energy which may otherwise be curtailed e.g. wind. The best market potential for high temperature heat pumps is in retrofit properties in the off-gas grid. The UK housing stock has a high proportion of thermally inefficient homes and high temperature heat pumps offer a fast deployment solution for decarbonisation of the high heat demand homes. However, this is best combined with insulation measures as a first priority.

Some of the major barriers facing high temperature heat pump deployment are the high upfront costs and the lack of running cost savings comparable to gas and oil boilers. There is generally a low technology awareness of high temperature heat pumps. Lack of field trial data means there is an issue surrounding confidence in the product which combined with cost creates a high-risk factor. For cascade heat pumps there is a higher space requirement than a standard heat pump as it is effectively two heat pumps. The cost differential between oil/gas and electricity is high however the advantage over oil is that electricity is a regulated fuel whereas home heating oil is not and can therefore be subject to market volatility and demand. The heat pump market is relatively immature compared to the gas market and therefore there is a lack of skilled technicians for installation and maintenance compounding cost barriers. There may be issues surrounding connections in areas were the grid requires reinforcement however this is analogous with the electric car market. High deployment of electrical heat pumps will add significant demand to the electricity grid however this may represent an opportunity in combination with demand side management and energy storage to improve the efficiency of the grid and increase renewable energy penetration onto the

grid. The majority of homes in the UK have a single-phase connection typically 65/100 amps and as a result international products designed for 3 phase supply are unsuitable. In addition, there is a maximum limit to the heat pump capacity that can be installed as a result of the amperage capacity to UK homes.

2.2   Thermal Energy Storage

When considering coupling thermal energy storage (TES) with a domestic heat Pump (HP) the current incentive for a domestic consumer is to take advantage of lower night time "Economy 7" tariffs to charge the store and discharge it when required within the higher daytime tariff. This type of heating system was conventionally used with electric resistance storage heaters operated by a static timer or radio teleswitch signal (Energy Networks Association, 2018) to charge the storage at the lower tariff rate with electricity consumption metered by a dedicated Economy 7 meter. The advantage of using a heat pump over resistive storage heaters is the ability to achieve an efficiency greater than 1 and therefore a greater overall system efficiency can be achieved i.e. an ideal resistive heater will convert 1 unit of electrical energy to 1 unit of thermal energy whereas a heat pump of COP 2.5, for example, will convert 1 unit of electrical energy to 2.5 units of thermal energy. The TES applicable in either situation will obviously differ with storage heaters the medium used for space heating is typically a solid media heated to a high temperature and water storage tank for domestic hot water (DHW). With a domestic heat pump the storage temperature is limited to the flow temperature achievable which will be based on the method of heat delivery to the house. In the UK this will overwhelmingly be via a hydronic central heating system in which heated water is circulated through an emitter installed in the space to be heated. The most common emitter for this system will be a radiator which is sized to meet the calculated heat demand for a given room. The conditions for radiator design are typically a flow temperature of 75°C, return temperature of 65°C, and mean temperature difference of 50°C with the heated space (Shah & Hewitt, 2015). This type of system would therefore require a heat pump capable of producing flow temperatures in excess of 75°C and a thermal store of similar capabilities. Daikin makes such a heat pump, the Daikin Altherma HT air source split unit capable of producing flow temperatures up to 80°C and specified to achieve a COP of 2.50 with flow/return temperatures of 80/70°C at 7°C ambient air conditions. In new houses there is a move towards installing underfloor heating, which can be a disruptive and expensive retrofit, were, due to the large surface area of the emitter, water can be circulated at a relatively low temperature (typically around 40°C), compared to radiators (NHBC Foundation, 2016). With this type of system, the heat pump would therefore only be required to produce maximum flow temperatures of approximately 45°C and similarly a TES of these capabilities would only be required. The lower flow and storage temperatures will result in an improved system efficiency due to improved HP COP (lower temperature lift required) and reduced losses from the thermal store (reduced rate of heat loss due to smaller temperature difference with

surrounding environment). In addition, newer houses, which will be more likely to have underfloor heating, will tend to have lower heat demands as a result of stricter building regulations improving the thermal insulation of the building.

Taking these points into consideration the capacity of TES that will be suitable for a given building will be determined by:

1. Space requirement. There will be a practical upper limit to the space available and therefore volume of store that can be retrofitted into existing housing. In new build houses this may be more flexible as it could be designed into the build. In houses which have been built in the combi-boiler era this will be the most difficult constraint as no space for thermal storage will have been incorporated into the design (BEIS, 2016). For older properties it is likely that they may retain a DHW tank or it has been replaced by a combi-boiler, either way TES space will have existed in some form in the past. Hot water cylinders and thermal stores still remain common in the UK with a total of 398,273 greater than 50 litres sold in 2015 (BEIS, 2016).

2. The capacity of the store will then be limited by the type of storage medium used which must be relevant to the designed central heating system i.e. relevant storage temperatures. There are three main categories of heat storage: (1) sensible; (2) latent; (3) thermochemical. Sensible storage is well established in the domestic market and is typically through water storage at temperatures under 100°C. Latent storage involves the selection of materials (known as PCMs) which change phase at the desired temperature to increase storage capacity and is becoming much closer to being commercialised although there remains a gap around development of PCMs with the right temperature input for heat pumps (BEIS, 2016). Thermochemical storage involves reversible chemical reactions to store large quantities of heat in a compact volume with potentially 100% efficiency (no thermal degradation with time) however it has only been investigated in an academic context and lacks demonstrator projects in the UK (BEIS, 2016). In the context of coupling TES with a HP in a domestic setting, appropriate storage mediums are outlined in Table 2-2.

3. Ultimately if space and capacity are not the major constraints, the heat demand for the house and relative proportion to be provided from storage will need to be considered i.e. for older houses with high heat demand it is unlikely all of the daily heat requirements could be provided from storage, however for modern new builds with low heat demand this may not be an issue and therefore storage sizing could be based on maximum peak heat load.

Table 2-2 Thermal energy storage (TES) overview for application at a domestic level. Adapted from BEIS (2016).

Type of TES:	Sensible	Latent	Thermochemical
Storage Medium	Water - most common for domestic market.	PCM - organic or inorganic compound which can be used to store thermal energy in the material's change of phase.	Reversible chemical reaction to store large quantities of heat in small volume. Typically, a reaction between two liquids or a solid and a vapour.
Cost (£)/kWh	26-183	250-350	Not currently commercially available.
Efficiency (%)	50-90	75-90	100 (Potentially)
Key Advantages	• Established and proven • Scalable • Wide application range • Cost effective	• High energy density and therefore smaller store compared to sensible heat storage • Constant temperature during charging and discharging	• Very high energy density • Long term storage without degradation
Key Disadvantages	• Large space requirement • Smaller stores have higher heat loss and are suitable for short term storage only (i.e. daily)	• Relatively immature technology for domestic application • Selection of suitable PCM material for desired melting point vital	• Market commercialisation not likely within next 10 years • Lack of real-world proof of potential

2.3 Demand Side Management

The combination of thermal storage with a heat pump at a domestic level has obvious benefits for both grid management and consumer flexibility in terms of their energy use. A smart grid is broadly perceived as the delivery of electricity from generator to consumer in a controlled way with consumers integral to the control i.e. they modify demand in reaction to incentives and disincentives (Siano, 2014). Heat pumps (along with electrical cars) are likely to represent some of the highest loads in future decarbonised housing stock and therefore have the highest potential for impact in terms of demand side management or demand side response. At a household level it is estimated heat pumps can increase electrical load by 2.5-5.5 kW, with the upper end of the demand likely on a '1 in 20' winter day (Harkin & Turton, 2017). Decoupling thermal demand from electricity demand can allow the benefits of a smart grid to be realised such as: minimum grid infrastructure and operating cost; stable and secure operation of the grid in terms of frequency, voltage and transmission capacity; optimised use of generation in order to minimise electric CO_2 intensity or cost (Fischer & Madani, 2017). Using the built environment as an energy store has been presented as a promising method of renewable energy integration onto the grid (Hewitt, 2012) with the benefits of heat pumps for decarbonisation having been detailed in previous sections.

This section of the literature review will look at historical and emerging techniques of demand side management and applicability to high temperature heat pumps coupled with thermal energy storage. The aim will be to establish the best method of applying demand side management control or demand side management response which will best benefit the grid in terms of integration of electrical heating in addition to providing a grid service which offers flexibility with regards to grid management. This will be mirrored with the need to establish a method of control which is reliable for the grid operator in terms of consumer compliance and thus consumer acceptance. Ultimately if the consumer does not accept the demand side management element of electrified heating or engage consistently with it the system cannot be relied upon by the grid operator as a grid service.

2.3.1 Grid Focussed

Demand side management with regards to HPs weighted towards grid benefit is generally aimed at providing some sort of grid service which allows stable cost-efficient operating of the grid (Fischer & Madani, 2017). The types of services include voltage control, congestion management, and provision of spinning and non-spinning reserve (Hirst & Kirby, 1996). With voltage control applications the HP is regulated up or down varying the active power consumption at times of local under or over voltage. Such an example is detailed by Dallmer-

Zerbe & Fischer (2016) who used a variable speed heat pump to provide voltage stabilisation by using droop control to adjust the compressor speed in proportion to the degree of voltage deviation.

Congestion management aims to avoid local constraints caused by transformer and line capacity. The rationale is to operate HPs in such a manner as to avoid transformer overloading thus reducing or postponing network reinforcement (Leeuwen, et al., 2011). With HPs this can be done through planning by avoiding the coincidence of peak loads at household and grid levels as discussed by (Nykamp, et al., 2012). Real-time control which can react to unforeseen events and day-ahead planning to avoid HPs impacting on peak grid demand provide a common studied solution to transformer loading and voltage deviation (Brunner, et al., 2013). This can often be realised by demand shifting were the HP operation is planned in the day ahead and the load of the HP is concentrated at low household or grid load by using a demand profile as a signal for appropriate operation (Logenthiran, et al., 2012; Arteconi, et al., 2013; Arteconi, et al., 2012). The benefits of peak demand avoidance for the grid include lower electricity generation prices: generators bid in capacity to the market at a price which is ranked from lowest to highest with the generator who can then meet the demand setting the price for the other generators ranked below it. In other words the lower the peak demand the greater additional generation capacity that is available to act as replacement reserve and lower cost generators (which are likely to be more efficient) would put downward pressure on the system marginal price (SMP) (Finn, et al., 2011). In addition, when DSM can be used to counteract feed-in peaks from renewable generation it effectively increases capacity and in turn assists with renewable integration onto the grid. This can be especially beneficial at a local distribution level (Fischer & Madani, 2017).

To maintain the grid frequency and the balance of generation and demand, the grid uses spinning and non-spinning reserve. The reserve capacity is provided by generation units or consumers that can regulate the grid frequency up and down. Generators are dispatched at time of under frequency i.e. low generation capacity and consumers can be dispatched at either low or high frequency (over generation) to increase or decrease demand to regulate the grid. The speed of response is categorised as primary (responds in seconds), secondary (responds in seconds to minutes) and tertiary (responds in minutes to tens of minutes). A summary of EirGrid categorisations for frequency response are included in Table 2-3.

Table 2-3 Categorisation of frequency response for grid services (Pratt, 2018)

Service name	Unit of payment	Description
Fast Frequency Response / FFR	MWh	MW delivered between 2 and 10 seconds
Primary Operating Reserve / POR	MWh	MW delivered between 5 and 15 seconds
Secondary Operating Reserve / SOR	MWh	MW delivered between 15 to 90 seconds
Tertiary Operating Reserve 1 / TOR1	MWh	MW delivered between 90 seconds to 5 minutes
Tertiary Operating Reserve 2 / TOR2	MWh	MW delivered between 5 minutes to 20 minutes

The use of small responsive loads for frequency regulation is discussed by Kirby (2003) and Wang et al. (2013) however there are limited examples which concern HPs (e.g. Bhattarai, et al. (2014), Biegel, et al. (2014), Hao, et al. (2015)). In Ireland in order to operate in the market for frequency regulation a demand side unit (DSU) must have a minimum demand reduction capability of 4 MW which can be made up of a number of aggregated units (EirGrid Group, 2015). Therefore, a large number of small loads need to be aggregated which poses challenges for the aggregator such as estimating flexibility, planning bidding strategies, and control of a large number of units (Fischer & Madani, 2017). Methods of forecasting the heat and electric demand of the HPs are required however alternative methods such as decoupling the HPs from the network in conjunction with thermal storage are possible solutions (Hewitt, 2012).

2.3.2 Renewable Energy Focussed

When using DSM in conjunction with HPs that has a focus on renewable energy integration onto the grid the aim is to increase renewable penetration, reduce feed-in peaks and smooth the load curve (Fischer & Madani, 2017). This type of DSM generally focusses on wind and PV integration which are the fastest growing forms of intermittent electricity generation. In Ireland wind is by far the most dominate form of intermittent renewable energy and thus the main focus here.

Poulet & Outbib (2015) showed that at a building level the integration of wind can be supported by a HP with maximum reduction of electricity consumed from the grid reaching 95%. In addition, the use of a variable speed HP allowed constant adjustment of the electricity consumption to match the wind production. At larger scale however aggregation of HPs is required in order to utilise the larger volumes of electricity generated. Often an external signal such as price or current wind production is used to schedule HP operation (Fischer & Madani, 2017). Real time carbon intensity of the grid may also be a useful signal

to use as it indicates the volume of low carbon generation on the grid (not just wind for example). The website carbonintensity.org.uk created by the National Grid (Bruce & Ruff, 2018) makes a 2-day carbon intensity forecast for Great Britain available for those interested in changing their energy consumption in relation to such a signal. EirGrid also makes their own data available online also (EirGrid Group, 2017). Typically, levels of high wind occur in the winter months matching well to the seasonal electric and heating demand variation. Hedegaard & Münster (2013) and Papaefthymiou, et al. (2012) demonstrated that with optimization, pools of HPs can increase the penetration of wind power onto the grid whilst reducing the impact of HPs on peak demand in turn reducing the cost of electricity.

2.3.3   Price Focussed

Price focussed DSM provides a clear signal to a consumer on how they should vary their electric consumption and thus is a strong unsophisticated signal to encourage participation in DSM (something an aggregator or the grid needs). A common well-known example of DSM by way of a price signal is a time-of-use tariff such as Economy 7 which is most often associated with domestic electrical storage heaters. Economy 7 is an example of a tariff which provides 7 hours of night time electricity at an incentivising low rate and a day rate which is higher than the standard fixed tariff with aim of providing a disincentive for electricity consumption in this period. Tariffs such as Economy 7 tend not to change over long periods, typically years, and so DSM is non-reactive in terms of the daily changes which might occur across the grid. Arteconi, et al. (2013) used a time-of-use tariff to simulate how a HP coupled with a thermal energy store could be used as a DSM strategy however electric bills also required further incentives in order to be reduced.

Variable (dynamic) electricity prices are more closely linked to the state of the grid and are closer aligned with renewable energy focused applications and are considered central to a smart-grid system (Fischer & Madani, 2017). Dynamic pricing in comparison to time-of-use pricing changes in short time frames, typically day-ahead or in shorter intervals reflecting real time pricing. EirGrid's SmartGrid dashboard (EirGrid Group, 2017) provides access to the system marginal price (SMP) which is forecast for 48 hours ahead in half hour intervals. Finn, et al. (2011) used this price as an indicator of renewable energy penetration levels on the Irish grid and in turn as a DSM signal for simple hot water storage (heated by electrical immersion heater) with aim of increasing wind energy onto the grid and reducing cost and demand of conventional generation.

From literature it is difficult to ascertain the expected cost savings that may be derived from price-based DSM strategies as it is highly dependent on the different tariffs, different operating modes, different variables and different incentives that are applicable. It is critical that DSM operation is balanced with cost savings and energy efficiency and therefore precise management is required.

2.3.4   Possible DSM Impact on HP Energy Consumption

There is the possibility and in some cases certainty, depending on the nature of the DSM shift, that by altering the designed for operation of a HP will result in an increase in energy consumption. This is particularly true for time-of-use tariffs which shift energy loads through storage. Finn, et al. (2011) found that if scheduling of load shifting is designed to take this into account the benefits of increased demand for wind generation can negate any increase in demand that would otherwise be provided by conventional generation. Fischer, et al. (2014) showed that operation of an ASHP may lead to reduced COP due to lower ambient air temperatures when charging a thermal store at night and also due to the relative high storage temperatures required for storage. It should be borne in mind that possible lower operational cost when using DSM strategies do not necessarily equate to lower energy consumption. Some studies have demonstrated reductions in energy costs of 8% but increased electric demand of 2% (Klaassen, et al., 2015) and up to 19% electric consumption in some cases of load shifting (Miara, et al., 2014).

2.3.5   Controls

Within the context of a smart grid, methods of HP control with respect to DSM have emerged in the form of low cost, small, computationally sufficient computers that encompass communication technology and have the ability to be programmed to run custom designed algorithms. These types of devices are broadly used in the so called "Internet of Things" (IOT) were low cost remote communication enables software control of all manner of things and data collection from any number of sensors for very little cost.

When considering the control of a HP for DSM the approach taken is highly dependent on the desired outcome which has been detailed in the previous sections i.e. grid, renewable or price focussed. It must be considered that the primary purpose of a domestic HP is to provide thermal comfort for the occupant (and possibly hot water) and the HP has been designed as such (Fischer & Madani, 2017). Thus, designing controls for HPs that do not have this in-built capability must try to leverage the HPs in built controls, be that on/off thermostatic control, room thermostat setback, or flow temperature modulation, to name a few. In addition, if the

HP is coupled with a thermal store, planning and scheduling of charging/discharging, and methods of providing this must be considered. This control design must also facilitate the signal it plans to react to e.g. forecast grid demand/price, or real-time reaction to changing state of the grid (Fischer & Madani, 2017). It is important that the thermal comfort of the occupant is respected at all times whilst attempting to achieve the desired objectives such as: minimum cost of operation; maximum system COP; or maximum benefit for the grid. Objectives can sometimes be mutually beneficial to one and other or work against one and other. The DSM strategy and control design should aim to find the ideal balance without overly penalising any of the elements (be that cost or hardware) that make up the systems operation.

Fischer & Madani (2017) describe the control hierarchy required for the use of HPs in a smart grid context, which is illustrated in Figure 2-2. The hierarchy has three main boundaries, moving from high to low: (1) the power system level (e.g. grid control, grid signals, aggregation control); (2) the building level (e.g. room thermostatic control, heat pump control, thermal storage control) and; (3) the heat pump unit (e.g. refrigerant cycle, compressor control, fan control). To implement DSM the three levels need to interact i.e. the high level (grid) sends a signal to the lower levels (building control or HP embedded controls) which may or may not provide feedback. Typically, were feedback is provided this would be used to adjust the signal according to the state of the grid in relation to the feedback e.g. aggregated pools of HPs.
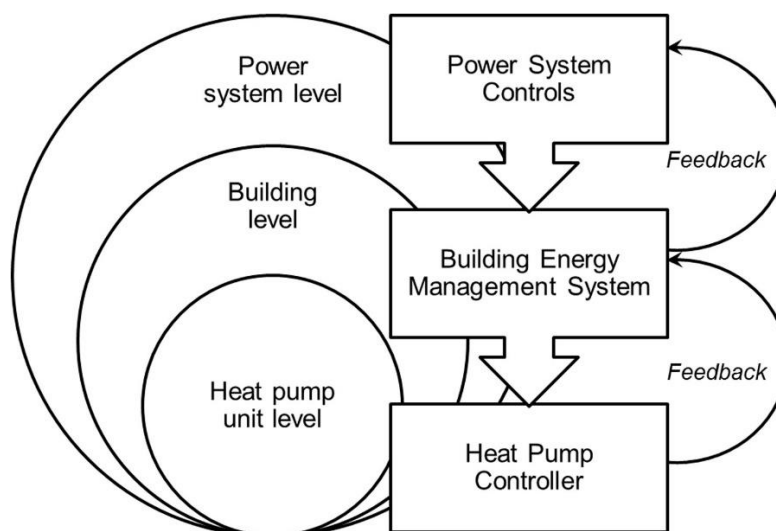
Figure 2-2 Control hierarchy in the context of HPs in a smart grid (Fischer & Madani, 2017)

Were signals are sent from the higher level it is dependent on the DSM strategy implemented at the lower level on the response that should be taken. For example, a frequency regulation

signal may automatically adjust the HP in response to the signal for the sake of the grid benefit whereas with a price signal the lower level may decide what response to take for the sake of the consumer benefit i.e. the controller may have different degrees of autonomy. The levels of autonomy can generally be classified as: (1) passive (direct control - low level device tries to follow signal); (2) passive intelligent (indirect control - low level optimises based on signal) and; (3) active systems (agent based control) (Rohbogner, et al., 2012).

The approach that can be taken by a passive intelligent system at the building level is illustrated in Figure 2-3 (Fischer & Madani, 2017). Typically, the approaches are categorised as predictive and non-predictive. Non-predictive methods are the most common methods used for heat pumps currently. This type of control consists of the HP reacting based on a calculated decision using input data from real-time sensor values and or a grid signal. Fast frequency response is a DSM strategy were this type of rule-based control is most applicable e.g. the HP regulates up or down based on simple rule-based logic (Dallmer-Zerbe & Fischer, 2016). The main advantages of non-predictive include simple implementation and design, and computationally cheap. However, rule-based systems are generally inflexible and cannot adopt to unspecific systems (i.e. learn system properties) and a good understanding of the system is required.
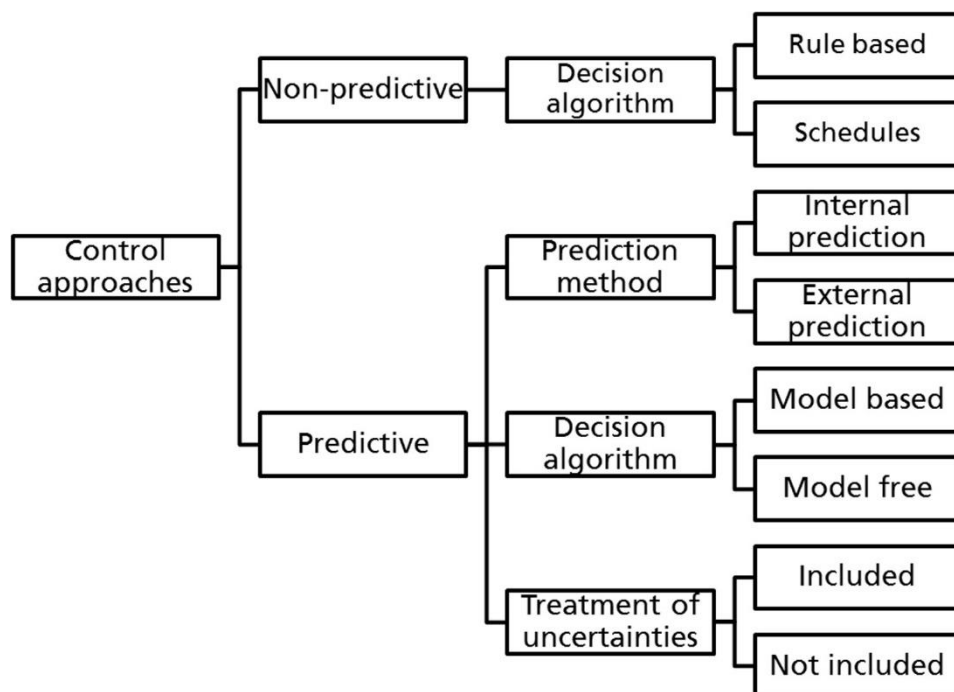
Figure 2-3 Passive intelligent controller strategy for HPs at the building level (Fischer & Madani, 2017).

Predictive approaches to DSM control can use measurements to learn and adopt response based on, for example, using historic measurement to predict a future value from the past, use artificial neural network modelling, or statistical methods. Predictive methods may have an advantage over non-predictive methods as the controller can adopt to the characteristic of individual systems (e.g. building heat up and cool down rate), heating patterns, occupancy etc. However, uncertainties in predictions may result in variable behaviour and therefore they may not be as robust as rule-based approaches. In addition, models can be computationally expensive in turn leading to a more complex and expensive design.

2.3.6   Examples of Smart Controllers on the Market

The most common smart heating controllers that have emerged onto the market in the UK are arguably the Nest and Hive thermostats. Although the thermostats are essentially digital thermometers with a relay attached, they may have a degree of applicability when trying to implement DSM strategies with HPs. The Nest in particular will be discussed. The thermostat learns the heat up time and cool down time of the home in which it is installed and can combine this with other information such as the local air temperature and the occupancy of the house (based on occupants' phone location) in an attempt to reduce fuel consumption for heating whilst maintaining thermal comfort. A protocol it has integrated is the OpenTherm standard for heating controllers (OpenTherm Association, 2018). The protocol enables the thermostat to modulate the flow temperature of an OpenTherm compatible boiler (which is preferred to on/off modulation) to improve thermal comfort and increase the energy efficiency of the boiler. HPs with this protocol enabled would allow similar modulation to take place and the implementation of DSM strategies could be handled by Nest essentially acting as an aggregator. Nest offers such a program in America called Rush Hour Rewards (Nest, 2018). The program allows consumers to sign up to receive rewards (like bill credit or discounts) from their energy company in return for reducing their air conditioning load on the electrical grid at peak demand times or reducing the gas consumption at time of high heat demand in the winter season. The rush hour events are dependent on the stress level on the grid and happen 15-20 times per season with the consumer being notified (unless in extreme events) and maintaining the ability to adopt out by manually adjusting their thermostat (Nest, 2018).

The rush hour reward scheme was introduced after this research had commenced (including the design and implementation of the HP controller) but it gives an example of how a popular device could be used to bring forward DSM opportunities in the UK and Ireland given a possible increase in the deployment of HPs.

3   METHODOLOGY

3.1   Introduction

In order to meet the aims and objectives of the project an 'off-the shelf' high temperature air-source heat pump (ASHP) was procured and retrofitted into one of two purpose-built demonstration test houses located on the Jordanstown campus of Ulster University. The houses were built to replicate common early 20th century terrace houses typical of those located in Belfast, Northern Ireland. The houses are occupied by University staff and family.

3.2   Test Houses

A front elevation of the test houses is shown in Figure 3-1. The building consists of two identical houses, house 63 on the right and house 64 on the left. Each house, 63 and 64, has an air conditioned thermostatically controlled room (guard chamber) located to the right and left respectively. This allows the simulation of a continuous row of terraced houses. The temperature can be varied in the guard chambers to simulate, for example, a vacant property or varying heating profiles that may occur in adjacent properties in a terraced street. For this study the temperature of both guard chambers was set and maintained at 21°C.

| 64 Guard Chamber | 64 House | 63 House | 63 Guard Chamber |

Figure 3-1 Front elevation of test houses located on Jordanstown campus of Ulster University.

A floor layout of house 64 is illustrated in Figure 3-2. House 63 has identical layout with the exception of the guard chamber being located on the right side of the building.

Figure 3-2 Test house 64 and guard chamber floor plan (house 63 is identical with the exception of the guard chamber located to the right side of the building). Ground floor plan is on the left of the figure and 1ˢᵗ floor plan is on the right of the figure.

Each house is occupied by staff working in the University and their families. House 63 is occupied by a mother and young child of primary school age (5-11 years). House 64 is occupied by a mother and two working adult children. The 2011 UK census (Office for National Statistics, 2011) recorded an average household size of 2.5 persons per household in Northern Ireland with a UK wide average of 2.3. Thus, it was envisaged that either house could provide a representative case study in terms of heating demand comparable to the Northern Ireland and UK average. House 64 was chosen for the retrofit of the ASHP whilst house 63 retained the original gas boiler heating system.

3.2.1   Original Gas Heating System

Each house was originally fitted with identical central heating systems consisting of condensing natural gas boiler, fully pumped water heat circulation, radiator heat emitters, and mains fed vented domestic hot water storage tank. Gas boiler specifications for both houses are outlined in Table 3-1.

Table 3-1 Gas boiler specification for test house 63 and 64 (Baxi Heating UK Ltd, 2014).

Detail	Value
Boiler type	Condensing natural gas
Model	Baxi Solo 24 HE A
Maximum/minimum heat output (non-condensing 70°C mean water temperature)	22.00/9.14 kW
Maximum/minimum heat output (condensing 40°C mean water temp)	23.8/10.1 kW
Electrical power consumption	80 W
Flow temperature (manually adjustable)	55°C – 78°C (± 5°C)
Recommended system temperature drop (condensing)	20°C
Flow temperature modulation	Varying fan rate (and thereby gas rate)
SEDBUK efficiency declaration	90.9%
Circulation pump (independent)	

Heat output to the house is via radiators fed from the boiler with 22mm copper pipe and 15mm tees to each radiator. The domestic hot water tank (DHW) has a volume capacity of 162 litres and is fed from the boiler with 28mm copper pipe. The radiator specifications are outlined in Table 3-2 and DHW tank specifications are outlined in Table 3-3.

Table 3-2 Radiator specification for test house 63 and 64 (JCP Consulting, 2011).

Location	Size (mm)	Type	Rated output (kW)
Living room - 1	1000 × 354	Double panel, double fin	0.9
Living room - 2	750 × 425	Double panel, double fin	1.0
Dining room	1000 × 283	Double panel, double fin	0.8
Kitchen	1000 × 425	Double panel, double fin	1.0
Ground floor hall	1000 × 425	Double panel, single fin	0.8
Upstairs landing - 1	500 × 567	Double panel, double fin	0.8
Upstairs landing - 2	750 × 496	Double panel, double fin	1.0
Master bedroom (×2)	1000 × 212	Double panel, double fin	0.5 (×2)
Second bedroom	1000 × 283	Double panel, double fin	0.7
Box bedroom	500 × 567	Double panel, double fin	0.8
Bathroom	500 × 425	Double panel, double fin	0.5

Table 3-3 DHW tank specifications for test house 63 and 64.

Detail	Value
Manufacturer	Albion
DHW tank type	Copper, vented, indirect
Water capacity	162 litres
Maximum standing heat loss	2.74 kWh/24hrs
Heat exchanger coil area	0.88 m^2
Heat storage capacity (45°C/65°C)	3.78 kWh
Water inlet	Cold water header tank
Immersion heater size	2.7 kW @ 230 V

A schematic representation of the original central heating system fitted in the test houses is illustrated in Figure 3-3. The system is typical of domestic central heating systems used in the UK and Ireland.
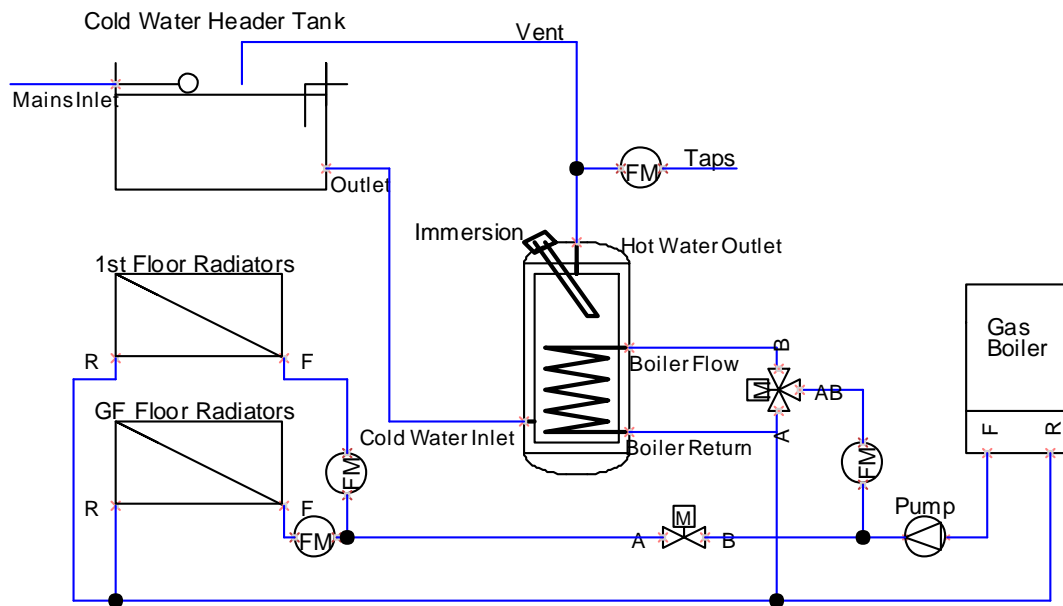
Figure 3-3 Schematic of the original central heating system fitted in the test houses 63 and 64. Central heating flow to the ground floor (GF), 1st floor, and DHW cylinder are monitored separately, as well as hot water draw off from the DHW cylinder. All radiators except the bathroom radiator (heat leak radiator) have thermostatic radiator valves attached. Letters 'F' and 'R' represent flow and return line respectively.

3.2.2 Original Heating System Wiring and Controls

The original heating system uses a Danfoss electronic 2-channel programmer (model FP715SI) capable of controlling heating and hot water separately. The circuit diagram for the heating system is illustrated in Figure 3-4. Space heating is controlled via a room thermostat located in the dining room and timed or manual on/off control (heating controller). A motorised 2 port valve (see Figure 3-3 and Figure 3-4; SH 2-PV) controls flow to the radiator circuit when there is a call for space heating. When space heating is satisfied the valve will close and the boiler will switch off if there is no simultaneous call for hot water storage.

Hot water storage is controlled via a thermostat located on the DHW tank and timed or manual on/off control (heating controller). A motorised 3 port valve (see Figure 3-3 and Figure 3-4; DHW 3-PV) controls flow to the DHW tank. When there is a call for DHW storage and no space heating the heating circuit flow will be directed through the coil in the tank (DHW 3-PV in position B). When the DHW is satisfied either by the tank thermostat (set at approximately 65°C) or the timer the boiler will switch off. If there is simultaneous call for space heating and hot water the DHW 3-PV will move to mid position. When hot water

storage is satisfied the DHW 3-PV will move to position A, if there is still a call for space heating, thereby bypassing the DHW tank.
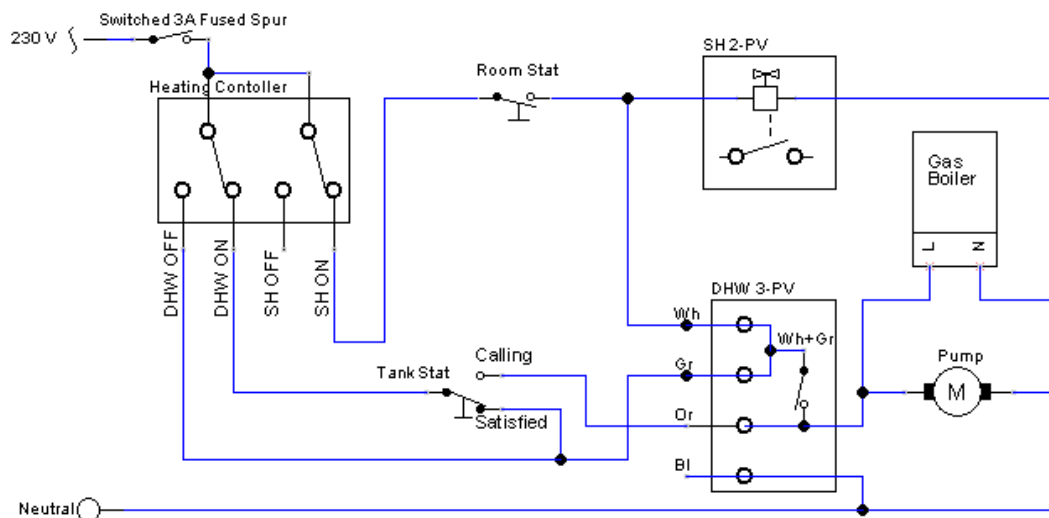
Figure 3-4 Circuit diagram of the original heating control circuit used in the test houses. SH 2-PV is normally closed, opening when energised. DHW 3-PV is normally port B (not energised), mid-position when Wh is energised, port A when Wh and Gr are both energised (also causes internal switching to energise Or). Power only on Gr will cause DHW 3-PV to maintain position. Terminals for DHW 3-PV: Wh-White, Gr-Grey, Or-Orange, Bl-Blue (neutral).

3.2.3 Test House Data Collection and Management

In order to monitor the performance of the heating systems, the test houses were instrumented with an Eltek GenII wireless telemetry data logging system (Eltek Ltd., 2017). The system consists of a receiver/logger and wireless sensor transmitters capable of interfacing with a range of sensors. Each room in the house was fitted with a temperature and humidity sensor except for the hallway, landing and boiler room due to limited availability. The central heating system was also fitted with a number of flowmeters (see Figure 3-3), which produce a pulsed output relative to volumetric flow, in combination with temperature sensors on flow and return pipes, thus enabling heat transfer to be measured. Flowmeters where positioned to measure flow to the ground floor radiators, first floor radiators, DHW storage tank, and hot water draw off from the DHW tank. The latter allowing hot water energy consumption and hot water tank efficiency to be calculated. At a later date, gas and electrical consumption measurement was added, via pulse output from the gas and electrical meters respectively. A general list of the sensors and transmitters used is shown in Table 3-4. Each house was instrumented with identical sensors. For location of the sensors within the building refer to Figure 3-2. For a complete and detailed list of the Eltek specific sensors, refer to Appendix A (Table 8-1). A location reference figure for the central heating

side sensors is also included in Appendix A, Figure 8-1. Data is logged at an interval of 1 minute.

Table 3-4 Specification of sensor instrumentation used in test houses. Data collected, transmitted and logged via Eltek GenII wireless telemetry data logging system.

Measurement	Measuring Device	Eltek Transmitter	Unit	Resolution	Accuracy
Room Temperature	Eltek GC-10	GC-10	°C	0.1 °C	± 0.4 °C
Room Relative Humidity	Eltek GC-10	GC-10	%	0.1 %	± 2 %
Volumetric flow ground floor radiators	Zenner Sonar Ultrasonic Flowmeter	GC-62	ltr	1 pulse / ltr	Information unavailable
Volumetric flow first floor radiators	Zenner Sonar Ultrasonic Flowmeter	GC-62	ltr	1 pulse / ltr	Information unavailable
Volumetric flow DHW tank	Zenner Sonar Ultrasonic Flowmeter	GC-62	ltr	10 pulse / ltr	Information unavailable
Volumetric flow hot water consumption	Multi-jet volume flowmeter	GC-62	m^3	1000 pulse / m^3	Transitional flow: ±5 %; Nominal flow: ±2 %
Pipe temperature	T-type thermocouple (surface)	GD24	°C	0.1°C	± 0.3 °C
Gas consumption	Metrix G6 Gas Meter	GC-62	m^3	100 pulse / m^3	Information unavailable
Electricity Consumption	Landis + Gyr Electricity Meter	GC-62	Wh	1 pulse / Wh	Information unavailable

3.2.4   Test House Data Management

Data from the system is transferred from the datalogger to a dedicated PC via automation software which downloads the data daily at midnight in CSV format. The data is backed up to a cloud server and the datalogger is cleared before commencing logging for the subsequent day. The datalogger uses the system time of the local computer which updates daily. The system time of the local computer itself is synced to the University's network time server and is updated twice daily. This ensures an accurate and consistent timestamp for the data. The time of the local computer is set to maintain GMT to avoid possible issues with BST (British summer time) changes.

A Microsoft Access database was built to manage and analyse the data. An automation script is used to import new files into the relational database. Each data row uses the timestamp (format: dd/mm/yyyy hh:mm:ss) as the unique identifier. This not only prevents accidental

data duplication but also enables the data to be linked to other time series data sources from different data logging systems for combined analysis.

3.3   ASHP Retrofit

The retrofit of the ASHP is illustrated in Figure 3-5, Figure 3-6 and Figure 3-7. The heat pump tapped into the existing central heating system in house 64 via an underground heavily insulated pipe just after the gas boiler. Manual valves and changeover switches allowed the gas boiler to be manually brought back online in the event of a failure with the HP system. Later, electric 3-port valves were added so that the DSM controller could change between the gas boiler and HP via activation of relays. The data logging equipment was housed in the shed.

Figure 3-5 Rear of test house on campus. HP and monitoring equipment located in right shed.

Figure 3-6 Shed with cascade HP. Outdoor unit shown.

Figure 3-7 Retrofitted cascade HP. Indoor HP unit and thermal storage tank shown.

3.3.1 High Temperature ASHP & Thermal Store

A heat pump capable of heating to temperatures equivalent to a gas boiler was chosen to allow for a retrofit style installation. By retrofit, this means replacing the gas boiler only with the heat pump, retaining the existing central heat circulation system including pipework, radiators, and heating controls. The idea of this style of installation was to emulate older gas or oil boiler replacement applications similar to schemes which have seen upgrades to high efficiency condensing boilers over the last decade or so. The Daikin Altherma high temperature air to water heat pump was chosen as suitable. The heat pump uses a split system with an outdoor refrigerant cycle using refrigerant R410-A to extract heat from ambient air temperatures as low as -20°C providing heat to the indoor unit which runs a second cycle. The indoor unit refrigerant cycle uses refrigerant R134a to provide a central heating leaving water temperature up to 80°C. A general specification of the heat pump is outlined in Table 3-5.

Table 3-5 Specification details for the Daikin high temperature air-water heat pump retrofitted to test house 64. The heat pump uses a cascading indoor and outdoor unit.

Detail	Value	
Model name	Daikin ALTHERMA HT	
Heat pump type	Air to water (cascade unit)	
Indoor Model Number	EKHBRD011ACV1	
Indoor refrigerant	R134a	
Indoor water circulation pump consumption (inverter controlled)	87 W	
Crankcase heater power consumption	33 W	
Indoor max running current	21.7 A	
Outdoor Model Number	ERSQ011AAV1	
Outdoor refrigerant	R410-A	
Crankcase heater power consumption	33 W	
Outdoor max running current	27 A	
Leaving water temperature	25 - 80 °C	
For combination indoor + outdoor units (EW:55°C, LW:65°C, ΔT:10°C, Ambient conditions: 7°CDB/6°CWB)	Heating capacity	11 kW
	Electrical power input	3.57 kW
	COP	3.08
For combination indoor + outdoor units (EW:70°C, LW:80°C, ΔT:10°C, Ambient conditions: 7°CDB/6°CWB)	Heating capacity	11 kW
	Electrical power input	4.40
	COP	2.50

In order to run and test the heat pump with DSM, a thermal energy store was required. The purpose of the energy store was threefold. Firstly, the energy store should be large enough so that a meaningful amount of energy could be shifted from low grid demand to high grid demand. Secondly, the energy store should be capable of meeting the household heat demand, without supplementary heating, within the high demand window. Thirdly, the heat store should have a high enough thermal efficiency to ensure the energy shift from low demand to high demand is economically sensible. Water was chosen as the heat storage medium as it is low cost, non-toxic, and has a high specific heat capacity. The tank, which was custom built (Figure 3-8), was constructed of copper with two internal heat exchanger coils, one for charging via the heat pump, and one for discharging to the house central heating system. The specifications of the thermal store are outlined in Table 3-6. The tank was factory insulated with 50mm spray polyurethane foam, however a further layer of 100mm glass fibre loft roll was added at a later date to improve system efficiency. The tank was fitted with a removable lid to allow future modification within the tank.

Figure 3-8 Left (A): thermal energy storage tank installed with factory 50mm spray foam insulation. Right (B): thermal energy storage tank installed with additional 100mm glass fibre insulation.

In addition, the tank was also fitted with two immersion heaters (providing the flexibility of additional heating power), a de-stratification pump (to test for advantages/disadvantages of tank stratification), and ports for seven temperature sensors (spaced equidistant along the height of the tank). For the purposes of this research project the de-stratification pump was never used.

Table 3-6 Specification details of thermal store used in conjunction with retrofit heat pump set-up for house 64. Theoretical maximum heat storage capacity, assuming no heat loss, is calculated using: M=600kg, c_w=4.188 @ 65°C, ΔT=specified in table

Detail	Value
Manufacturer	Copper Industries (custom design)
Water storage capacity	600 litres
Heat storage capacity (55°C/75°C, ΔT=20°C)	13.961 kWh (theoretical max - no heat loss)
Heat storage capacity (65°C/75°C, ΔT=10°C)	6.981 kWh (theoretical max - no heat loss)
Dimensions	2m (height) × 0.6m (Ø)
Primary Insulation	50mm spray polyurethane foam (factory fitted)
Secondary Insulation	100mm glass fibre loft roll (added at later date)
Heat pump heat exchanger coil area	3.5 m^2
Central heating heat exchanger coil area	3.5 m^2
Immersion heater size	2 × 2.7 kW @ 230 V

The heat pump and thermal store were set up so that the heat pump could heat the house central heating system directly or be used to heat the thermal store, this was achieved via two motorised 3-port diverter valves and a custom designed wiring configuration. The hydraulic system is detailed in Figure 3-9 and the corresponding wiring configuration is detailed in Figure 3-10 to Figure 3-13 (refer to figure captions for detailed operation). The wiring was designed as an add on to the existing heating controls in the house (Figure 3-4) allowing these controls to remain unchanged and in turn the occupant's behavioural interaction with the heating system to remain largely unchanged. This was achieved by intersecting the call for heat signal immediately before the gas boiler and central heating pump where a manual changeover switch was placed. The changeover switch allowed the heating system to be changed between using the gas boiler as the primary heating source to the HP and thermal store system as the primary heating source. The HP and thermal store configuration were set up so that the HP could directly heat the house central heating (direct mode), the HP could charge the thermal store (charging mode), and the thermal store could discharge to house central heating system (discharging mode). A custom designed controller was created to achieve the automated and dynamic DSM requirements of the charging and discharging of the thermal store. The wiring configuration was designed so that in the event of a controller fault, i.e. no DSM function, heat would always be provided directly to the house from the HP when it was required. Details of the complete system (hydraulic, wiring and sensors) is located in the appendix, section 8.

Heat Pump Retrofit: Schematic Layout
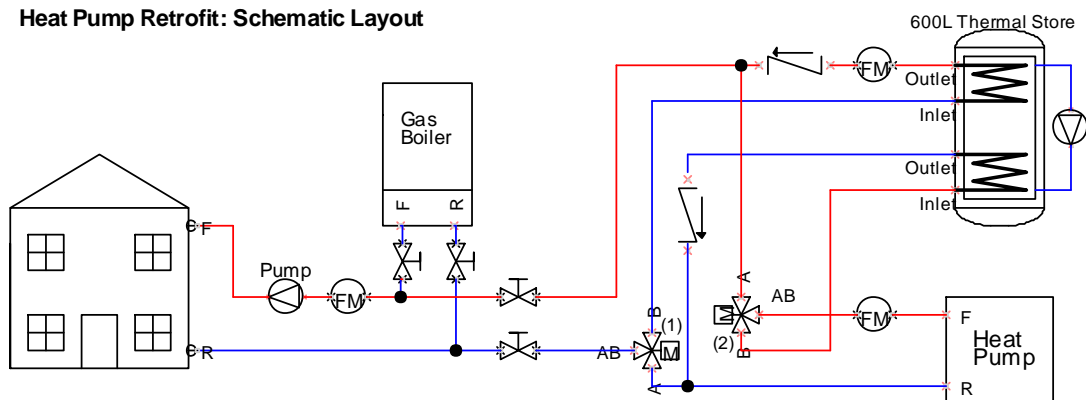
Heat Pump Retrofit: Direct Mode
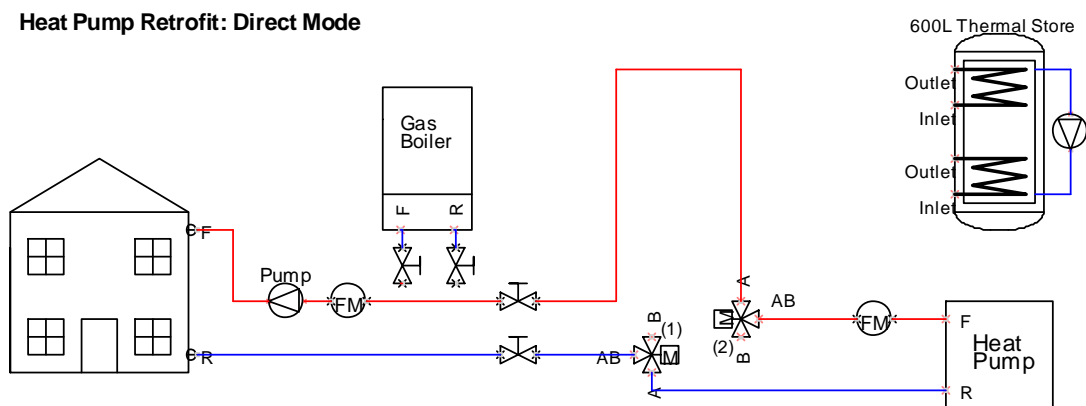
Heat Pump Retrofit: Charging Or Discharging Mode
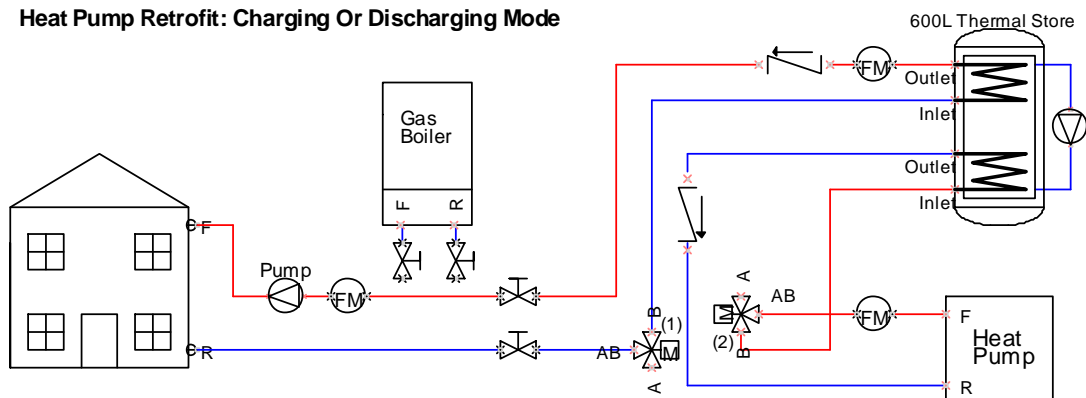
Figure 3-9 Schematic layout of heat pump retrofit (house symbol represents central heating system outlined in Figure 3-3). The top image shows the complete schematic. The flow and return pipe work for the heat pump/thermal store was connected via tee fittings to the gas boiler flow and return water circuit respectively. Manual gate valves were used to isolate the gas boiler water circuit and the heat pump/thermal store was used as the primary heating source for house 64. The heat pump and thermal store was set up to operate in direct mode (middle image) and charging/discharging mode (bottom image) with automated switching via 2 3-port valves (lines in middle and bottom images are removed for clarity). The pump attached to the thermal store was not used for the project.
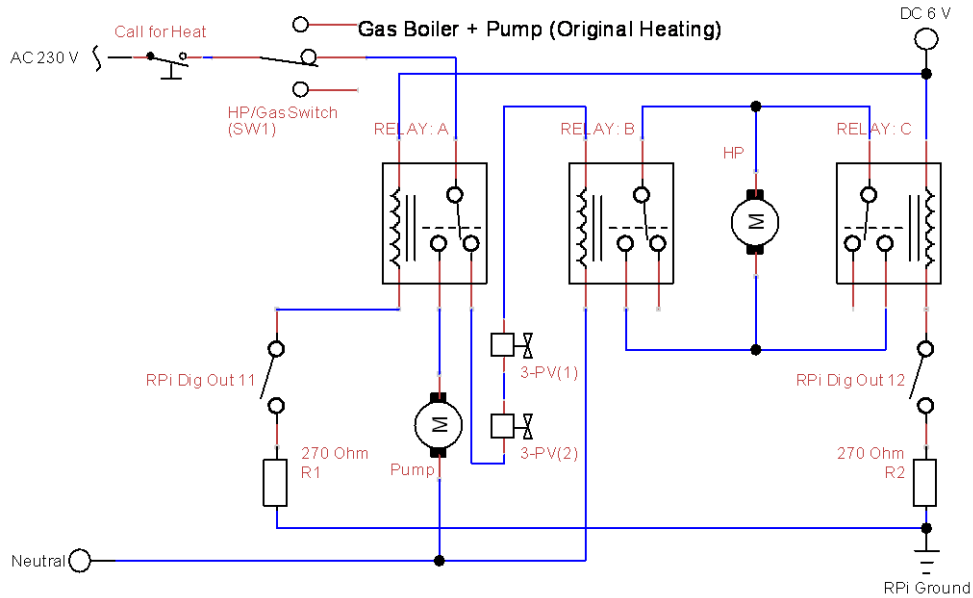
Figure 3-10 Circuit diagram of controls used to implement the heat pump/thermal storage modes described in Figure 3-9. The call for heat switch represents the original call for heat signal which powered the gas boiler and central heating circulation pump (see Figure 3-4). The changeover switch SW1 in this figure was placed just before the gas boiler and pump so the wiring could be manually switched between gas boiler operation or HP and thermal storage operation. The HP has its own power supply and is activated by voltage free switching either by relay B or relay C. Relay B is energised by a call for heat from within the original household heating controls whereas relay C is energised by a custom designed automated controller. The purpose of relay C is to store heat in the thermal store when there is a calculated benefit to do so. Relay A is also energised by the custom controller and its purpose is to switch the heating system to discharge the thermal store when there is a calculated benefit to do so.
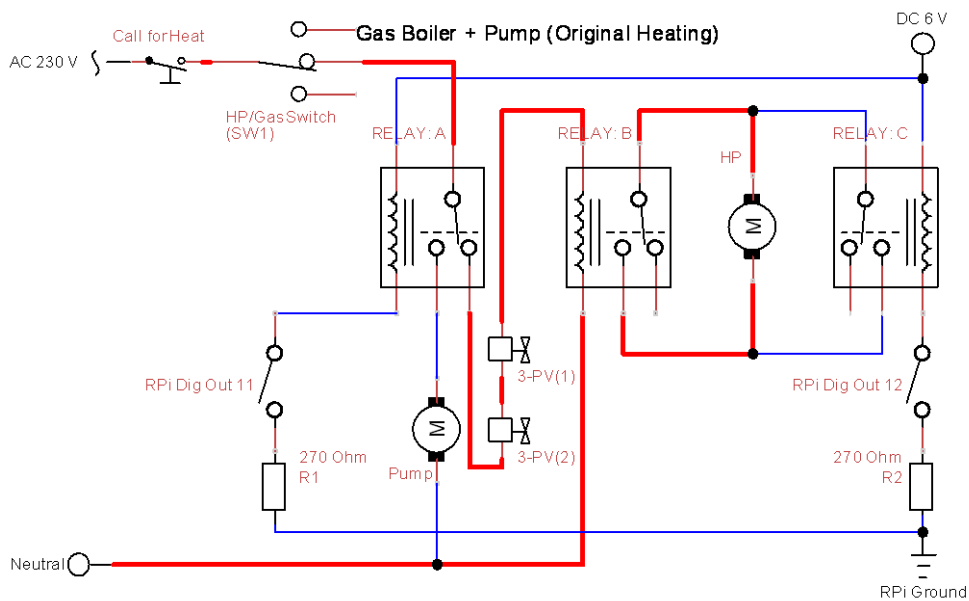
Figure 3-11 HP direct mode heating. Highlighted in red is the energised lines when there is a call for heat from the house. Electric flows through the normally closed contact of relay A, powering the 2 3-ports valves (1 and 2 Figure 3-9) turning them to port A, and the coil of Relay B is also energised in turn activating the HP.
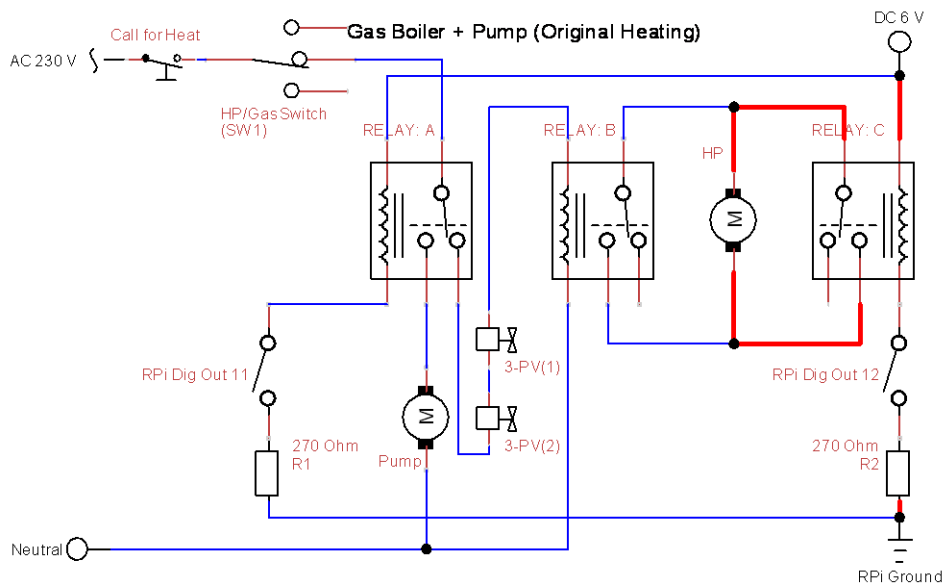
Figure 3-12 Thermal store charging mode. Highlighted in red are the energised lines indicating the circuit operation. A custom controller represented in the above circuit by "RPI Dig Out 12" controls a 6-volt supply to the coil of Relay C. Software designed for the controller decides the optimum time to activate Dig Out 12 and in turn Relay C and subsequently the HP is turned on. Referring to Figure 3-9, the 3 port valves are not energised and so are normally in port position B. In the meantime, if there was a call for heat from the house in this mode, the circuit would default to direct heating mode and thermal store charging would cease until the call for heat ended.
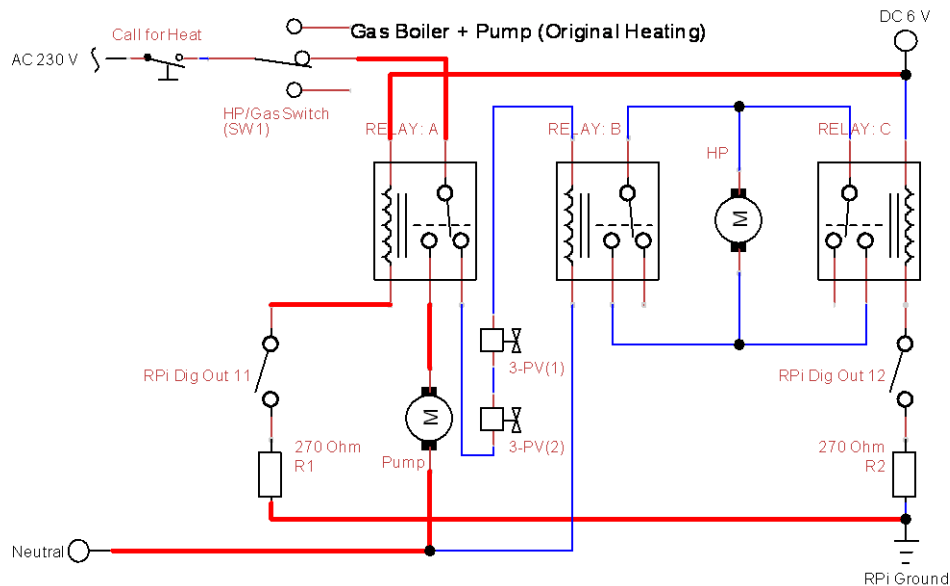
Figure 3-13 Thermal store discharging mode. Highlighted in red are the energised lines indicating the circuit operation. A custom controller, represented in the above circuit by "RPI Dig Out 11" controls a 6-volt supply to the coil of Relay A. Software designed for the controller decides the optimum time to activate Dig Out 11 and in turn Relay A. Subsequently a call for heat from the house will power the central heating pump thus discharging heat from the thermal store to the central heating system. Referring to Figure 3-9 (charging or discharging mode) the 3 port valves are not energised and so are normally in port position B, therefore the house central heating system will extract heat from the thermal store when the central heating pump is activated.

3.3.2   Hybrid ASHP & Gas Boiler

Further to the setup outlined in section 3.3.1 in which DSM was investigated using the HP and thermal store only, the opportunity for advanced development of the system by incorporating the existing household gas boiler was identified. With some modifications to the hydraulic set-up and circuitry, detailed in Figure 3-14 to Figure 3-17 and Figure 3-18 to Figure 3-21 respectively, a number of different heating combinations using the HP, thermal store, and gas boiler became possible. The set-up was designed so switching between the various modes could be automated and controlled via a custom designed controller and software. The different heating combinations include:

A. HP direct
B. Gas direct
C. Thermal store discharging direct
D. HP and gas boiler in series (HP feeds gas boiler return line)
E. Thermal store discharging and gas boiler in series (thermal store feeds gas boiler return line) – would work only until return to thermal store from house central heating is still lower than tank temperature
F. HP charging thermal store

The purpose of the further modifications was primarily to allow DSM of the HP using the gas boiler at peak grid electricity demand, replacing the thermal store (thus removing the heat loss of the thermal store), and therefore improving the system efficiency. However, the system design allowed for flexibility for experimentation with other scenarios, including:

A. Peak grid electricity price shifting. Time of peak electricity pricing can vary from day to day whereas peak demand is generally a static profile from day to day. This is difficult with a thermal store due to heat loss and therefore complicates designing an efficient strategy to meet household heat demand.
B. Real time HP versus gas boiler COP relative to current ambient temperature.
C. Real time HP versus gas boiler fuel economy relative to historical COP and current ambient temperature.
D. Instantaneous grid frequency response by using the HP as a controllable load whilst having the ability to maintain heating to the home using the gas boiler.
E. Increased heat power for house when HP and gas boiler run in series, particularly beneficial for start-up were HP heat output can be low.
F. Thermal store remains in place, so a load is available for storage of curtailed renewable energy or low grid electricity prices.
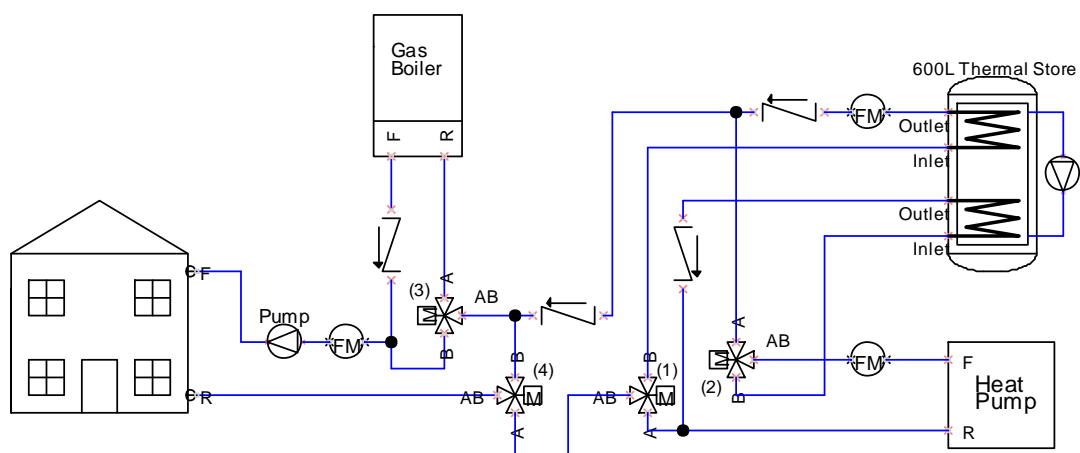
Figure 3-14 Schematic hydraulic layout of HP/Gas boiler hybrid system. Modifications to the hydraulic configuration detailed in Figure 3-9 include the addition of a further two 3-port valves (labelled 3 and 4), additional pipe work, and a check valve on the gas boiler flow line. The modifications allow the system to switch between gas boiler as primary heating system to HP/thermal store via custom designed controller and wiring configuration. In addition, the configuration allows the HP and gas boiler to cascade in series with the HP feeding the gas boiler return so that the HP can provide a lower thermal lift and the gas boiler providing a secondary additional thermal lift to produce flow temperatures of 75-80°C.
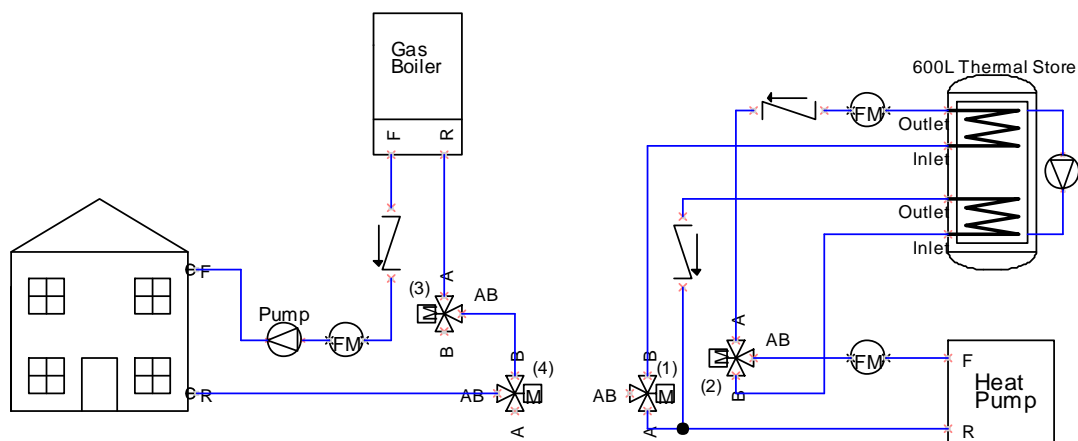
Figure 3-15 Hybrid gas boiler only mode (lines removed for illustration). In this mode the controller calculates it is more efficient/preferable to use the gas boiler only. 3-port valve (3) is energised and moves to port position A. The gas boiler can be used instead of the thermal store for DSM in conjunction with the HP.
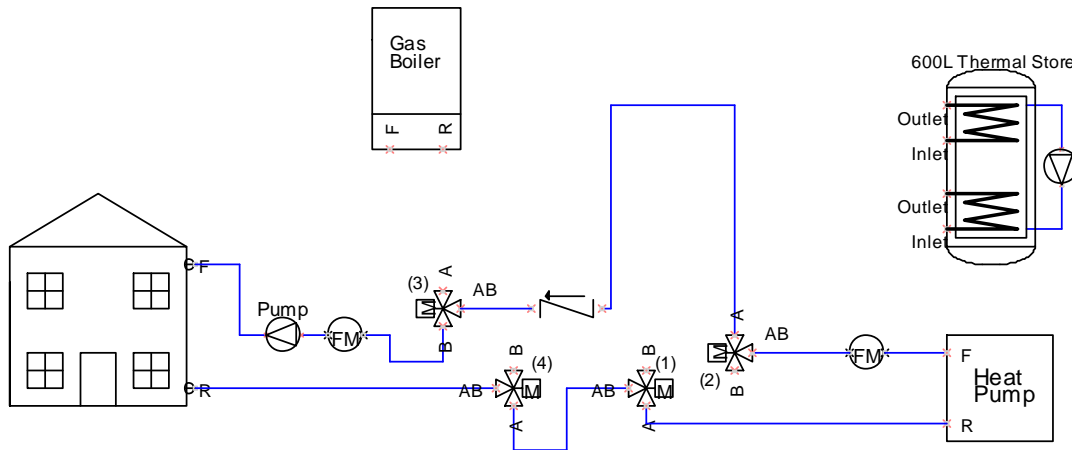
Figure 3-16 Hybrid HP only mode (lines removed for illustration). In this mode the controller calculates it is more efficient/preferable to use the HP only. 3-port valves (4, 1, and 2) are energised and move to port position A.
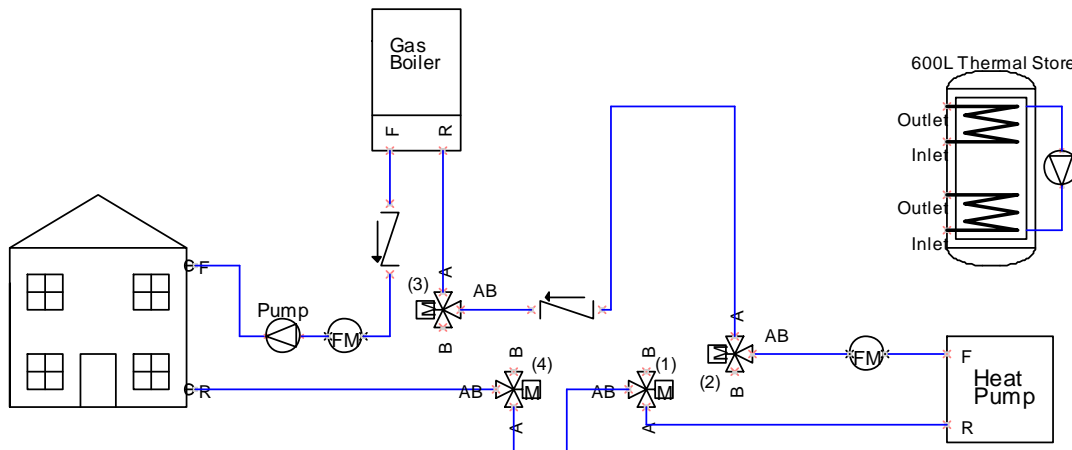
Figure 3-17 Hybrid HP and gas series mode (lines removed for illustration). This mode was run as experimental with the purpose of achieving a higher HP COP and improved heat power for the house rather than for DSM purposes. In this mode all 3-PV's are powered, and the central heating water circulates through the HP where it is heated firstly, and then through the gas boiler where it is further heated. In this situation both the HP internal variable speed water circulation pump and the main central heating circulation pump will be on. However, it was envisaged that the variable speed circulation pump in the HP would regulate down to its lowest level to achieve the desired delta T across the HP flow and return.

Figure 3-18 Hybrid circuit schematic. The circuit diagram detailed in Figure 3-10 was modified to control the modified gas boiler/HP hybrid system detailed in Figure 3-14. Two additional 3 port valves were added (BR1 and BR2) along with 2 additional relays (relay D and relay E). The manual changeover switch located in the boiler room was also replaced with a double-throw double-pole changeover switch. The circuit allows complete automated control of the system using the custom-built controller and software. The controller has the ability to control the circuit via the DC 6-volt circuit which will switch relays A, C, D, E, using digital output pins 11, 12, 13, 15, respectively depending on the desired operation mode calculated by the controller software. The manual changeover switch allows the automated control of the system in one position and standard gas boiler function in the other (automated control circuit is isolated). This allows the house heating system to have a backup in the event of controller or HP failure or for HP servicing purposes.
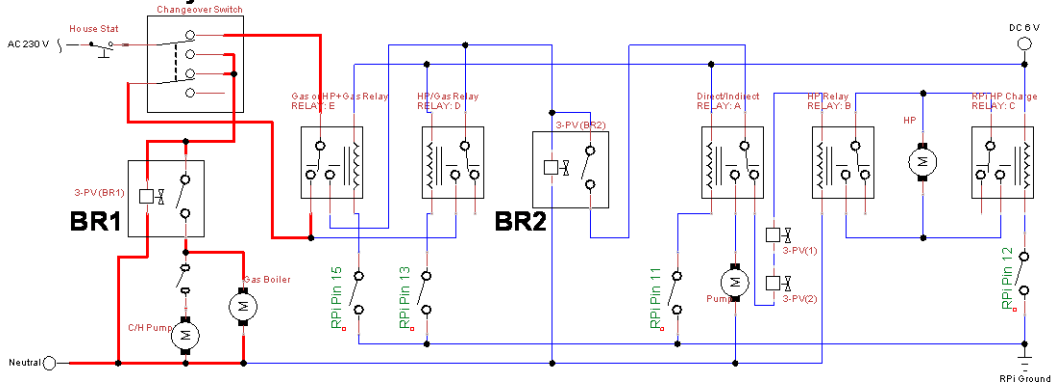
Figure 3-19 Gas boiler only mode (energised AC 230 V shown as red line). This is the default mode of the system which will be active with no input from the controller (Relay E not energised). When a call from heat comes from the house (Figure 3-4) 3-PV (BR1) will be energised and move to port position A (see Figure 3-15) and the internally linked valve switch will close subsequently powering the gas boiler and central heating pump. Wiring the gas boiler and central heating pump via the 3-PV internal switch provides safety in the event of valve malfunction (will not come on until 3-PV (BR1) is in port position A).
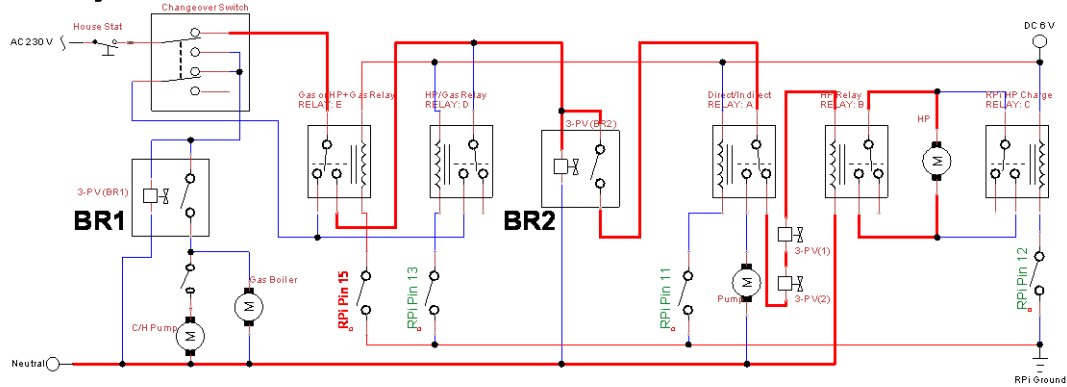
Figure 3-20 HP only mode (energised AC 230 V; thick red line, energised DC 6 V; thin red line). In this mode the HP will heat the house directly as in Figure 3-6. When this mode is required the controller will activate digital output pin RPi Pin 15 thereby energising and switching Relay E. This in turn will energise 3-PV (BR2) which will move to port position A (see Figure 3-16) and the internally linked valve switch will close. If Relay A is not energised the HP will come on and provide heat directly to the house central heating system. If the thermal store was to be used instead of the HP in this situation, this could be achieved by energising Relay A (as detailed in Figure 3-13). Wiring the HP/thermal store via the internally linked switch of 3-PV (BR2) provides safety in the event of valve malfunction (will not come on until 3-PV (BR2) is in port position A).

Figure 3-21 Gas boiler and HP hybrid series mode (energised AC 230 V; thick red line, energised DC 6 V; thin red line). In this mode the HP feeds the gas boiler return which then circulates heated water to the house central heating system as detailed in Figure 3-17. This is achieved by switching Relay E and Relay D via controller digital output RPi Pin 15 and RPi Pin 13 respectively. With both relays switched, a call from heat from the house circuit results in 3-PV (BR2) moving to port position A and subsequently the internal switch of the valve causes the HP to come on. Additionally, 3-PV (BR1) will also be activated and move to port position A and subsequently the internal switch of the valve will cause the central heating pump and gas boiler to come on. It should be noted that in this mode both the HP internal water circulation pump and central heating pump will be active. However, it was envisaged that the variable speed circulation pump in the HP would regulate down to its lowest level to achieve the desired delta T across the HP flow and return.

3.4   Demand Side Management Controller

In order to control the circuits outlined in section 3.3 a controller was required to switch the relays in the circuits and thereby operate the various heating modes. The controller was required to switch to the various heating modes based on a DSM response reflective of real-time and forecast electricity data available from the electricity grid system operator. Thus, the controller needed to be able to communicate and retrieve data in order to respond to the state of the electricity grid in near real-time and this was best achieved by using a network connected controller (internet connected). As the DSM scenarios were concept ideas, modification and adaption for the purposes of experimentation and improvement was desirable and therefore a controller which was software controlled was ideal. In addition, a controller which was cheap and readily available and practically feasible, in a mass deployment situation, was desirable. After some research a Raspberry Pi computer was chosen as an appropriate match to this specification. Prototype software was developed to run on the Raspberry Pi to meet the aims of the research which was improved as the project progressed. The controller design and development are outlined in the sections that follow.

3.4.1   Raspberry Pi and Hardware Components

The Raspberry Pi is a low cost, credit card size, high performance computer developed by the Raspberry Pi Foundation (Raspberry Pi Foundation, 2017). It has a range of models which have developed from the initial launch of the Raspberry Pi A+ in 2010 (launch price; $20) through to the most powerful current model the Raspberry Pi 3 (launch price; $35). The Raspberry Pi Zero W (launch price; $10), a micro, low power version, is a notable addition to the range launched in February 2017. With built in Wi-Fi and Bluetooth connectivity, albeit much slower than the most powerful model, it is envisaged it could meet the requirements of this project at a significantly reduced price.

For this project the Raspberry Pi 2 Model B was used, the most recent and powerful model at commencement of the controller prototyping. The model specifications include; a 900MHz quad-core ARM Cortex-A7 CPU, 1GB RAM, 4 USB ports, 40 GPIO pins, full HDMI port, Ethernet port, combined 3.5mm audio jack and composite video, camera interface, display interface, micro SD card slot, and VideoCore IV 3D graphics core. The Raspberry Pi comes as a bare board and requires a micro-SD card to load and run the operating system on, with a minimum size of 8GB class 4 recommended however smaller sizes can be used with lightweight operating systems. The recommended operating system is Raspbian; it is a free operating system optimised for the Raspberry Pi and is actively developed to maintain stability and performance. Additional operating systems are available to choose from (too many to detail)

however the recommended system Raspbian was chosen predominately for reliability purposes. In addition to the micro-SD card, a 5V DC PSU (power supply unit) with a recommended 2 Amp capacity, are the minimum essentials required for the computer to operate.

To increase functionality of the device, a wireless USB Wi-Fi adapter and 'Custard Pi 2' add-on board was included. The Wi-Fi adapter was not necessarily required as a wired Ethernet connection was used. The 'Custard Pi 2' board plugs into the Raspberry PI GPIO to provide analogue and digital inputs and outputs whilst protecting the Raspberry Pi from possible damage from the wrong voltage being accidentally connected to the GPIO. The add-on board provides 4 open collector digital output pins using a ULN2801 IC which provides a current capability at the output pins of 500 mA and maximum voltage of 50V. The limit of the Raspberry Pi GPIO pins is a current capacity of 16mA at each pin (50mA across all pins) and maximum voltage of 3.3V. The Custard Pi add-on board inclusion was therefore necessary to provide the function of a relay driver as the Raspberry Pi pins would not have this capability. Although a custom circuit could have been designed using the ULN2801 chip at a greatly reduced price to the add-on board (ULN2801 approximate price; £0.64), the readymade board was justifiable in terms of speeding up the controller design at the prototype stage.

The controller was required to provide a means of charging and discharging the thermal store using software. For charging and discharging a temperature feedback was therefore required for the thermal store. The chosen temperature sensor was a Maxim DS18B20 1-wire digital. The sensor provides a range of -55 to +125°C with an accuracy of ±0.5°C (-10 to +85°C) and requires a power supply ranging between 3V to 5.5V. Coupled with its relative low-cost, and ease of integration with the Raspberry Pi, it provides an ideal means of temperature feedback for the controller software.

The final components required to control the circuits outlined in section 3.3 were the DC switching relays. Two relays were required for the first stage of the heat pump retrofit (Figure 3-10) and an additional two for the hybrid heat pump gas boiler setup (Figure 3-18). The circuit required single-pole double-throw relays (SPDT) however due to insignificant cost difference, double-pole double-throw relays (DPDT) were used in the design. Relays capable of switching 8 Amps were chosen which was more than adequate for the heating circuit which is fused at 3 Amps. DIN rail sockets for holding the relays were also required for positioning within a safe insulated wiring enclosure. In addition, relay coil suppression

modules were also included as a precaution to protect the Raspberry Pi and Custard Pi boards from potential large voltages created when electro-mechanical relays are de-energised.

A list of the components used with prices at the time of purchase in 2015 can be found in Table 3-7. The total price amounts to £112.14 inclusive of VAT which is relatively low cost for a custom prototype controller and components sourced at full un-discounted prices. It is envisaged however that using for example a Raspberry Pi Zero W and producing or sourcing a cheaper relay driver and relay combination board that the price could be significantly reduced.

Table 3-7 List of hardware components used to construct the Raspberry Pi based DSM controller including prices at the time of purchase in 2015.

Hardware Components	Price (ex-VAT)	Quantity	Total (ex-VAT)
Raspberry Pi 2 Model B Quad Core 1GB RAM	£26.40	1	£26.40
Kingston SDC4/8GB micro SDHC Card (Class 4) - 8GB	£3.81	1	£3.81
Raspberry Pi Model B+ Power Supply 5V 2A Micro USB	£5.99	1	£5.99
Custard Pi 2 Analogue and Digital I/O for the Raspberry Pi B or B+	£19.00	1	£19.00
Raspberry Pi Model B+ / 2 Case Clear	£4.99	1	£4.99
LogiLink® Wireless LAN USB 2.0 Nano Adapter 802.11n	£6.79	1	£6.79
Maxim DS18B20+PAR Temperature Sensor 3-Pin	£2.79	1	£2.79
Finder Relay 40.52 40.61 Series Socket Type 95.85	£2.02	4	£8.08
Finder 99.80.9.024.99 Coil Indication and EMC Suppression Module 6-24VDC	£1.52	4	£6.08
Finder 095.91.3 Retaining and Release Clip for Sockets 95.85 and 95.95.3	£0.15	4	£0.60
Finder 6V Relay (Miniature) DPDT DC 8A	£2.23	4	£8.92
		TOTAL (ex-VAT)	**£93.45**
		VAT	**£18.69**
		TOTAL (+VAT)	**£112.14**

The prototyping and setup of the controller is illustrated in Figure 3-22 to Figure 3-24. In Figure 3-22 bench testing was carried out to test the combination of software control with the relays in response to feedback from the thermal store temperature sensor. Figure 3-23 shows the controller in place with the main 230V circuitry and control relays contained within an insulated wiring enclosure. A single four core shielded cable was used to connect the relay coils (1 per relay) to the controller digital outputs. The cable shield was connected to the

Raspberry Pi ground to reduce electrical interference. The relays require a 6V DC supply to energise the coils and this is provided by a separate power supply unit. The controller has a hard-wired network connection although a Wi-Fi connection is also available. The temperature sensor runs to a sealed port on the thermal store located approximately half way up the tank. The port allows dry insertion of the sensor into the centre of the tank allowing an accurate average water temperature to be obtained. Figure 3-24 shows the inside of the wiring enclosure which contains the main connections for the electric circuits described in section 3.3. The use of the wiring enclosure allowed for modification of the circuit as required however it is envisaged a final PCB circuit solution would be a much neater and compact design.
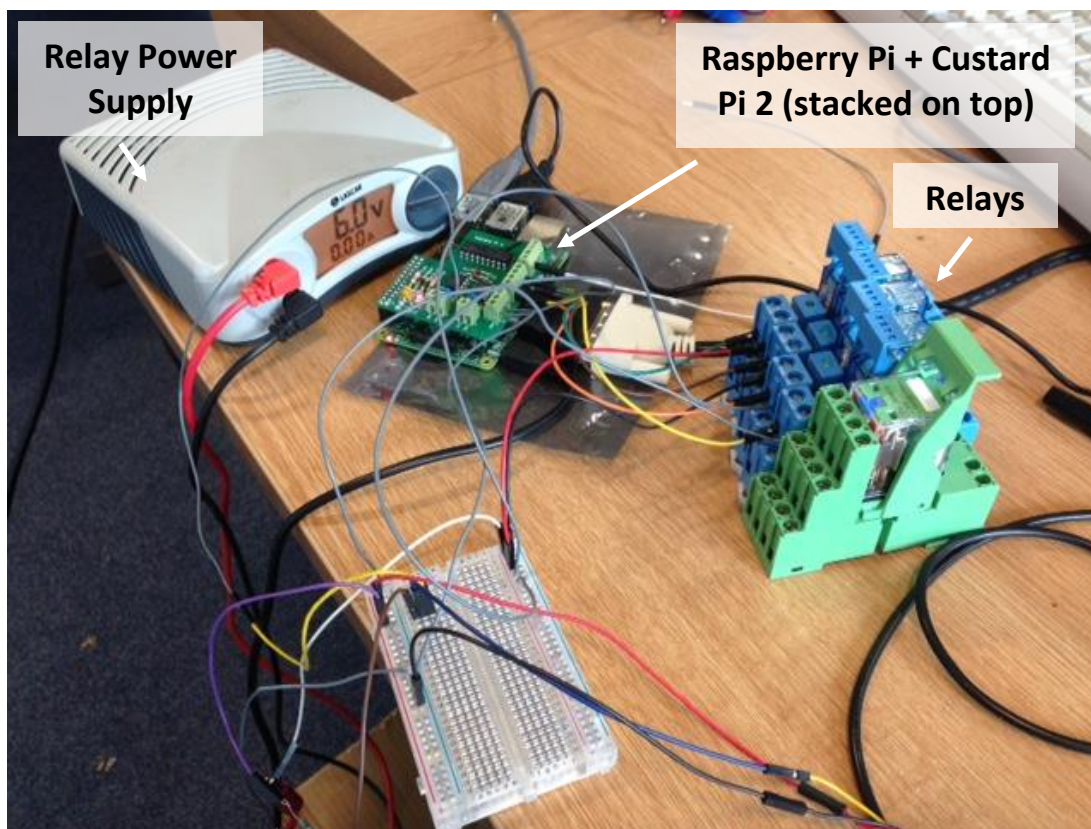
Figure 3-22 Raspberry Pi based DSM controller prototyping and testing.
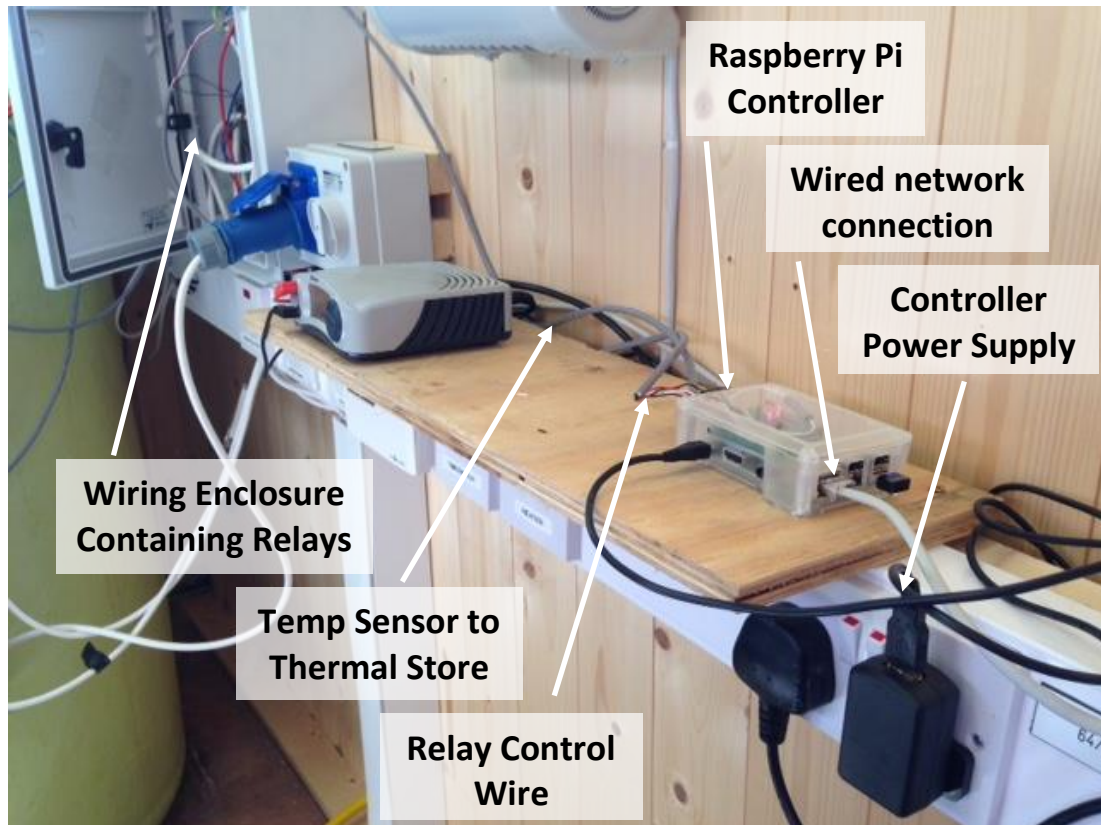
Figure 3-23 Raspberry Pi based DSM controller in place. Main wiring and relays contained within insulated enclosure.
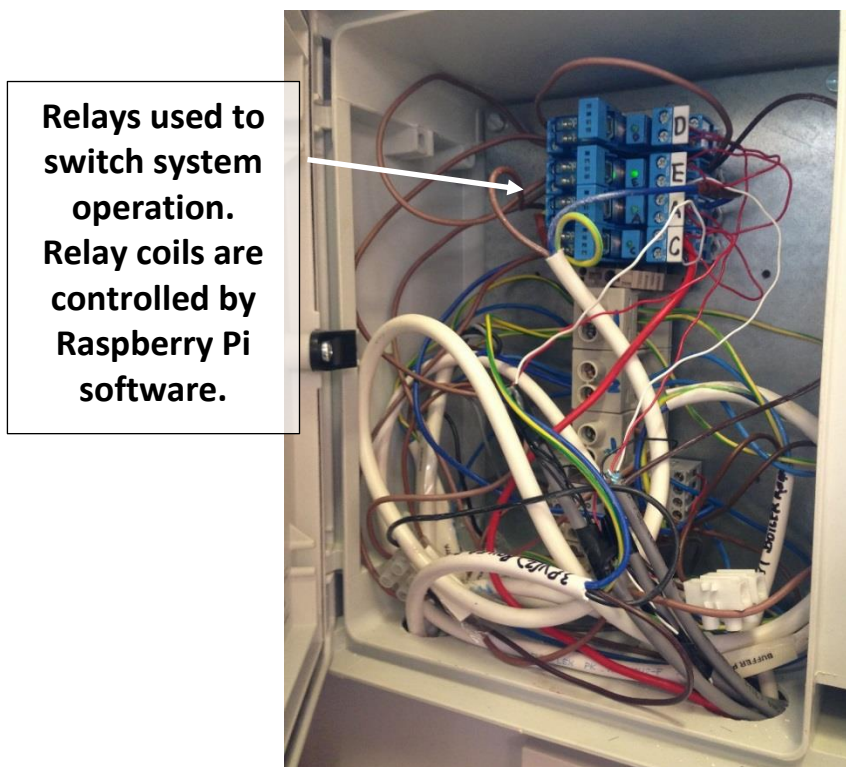
Figure 3-24 View inside wiring enclosure. Relays labelled A, C, D, and E, are consistent with labelling in circuit diagrams.

3.4.2 Raspberry Pi Control Wiring

The system setups described in section 3.3.1 (High Temperature ASHP) and 3.3.2 (Hybrid ASHP & Gas Boiler) are controlled by the Raspberry Pi DSM controller, achieved by switching the relevant relays in the circuits detailed in Figure 3-10 and Figure 3-18 respectively. A plan view of the Raspberry Pi controller and attached Custard Pi 2 board is shown in Figure 3-25. The relays are energised by one of the four digital outputs highlighted in the figure. The digital outputs are an open collector connecting the 6V supply required to power the relays (through each relay coil) to ground thus acting as a relay driver. The digital output pins can be thought of as a switch in this situation. Each of the digital outputs are connected to the Raspberry Pi's GPIO pins 11, 12, 13, and 15. The GPIO pins are controlled by software which is written and run on the Raspberry Pi. The GPIO pins are set as outputs in the software and can be taken high or low. When a GPIO pin is taken high it will in effect close the switch of the digital output and activate the coil of the attached relay and in turn switch the relay contacts. The GPIO pin will remain high until instructed to go low and vice versa.
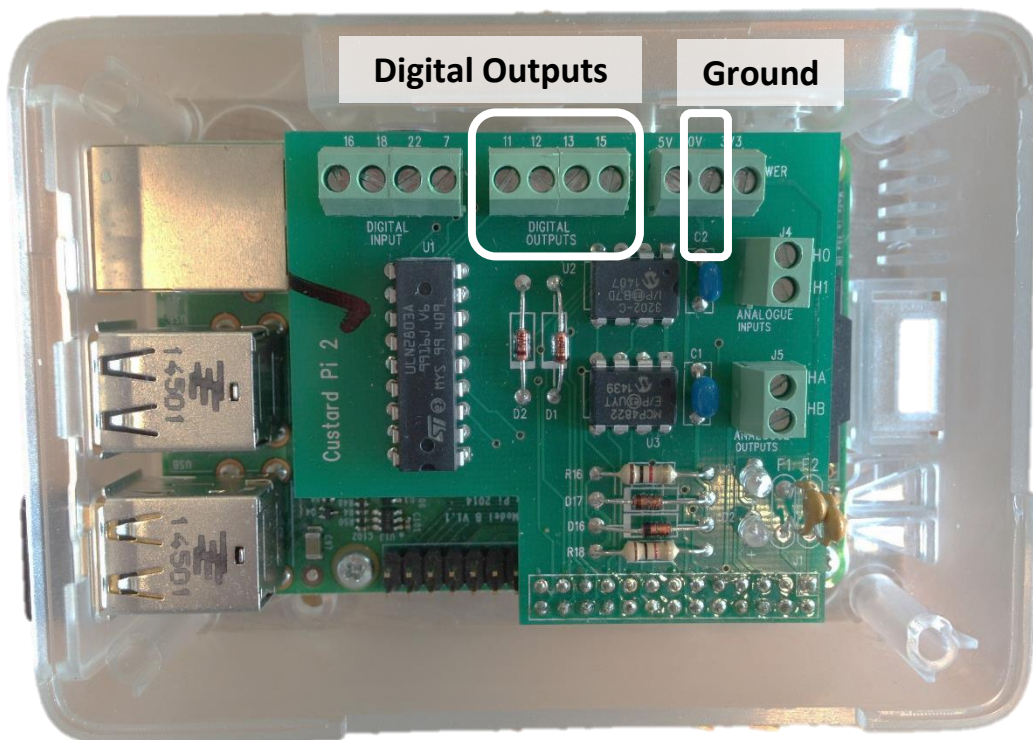
Figure 3-25 Top view of Raspberry Pi Controller with Custard Pi stacked on top (digital outputs are highlighted). The digital outputs 11, 12, 13, 15 are controlled by the Raspberry Pi GPIO pins 11, 12, 13, 15 respectively. The outputs are controlled by software running on the Raspberry Pi.

Figure 3-26 and Figure 3-27 show the control side circuit of the ASHP/thermal store setup and ASHP/gas-boiler/thermal store setup respectively. The digital outputs highlighted in Figure 3-25 are represented by a simple switch. By closing the switch (taking relevant GPIO pin high) the relay coils will be energised.
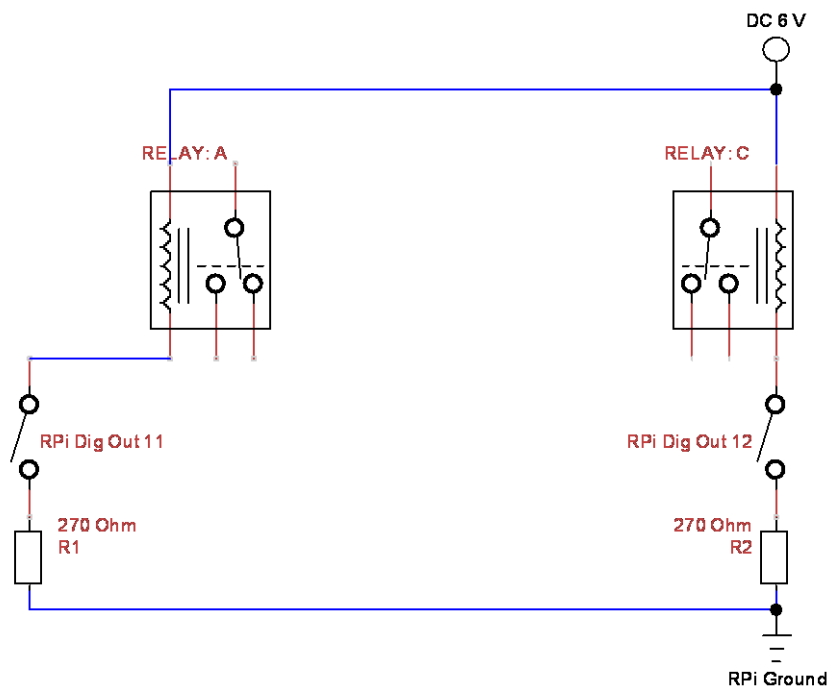
Figure 3-26 Raspberry Pi control circuit for ASHP retrofit and thermal store control setup detailed in section 3.3.1 (part of circuit detailed in Figure 3-10). Labels RPi Dig Out 11 and RPi Dig Out 12 refer to digital outputs 11 and 12 in Figure 3-25 respectively. The outputs act as an open-collector, taking the outputs high will energise the respective relay coil with the 6V supply and switch the relay contacts.
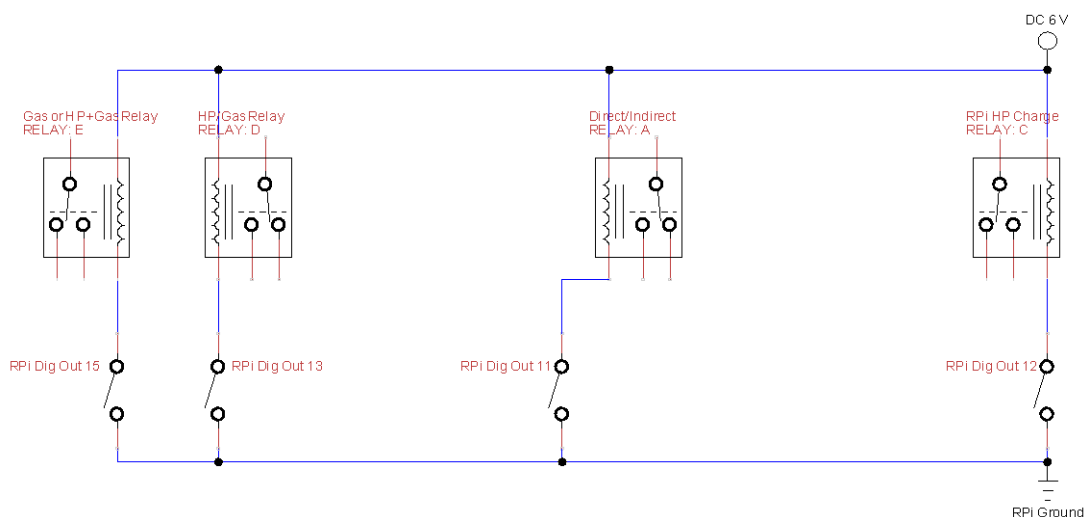
Figure 3-27 Raspberry Pi control circuit for hybrid ASHP/gas boiler control setup detailed in section 3.3.2 (part of circuit detailed in Figure 3-18). Labels RPi Dig Out 11, 12, 13, 15 refer to digital outputs 11, 12, 13, 15 in Figure 3-25 respectively. The outputs act as an open-collector, taking the outputs high will energise the respective relay coil with the 6V supply and switch the relay contacts.

3.4.3 DSM: EirGrid SmartGrid Dashboard

The main aim of the research project was to develop a means of providing a real-time or dynamic demand side management system using an ASHP. Fundamental to this was access to the electricity grids data in order to make the desired DSM response. In Northern Ireland and Ireland SEMO (Single Electricity Market Operator), part of the EirGrid Group, operates the Single Electricity Market across the island. Comprehensive electricity market data is freely available on the SEMO website (SEMO, 2017). EirGrid also provide online access to some of the main grid data through its 'Smart Grid Dashboard' (EirGrid Group, 2017). The EirGrid dashboard is shown in Figure 3-28, it is quite user friendly and was most suitable for providing the data required for the controller. The website provides access to actual and forecast system demand, actual system generation, actual and forecast wind generation, actual interconnection import/export with Great Britain, historical grid frequency, electricity SMP (system marginal price), and electricity CO_2 intensity. The data can be viewed for Northern Ireland, Ireland, or on an all island basis. It should be noted however that SMP market price is a single price set across the island. The website is updated every 15 minutes with forecast data calculated in 30-minute intervals and actual data available recorded in 15-minute intervals.
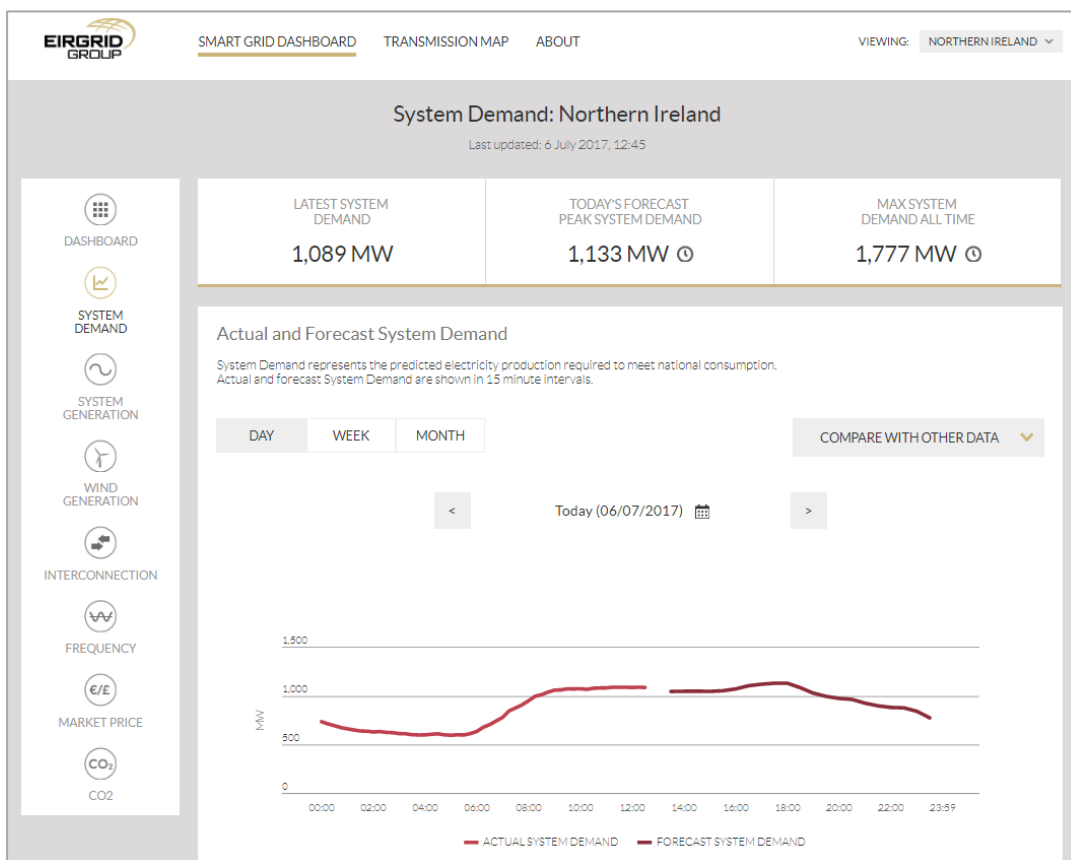
Figure 3-28 EirGrid 'Smart Grid Dashboard' (EirGrid Group, 2017)

The first stage of this project involving the ASHP and thermal store utilised the system demand data to provide the input for the DSM algorithm (detailed in section 3.4.4). The rational was to reduce the impact of the heat pump on peak system demand by utilising the thermal store to meet any heat requirement at this time. The thermal store would be charged at the lowest system demand in the day and the thermal store would be discharged at the highest peak demand in the day. By charging the tank at the lowest system demand in the day the idea was to:

1. Limit the impact of the heat pump electricity load on the grid.
2. Avoid house heat demand conflict by charging when occupants are sleeping and likely to have heating turned off (i.e. at lowest daily heating demand).
3. Create an electricity demand on the grid at a time when curtailment of wind electricity is generally greatest and in effect provide a means of utilising renewable wind electricity which would otherwise be curtailed.

The amount of thermal energy that could be shifted was limited by the storage capacity of the thermal store and thermal losses between charge and discharge time. The shed in which the HP and thermal store was housed was maintained at a constant ambient temperature of 17°C using thermostatically controlled electric radiators. The thermal store was set to charge to 75°C and discharge down to 55°C giving a theoretical max heat storage capacity of 13.961 kWh with no heat loss (Table 3-6). The higher temperature is at the upper limits of the heat pump capacity but was chosen to maximise heat storage and also provide a temperature suitable for radiator heat emission. Conversely the lower temperature approaches the point at which the radiators will be able to emit a useful amount of heat to the rooms in the house whilst at the same time ensuring a good heat storage capacity. An initial test using the heat pump to charge the tank indicated an approximate charging time of 2 hours.

In order to ensure the heat pump was charging at the lowest grid demand in the day and discharging at the highest grid demand in the day, a method was required for the controller to be able to calculate the most suitable time to switch the heat pump and thermal store onto the relevant system mode. To do this the forecast daily electricity demand data for Northern Ireland was downloaded from the EirGrid Smart Grid Dashboard website page (Figure 3-28). Initially, using the heat pump and thermal store system only, the grid demand data was downloaded, from the EirGrid website, from the controller's current point in time forward for 24 hours. For example, if the current time was 13:01 the data downloaded would run from 13:00 through to 12:30 the next day inclusive (forecast data is only provided in half

hour intervals on the half hour). If the controller's current time was 13:30, the data downloaded would run from 13:30 through to 13:00 the next day and so on. This provided a total of 48 forecast electricity data points for 24 hours ahead. The controller performed this operation every minute even though the data was only updated on the half hour. The reason for this was twofold: the first was that on each loop (every minute) the controller was also acquiring the temperature of the thermal store and therefore needed to respond to its decreasing or increasing temperature at this higher resolution; the second was due to reliability of the EirGrid Smart Grid website which could be occasionally unresponsive to data requests and therefore with the 1 minute intervals the controller was much more likely to have the data for the relevant half hourly interval.

A simple calculation needed to be performed on the grid data, downloaded from the EirGrid website, in order to determine 'when to store' in the thermal store and 'when to use' the thermal store based on the lowest and highest forecast demand respectively. Examining Figure 3-28 it was evident that the relevant points on the demand profile take the form of either a valley ('when to store' window) or a peak ('when to use' window). Therefore, simply choosing the minimum or maximum value would not equate to a period of time at the lowest or highest demands in the day (i.e. they would start too late). A more ideal calculation would provide a window that started before and finished after the minimum or maximum value semi-symmetrically.

Trial and error on a sample of forecast electricity data, illustrated in Figure 3-29, led to the selection of a percentile calculation being suitable to fulfil the prior stated requirements. *A kth percentile calculation* ranks the data in order from smallest to largest and calculates a value which effectively can be used to split the data into two pieces. For example, the *50th percentile*, also known as the median, will be a value which separates a dataset where we can say 50% of the data is above this value and 50% of the data is below this data. When we consider our forecast electricity dataset consisting of 48 half-hourly data points (i.e. 24 hours) the *50th* percentile would be a value where 24 data points lie above this value (equating to a 12-hour interval) and 24 data points lie below this value (equating to a 12-hour interval). It can be calculated then that each 2.08% (100/48) represents a half-hour interval in the dataset i.e. a 2.08% percentile would be a value were 1 data point lies below this value and 47 lie above it.
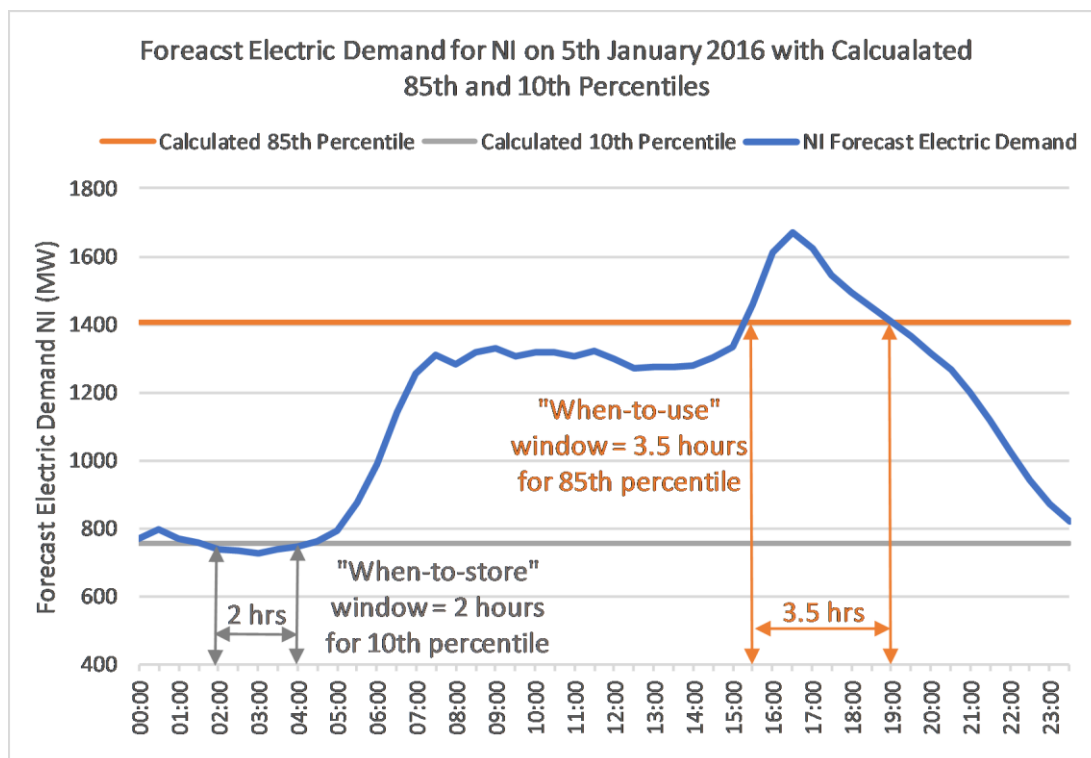
Figure 3-29 Illustration of percentile calculation used for deciding when-to-store and when-to-use heat to and from the thermal store. The data is a sample day of downloaded forecast grid demand data from the EirGrid website for 5th January 2016.

The 'when to store' window had to take into account the charging time of the thermal store i.e. it had to be a wide enough timeframe to charge the tank to 75°C but not so wide that the heat pump would cycle on and off trying to maintain a temperature of 75°C after it had been reached. Using the initial charge test of the thermal store, a timeframe of around 2 hours was chosen to be suitable. When we consider using the percentile calculation this equates to 4 data points (4 × 0.5hrs = 2hrs) and in terms of a percentile this equates to 8.32% percentile calculation (4 × 2.08%). For the calculation the 10th percentile was therefore chosen to be suitable. The 'when to store' window was therefore determined effectively by the 10th percentile threshold value below which the heat pump would store heat in the tank if the tank temperature was below 75°C. The comparative value for the 'when to store' threshold value was the 'forecast demand now' (the current demand forecast i.e. at time of data request) which was the first data point returned in each data column downloaded. Therefore, if the 'forecast demand now' is less than the 'when to store' threshold value and the tank temperature is less than 75°C then the heat pump would charge the thermal store.

The 'when to use' window was more difficult to establish as there were a few more parameters and uncertainties to consider, including:

1. Desire to use thermal store at peak demand to avoid heat pump impacting upon peak electricity demand but no guarantee there will be a household heat demand at this time. If there is no demand from the house for heat, we avoid this problem but the energy in the thermal store will not be utilised until the subsequent day and will be reduced due to thermal losses from the store. This favours a wider 'when to use' window so that it is more likely the heat will get utilised.

2. A wider 'when to use' window will mean the thermal store may be used too early and exhausted before peak grid electricity demand is reached. In this instance if there is still heat demand from the house the heat pump will end up impacting upon peak electricity demand. This favours a more precise, narrower 'when to use' window were the stores use would be maximised by using it at the highest peak demands in the day.

3. The 'when to store' window occurs at lowest system demand which is known to occur in the early morning whereas the peak grid electricity demand occurs in the evening. This results in around a 12-hour delay between charging and using the thermal energy stored in the tank. Heat loss from the thermal store is therefore going to reduce the overall thermal efficiency of the system. This favours using the thermal store at the first heat demand from the house.

4. In the event of a house heating demand the discharge properties of the system to the central heating system were not fully known. This includes the tanks thermal power discharge, the amount of heat required by the house to satisfy the dining room or DHW tank thermostats, or the users heating preferences. This uncertainty again favoured a wider 'when to use' window in order to reduce it.

3.4.3.1   HP/Thermal Store: Grid Demand Based DSM

Considering these points an initial test was run using the 90th percentile to calculate the threshold value over which the thermal store would be used. This equated to 2hrs of activation in which if there was a call for heat and 'forecast demand now' was greater than 90th percentile threshold value and the thermal store was above 55°C, the thermal store would be discharged to the house central heating system. This was altered to an 85th percentile calculation equating to a 3.5 hour 'when to use window', this is illustrated in Figure 3-29. Although the adjustment meant that there was the possibility the thermal store would be used before peak electricity demand, the wider window meant the energy stored would more likely be used on the same day it was stored, reducing storage losses, and the use of

the thermal store was more flexible in terms of the heat demand coming from the house (user preference, thermostat cycling).

3.4.3.2   HP/Thermal Store: Low Grid Demand Charging Only

Consideration was also given to point 3 were the heat loss from the tank favoured using the thermal store at the first heat demand in the day to maximise energy efficiency. A trial using this operation was also carried out. The system stored heat at the electricity grid low forecast demand, as previously specified, but the thermal store was discharged for any heat demand after this until the tank temperature reached 55°C. In this situation the demand shift is from the lowest demand in the day to any time when heat is required in the house. It is not as beneficial in terms of avoiding the HP impacting upon peak system grid demand, but it provides a baseline to assess the feasibility of using the thermal store with the HP. In other words, if this particular situation is not feasible in terms of energy efficiency, demand shifts with increased duration between energy storage and energy discharge will suffer from even poorer energy efficiency (i.e. energy efficiency reduces as the duration between energy storage and energy discharge increases).

3.4.3.3   HP/Gas Boiler Hybrid Mode: System Demand Signal

When the system was modified and upgraded to bring the gas boiler into the system, as detailed in section 3.3.2, there was much greater flexibility with regards to the DSM strategies that could be trialled. In this situation, initially, the thermal store was effectively replaced by the gas boiler in terms of the DSM strategy. As the gas boiler does not suffer any standing energy loss, like the thermal store, it provides an ideal energy source to avoid the impact of the electric HP on the electricity system. The gas boiler can come online at any time, as it has infinite energy storage, and provide the necessary and desirable DSM function as quickly as the signal is issued to the controller. For instance, the DSM or DSR function could be based on electricity demand, electricity market price, or frequency response. Demand is quite static with a well-defined daily profile and is ideal for storage with early charging and later discharging. However, market price is more volatile, changing on a daily basis, with price spikes possibly occurring at any time of the day. This does not lend itself well to a store/discharge strategy were a price spike could precede a price trough. Frequency response is an even greater challenge requiring DSR down to the second.

Initially the DSM strategy of the system replicated that of the HP/thermal store system were the gas boiler would come on in place of the HP at peak system grid demand (85th percentile).

However, no thermal storage occurred at the lowest system grid demand and the HP supplied heat to the house directly at all other times.

3.4.3.4 HP/Gas Boiler Hybrid Mode: Market Price Signal

Following on from the previous system demand-based strategy a DSM strategy using day ahead market price was employed. The strategy replicated the DSM demand strategy but replaced the forecast demand signal with forecast electricity price signal. The method of sourcing the signal changed slightly in this situation were previously the demand signal was sourced for 24 hours ahead (as detailed in section 3.4.3) the price signal was now acquired for the current day (00:00 to 23.45) and only rolled over on the following day (i.e. at 00:00). The data was still acquired every minute so that any updates that may have occurred in the market price forecast throughout the day were not missed.

The specific controls for this strategy entailed the gas boiler coming on at peak electricity price (85th percentile) with the HP providing heat, when required, at all other times of the day. No thermal storage occurred.

3.4.3.5 HP/Gas Boiler/Thermal Store Hybrid Mode: System Demand & Market Price Signal

This strategy was trialled to assess how the system would perform when combing the HP, gas boiler, and thermal store using signals from both the forecast system demand and the forecast market price. The thermal store was charged based on low system demand, lowest 10th percentile, as previously described. The thermal energy was then discharged based on peak forecast system demand or peak forecast market price, both 95th percentile in the day ahead. Once the thermal store was completely discharged the gas boiler was activated and used until outside of the peak demand and peak price windows. Outside of the peak windows the HP heated the house directly.

The peak percentile calculation was increased to the 95th percentile as there is two windows now, demand and market price. Reducing to 95th percentile means two windows of 1.5 hours, 3 hours in total. The windows are based on OR logic, therefore peak demand and peak price may occur at the same time and the window would be shorter on that day.

The thermal store was charged to 75°C and discharged down to 65°C (previously 55°C). The discharge set-point was increased as the DHW tank control thermostat was set to approximately 65°C and the trial was run during the summer months and therefore there was no space heating demand. If the thermal store was discharged at a lower temperature than the DHW tank temperature the discharge pump would run until the thermal store and DHW tank reached thermal equilibrium and therefore would not work effectively.

Although the algorithm was designed for this strategy (Figure 3-33) the experiment was not run due to time constraints.

3.4.3.6   Additional Testing: Hybrid HP/Gas Boiler in Series Test

The hybrid series mode was run for curiosity to see how the system would perform without a common optimised controller between the HP and gas boiler. In this mode the HP was run in series with the gas boiler (HP feeding return of gas boiler). The series test was run without any DSM for 1 month.

3.4.3.7   Summary of DSM Strategies

A summary of the DSM strategies presented in sections 3.4.3.1 to 3.4.3.6 is outlined in Table 3-8. The table provides an outline of the key parameters used to create the DSM shifts, the temperature set-points of the HP, thermal store, and gas boiler. Included also is the data-source used and the duration of the testing.

Table 3-8 Summary of DSM strategies using HP, thermal store, and gas boiler with forecast grid demand and market price signals (section: 3.4.3.1-3.4.3.6).

Description	SR[1]	HP[2]	Thermal Storage[3]	Gas[4]	Demand Signal		Market Price Signal		Data Source[7]	Date		Days
					LP[5]	HP[6]	LP[5]	HP[6]		From	To	
HP + Thermal Storage NI forecast grid demand	3.4.3.1	76	75/55		0.1	0.9			EirGrid (24 hours ahead forecast)	09/06/2015	11/06/2015	2
HP + Thermal Storage NI forecast grid demand	3.4.3.1	76	75/55		0.1	0.85			EirGrid (24 hours ahead forecast)	11/06/2015	01/12/2015	173
HP + Thermal Storage NI forecast grid demand (thermal store discharged at first call for heat)	3.4.3.2	76	75/55		0.1				EirGrid (24 hours ahead forecast)	01/12/2015	27/09/2016	301
HP/Gas Boiler Hybrid Mode: System Demand Signal	3.4.3.3	76		76		0.85			EirGrid (24 hours ahead forecast)	14/03/2017	13/04/2017	30
HP/Gas Boiler Hybrid Mode: Market Price Signal	3.4.3.4	76		76				0.85	EirGrid (00:00 to 23:45 all-island SMP)	13/04/2017	17/07/2017	95
HP/Gas Boiler/Thermal Store Hybrid Mode: System Demand & Market Price Signal	3.4.3.5	76	75/65	76	0.1	0.95		0.95	EirGrid (00:00 to 23:45 all-island SMP and system demand)	Not run	Not run	N/A
HP + Gas Boiler in series test	3.4.3.6	65		75						24/11/2016	31/12/2016	37

[1]Section reference; [2]Heat pump flow set-point (℃); [3]Thermal store charge-to-set-point/discharge-to-set-point (℃); [4]Gas boiler flow set-point (℃); [5]Low-percentile calculation parameter; [6]High-percentile calculation parameter; [7] (EirGrid Group, 2017); Grey shading – parameter not applicable

3.4.4 Controller Software Design

In order to implement the DSM strategies outlined in the previous section an algorithm was required to decide on the action to be taken based on the electricity grid signals and thermal store tank temperature sensor, correspondingly creating outputs in the form of switching the relevant relays on or off to control the systems electrical circuits. In addition, the software required suitable error handling so that if the controller failed, the house would still have a heating source available. Python, a high-level programming language, was chosen as suitable to code the algorithm due to being easy to read and write yet being suitably powerful to achieve the aims of the project.

The algorithm designed to control the HP and thermal storage system (Figure 3-9, Figure 3-10) is illustrated in Figure 3-30. The flow chart shows the logic used in order to decide when to charge and discharge the thermal store based on the electricity forecast system demand and the thermal store temperature. The programme loops and repeats every minute switching the digital outputs high or low depending on the programmed logic. Several modules were written to perform the necessary tasks, and these were called by the 'main' programme which calculated the desired outcome (the logic). The modules include:

- 'temp_buffer.py'; reads DS18B20 digital temperature sensor placed in thermal store
- 'webdata.py; reads data from EirGrid SmartGrid website, performs necessary data manipulation and calculation, and outputs if there is a 'benefit-to-store' (charge thermal store) or a 'benefit-to-use' (discharge thermal store) or else if neither 'sleep'
- 'mail.py'; sends email alerts to pre-set email address
- 'logger.py'; logs timestamp, input parameters, sensor data, logic output, stores locally and on additional network computer (backup)
- 'main.py'; calls required modules (above), performs logic, performs the necessary outputs, and provides error handling

Not shown in Figure 3-30 is the error handling created to deal with network connection problems (no internet connection, EirGrid website down for example) or abnormal sensor readings. Errors such as these were handled with error counters, passing over the error until a pre-set maximum count was reached, then subsequently taking all digital outputs low on the controller thus reverting the system to a default mode. The default mode of the system is to heat the house directly with the HP (no thermal storage or discharge) and this is the hard-wired mode when the relays are not energised. The programme would also send an alert email indicating the problem so that it could be rectified as soon as possible. Minor

errors, for example in data logging, were passed over so the system could continue to run in the DSM mode. Any unhandled errors causing the software to crash simply switched all digital outputs low, sent an alert email, and exited the program.
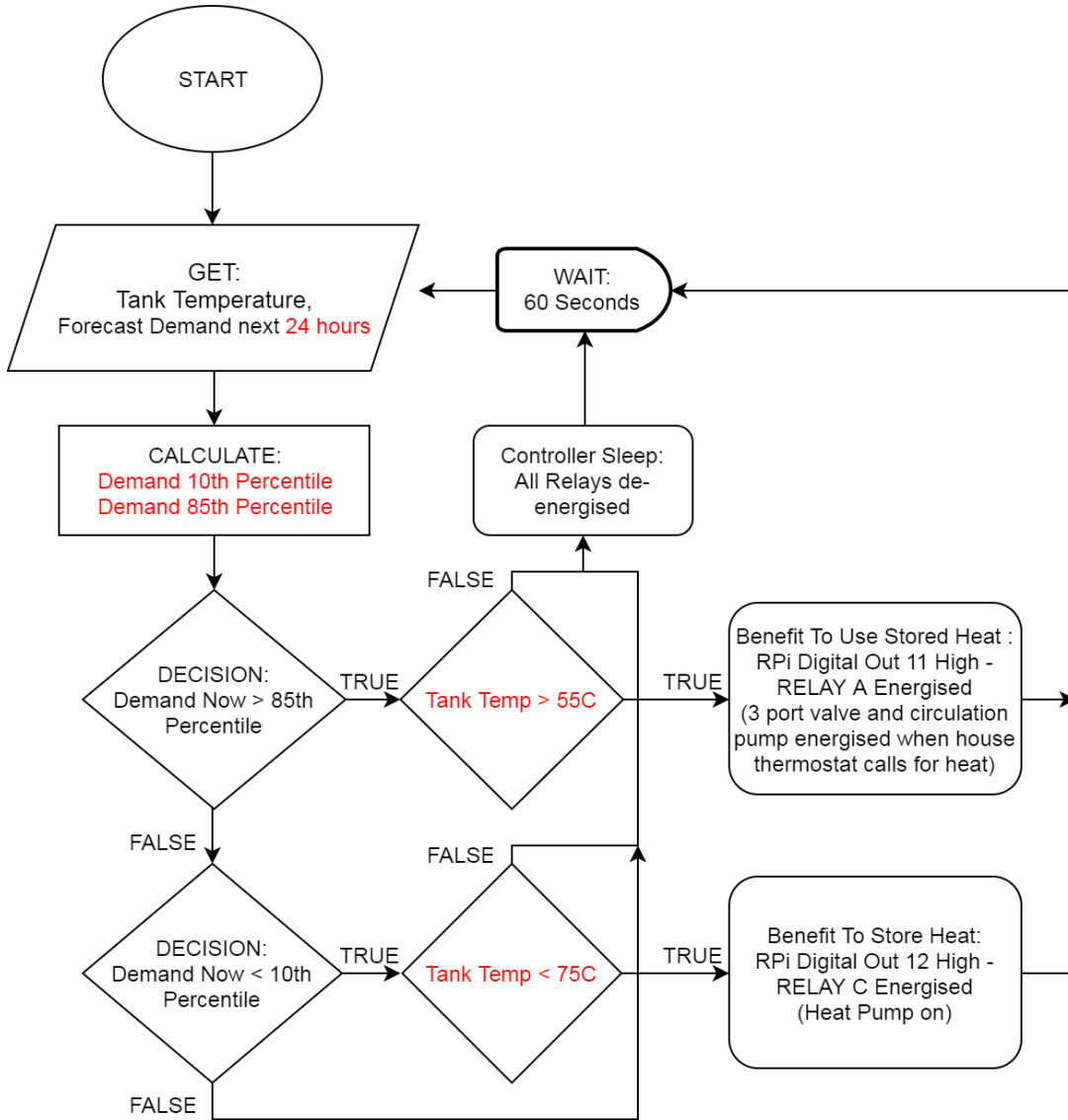
Figure 3-30 Algorithm used for the HP and thermal store system with demand-based DSM signal.

The algorithm in Figure 3-30 was the basis for the initial DSM strategy, as specified in section 3.4.3.1, which provided thermal storage at low system demand and discharged at peak system demand. The modification, as specified in section 3.4.3.2, were the thermal store was used at the first call for heat, was achieved simply by disabling the small 'benefit to use' block of code.

When the system was modified to the hybrid HP and gas boiler configuration a greater degree of code revision was required and effectively a newer version of the programme was

created, albeit based on the existing modules described previously. The updated algorithm is illustrated in Figure 3-31. The algorithm relates to the DSM strategy detailed in section 3.4.3.3. The code for the thermal store was removed and replaced by the gas boiler as the alternative heating source. The wiring configuration was set-up so that the gas boiler was the default heat source in the event of the controller failing i.e. if all the relays are de-energised the gas boiler is the hard-wired default. However, the DSM strategy only calls for the gas boiler to be used at peak system demand, therefore at all other times the HP should be the primary heating source, and as result Relay E needs to be energised in this instance.
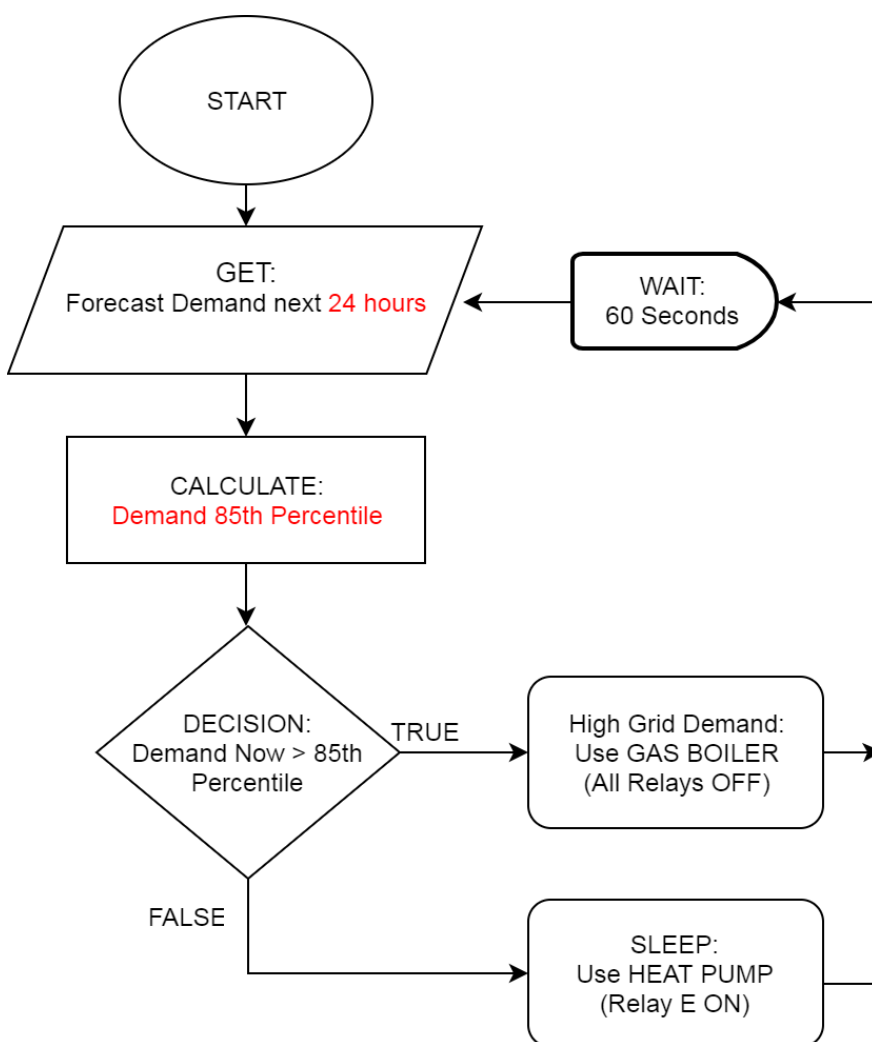
Figure 3-31 Algorithm used for the HP and gas boiler hybrid system using system forecast demand based DSM signal.

The algorithm in Figure 3-31 was adjusted to the algorithm in Figure 3-32 which uses electricity market price as a signal as opposed to system demand (described in section 3.4.3.4). In addition, the market price high percentile was calculated over the period of 00:00

to 23:45 as opposed to a rolling 24 hours ahead. This adjustment occurred due to initial analysis of the prior experiments, which will be discussed in the latter sections.
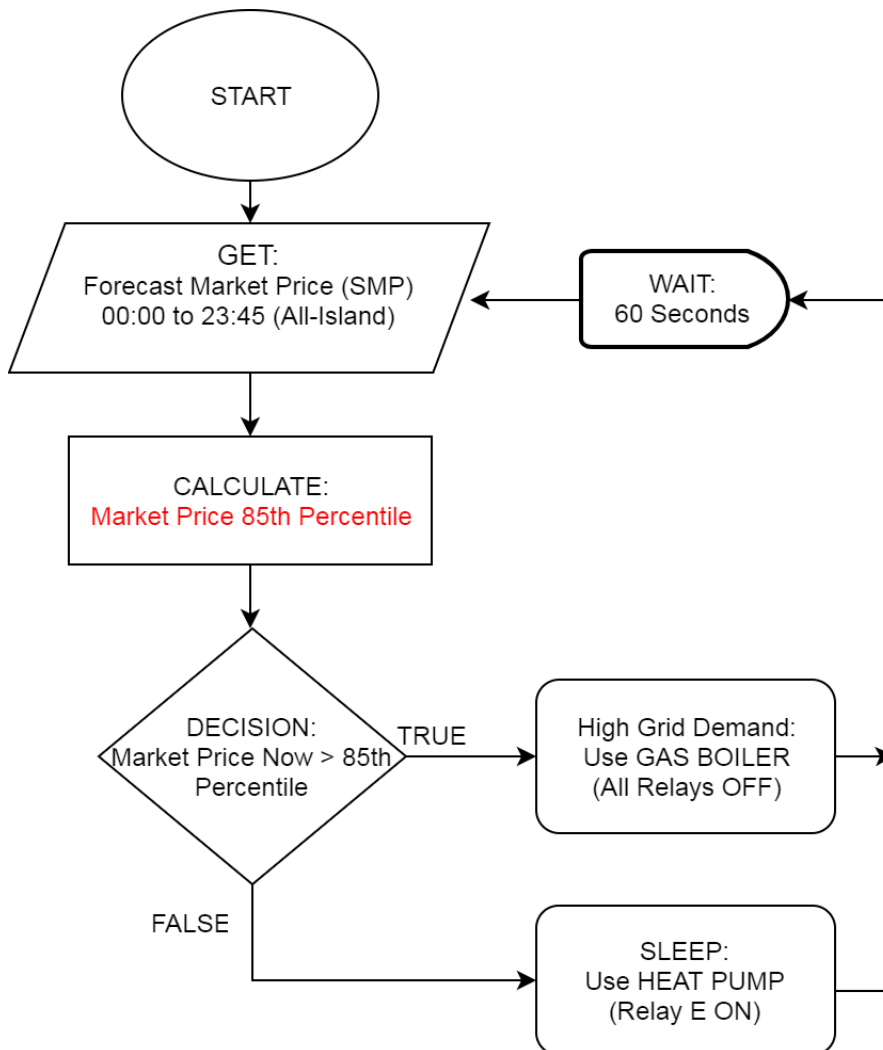
Figure 3-32 Algorithm used for the HP and gas boiler hybrid system using system forecast electricity market price (SMP) based DSM signal.

Finally, an algorithm which aimed to incorporate all three components of the system utilising low demand for thermal storage and high demand or market price for DSM of the heat pump impact on the grid was created. The algorithm is illustrated in Figure 3-33 and is described in section 3.4.3.5. Again, it uses forecast demand and market price from 00:00 to 23:45 to calculate the relevant percentiles. Thermal energy is stored by the heat pump at low system demand and used at high system demand or market price. After, or if the thermal store is discharged before the end of the day, the gas boiler will be used when there is a benefit to do so. The effect is to limit HP impact on system demand, and avoid price spikes during the day, which may be relevant in a real-time pricing scenario.
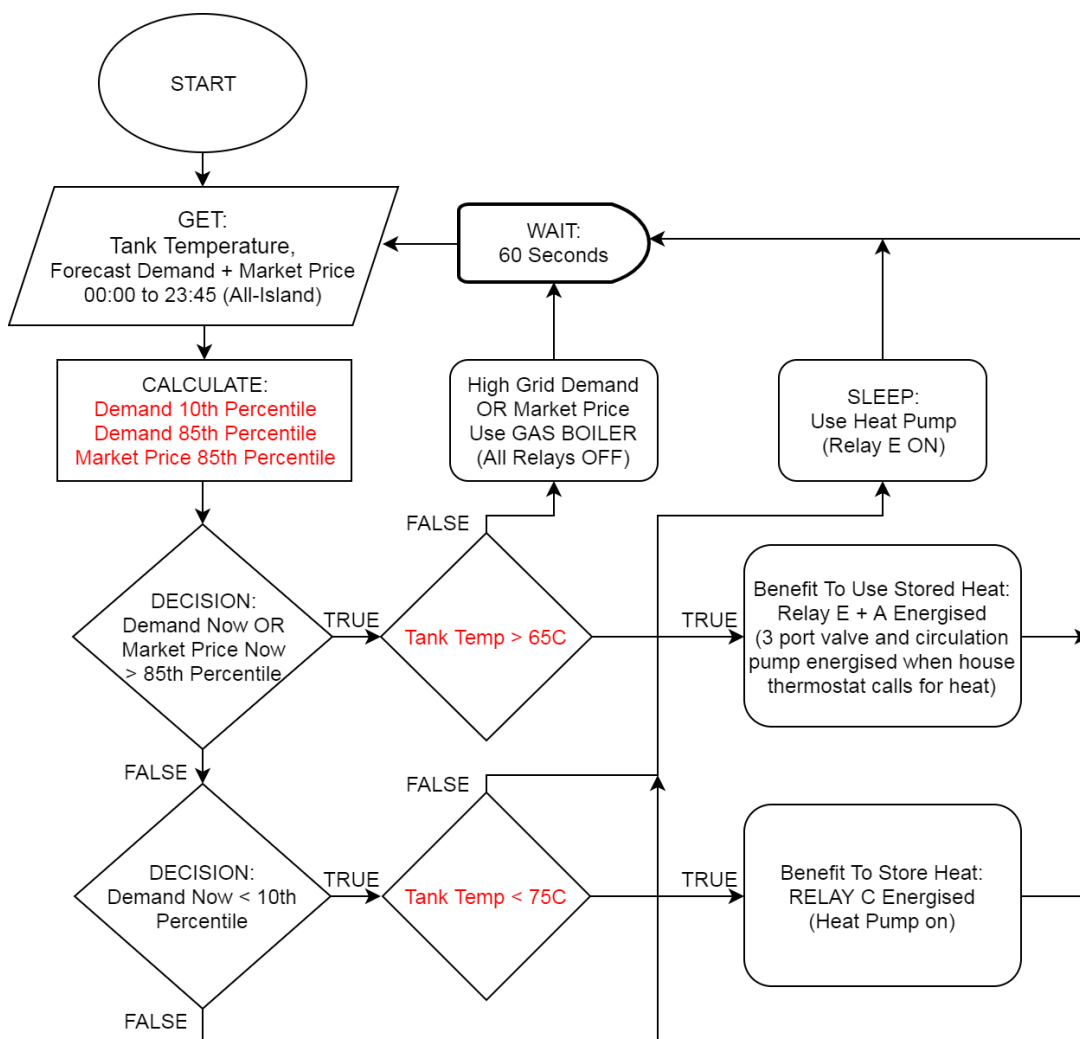
Figure 3-33 Algorithm for a fully automated hybrid system using the HP, gas boiler, and thermal store based on forecast system demand and market price (SMP) signals.

The python source code for the controller can be made available upon request. The code files are too long to include even as an appendix. There are two versions: one for the original HP and thermal store only system; and the second for the hybrid HP, gas boiler, and thermal store system.

3.4.5   Raspberry Pi Controller Data Collection and Management

Data from the Raspberry Pi controller was logged on each loop of the current running algorithm in a CSV file. A list of the logged data is indicated in Table 3-9. The data was stored locally on the Raspberry Pi SD card and also transferred via FTP to a network computer for backup. The network computer also backed up the data to a cloud server. Data was then imported into a Microsoft Access database for processing and preparation for analysis. The timestamp, used as a unique identifier for each data row, was rounded to the nearest minute and linked to the house and HP databases for cross analysis. In addition, the Raspberry Pi was set to run of the University network time clock to ensure consistent timestamps between data logging systems.

Table 3-9 Table and description of CSV logged data from RPi controller. [1]Eirgrid website makes data available for All-Island basis (ALL), Northern Ireland (NI) or Republic of Ireland (ROI). [2]Eirgrid website makes data available for: windactual (actual and forecast wind generation); demandactual (actual and forecast demand); marketprice (SMP price forecast and historical); generationactual (historical system generation all sources); interconnection (import and export over Moyle and East-West interconnectors), frequency (grid frequency at 5 second resolution updated every 15 minutes), c02intensity (estimated CO_2 emissions form all generators).

Channel Description	Channel Name	Unit/Data Format
Timestamp (GMT)	DateTime_GMT	dd/mm/yyyy hh:mm:ss
RELAY C Status	Relay_HP_Rpi	0=OFF, 1=ON
RELAY A Status	Relay_HeatMode_Rpi	0=OFF, 1=ON
RELAY B Status	Relay_call_for_heat	0=OFF, 1=ON
Text description of algorithm thermal storage instruction	store_status	Text
Text description of algorithm thermal discharge instruction	use_status	Text
Thermal store temperature (DS18B20 temperature sensor)	temp_buffer_c	°C
High charge-to setpoint set on controller (user defined)	setpoint_high_c	°C
Low discharge-to setpoint set on controller (user defined)	setpoint_low_c	°C
Demand side management instruction calculated by algorithm	dsmstatus	Text
Current electricity market price (SMP)	price_now	£
Calculated low threshold market price value	price_low_percent	£
Calculated high threshold market price value	price_high_percent	£
Current forecast electricity demand	demand_forecast_now	MW
Calculated low threshold electricity forecast demand	low_percentile_forecast_demand	MW
Calculated high threshold electricity forecast demand	high_percentile_forecast_demand	MW
Low percentile setpoint for calculation of threshold values (user defined)	low_percentile	decimal
High percentile setpoint for calculation of threshold values (user defined)	high_percentile	decimal
Region of downloaded data (user defined)	region	[1]ALL, NI, or ROI
Data for controller to download from EirGrid website (user defined)	area	[2]see table caption
Controller using HP or Gas boiler	hybrid_status	Text
Ambient Temperature	T_AMB	°C

3.5   Datataker Data Collection and Management

The HP, thermal store and central heating system was comprehensively instrumented with sensors to measure HP performance, energy efficiency, and thermal power delivery. Section 3.2.3 and 3.4.5 describe the data collection and management within the house and from the Raspberry Pi controller respectively. The heat delivery to the house was measured using an array of sensors and a Datataker DT85 (Thermo Fisher Scientific, 2017) smart data logger. A list of the measuring devices is indicated in Table 3-10. A complete list of the channels measured and a location reference figure for the central heating side sensors is included in Appendix A, Table 8-2 and Figure 8-1 respectively. The data logging was arranged into two schedules; Schedule A and Schedule B. Schedule A, measuring the HP performance, was set to measure every 30 seconds. Schedule B, measuring the thermal store temperature and central heating side of the system, was set to measure every 60 seconds. The higher measuring frequency of Schedule A was desirable for HP performance analysis however it was not thought necessary for Schedule B.

The data on the Datataker was downloaded daily at midnight onto a computer on the local network. The data consisted of two csv files, Schedule A and Schedule B. The files were stored locally on the computer and backed up to a cloud server. Data also remained on the Datataker itself for a period of approximately 1 month as an additional backup. The csv files were then imported into a Microsoft Access Database for processing and preparation for analysis. The timestamp, used as a unique identifier for each data row, was rounded to the nearest minute and linked to the house and Raspberry Pi controller databases for cross analysis. As with the house sensor data acquisition system and the Raspberry Pi controller, the Datataker was set to synchronise with the University network time clock to ensure consistent timestamps between data logging systems.

Table 3-10 List of sensors used with the Datataker data logging system. Column "Sensor Ref. No." can be used for cross-reference with the detailed list of sensors in Appendix A, Table 8-2.

Sensor Ref. No.	Measuring Device	Sensor	Unit	Resolution	Accuracy
1	PT100 (Inline)	Resistance	°C	-267 to 260°C	±(0.15 + 0.002*t)°C
2	PT500 (Inline)	Resistance	°C	-50 to 600°C	±(0.15 + 0.002*t)°C
3a	Siemens SITRANS F M MAG 1100 Flowmeter	4-20mA	l/s	0 to 10 m/s	0.2 % ±1 mm/s
3b	Siemens SITRANS F M MAG 6000 Transmitter	4-20mA	l/s	1 to 10 m/s	0.2 % ±1 mm/s
4	Omega FTB4607 Flowmeter	Pulse	l/min	20 pulse/ltr	Transitional flow: ±2%; Nominal flow: ±1.5%
5a	Landis & Gyr 5219 Polyphase Energy Meter (Energy)	Pulse	Wh	1 pulse/Wh	-
5b	Landis & Gyr 5219 Polyphase Energy Meter (Voltage)	Voltage	Volts	-	-
5c	Landis & Gyr 5219 Polyphase Energy Meter	4-20mA	Amps	0-50	-
6	Emerson PT5-30M Pressure Sensor	4-20mA	Bar	0-30	≤2% Full Scale
7	Metrix G6 Gas Meter	Pulse	m^3	100 pulse/m^3	-
8	Finder 230V Relay SPDT AC 16A	Digital	-	0 or 1	-

3.6   Data Analysis and Key Performance Indicators

The data from each data logger was imported into a Microsoft Access database for data integrity validation and processing. To assess the performance of the heating system electrical power and energy and thermal power and energy calculations were performed. These were then ultimately used to calculate the COP of the system which was used as the key performance indicator (KPI). In addition, the COP of the HP, gas boiler, and thermal store was used to calculate the domestic rate cost of thermal energy from each heat source respectively.

The carbon intensity of each heating source was also calculated using UK greenhouse gas (GHG) factors for 2017 (BEIS, 2017b) and methodology from BEIS green book (BEIS, 2018b). The electric GHG factor included a transmission and distribution loss. The gas GHG factor selected was Natural gas (gross calorific value) as recommended in the methodology.

The equations used are listed in Table 3-11 and a list of the calculations performed is listed in Table 3-12. The calculations were performed for every row of data in the database. It was therefore necessary to filter the data so that it could be attributed to the appropriate component in the system depending on the DSM strategy being employed. In other words, it needed to be known if the HP was storing heat in the thermal store, if the HP was providing heat to the house directly, if the house thermal store was discharging to the house, or if the gas boiler was providing the heat to the house. The most reliable way to do this was to use an AND logic matrix with the various flowmeters located in the system. If for example the boiler room flowmeter ≤ 0 AND the thermal store discharge flowmeter ≤ 0 AND the HP flowmeter > 0 then the HP must be storing heat in the thermal store. Table 3-13 lists the complete filter matrix used and which was applied across the entire database calculations. For reference the flowmeter locations are indicated in Figure 8-1, Appendix A.

Table 3-11 List of equations used to perform the calculations listed in Table 3-12. Table continues over page.

Equation	Formulae	Notes
3-1	$Electric\ Power\ (kW) = [\ Current\ (Amps) \times Voltage\ (Volts)\ ]/1000$	
3-2	$Electric\ Energy\ (kWh) = Electric\ Power\ (kW) \times Time\ (Hours)$	
3-3	$Thermal\ Power\ (kW) = Volumetric\ Flow\ Rate\ (m^3/s)\ \times Fluid\ Density\ (kg/m^3) \times$ $Specific\ Heat\ Capacity\ (kJ/kg\ °C) \times [\ Flow\ Temperature\ (°C) - Return\ Temperature\ (°C)\ ]$	Fluid density = 978 kg/m^3 Specific heat capacity = 4.191 kJ/kg°C (Water properties @ 70°C)
3-4	$Thermal\ Energy\ (kWh) = Thermal\ Power\ (kW) \times Time\ (Hours)$	
3-5	$COP\ HP = \dfrac{Thermal\ Energy\ Transferred\ (kWh)}{Electric\ Energy\ Consumed\ (kWh)}$	
3-6	$Gas\ Consumed\ (kWh) = Gas\ Volume\ Consumed\ (m^3) \times Natural\ Gas\ Conversion\ Factor$	Natural gas conversion factor = 11.3022 (Firmus Energy Ltd domestic gas conversion factor from personal bill, 3rd quarter 2016)
3-7	$COP\ Gas\ Boiler = \dfrac{Thermal\ Energy\ Transferred\ (kWh)}{Gas\ Consumed\ (kWh)}$	
3-8	$COP\ Thermal\ Store = \dfrac{Thermal\ Energy\ Transferred\ from\ HP\ (kWh)}{Thermal\ Energy\ Discharged\ from\ Store\ to\ House\ (kWh)}$	
3-9	$Electric\ Cost\ (£) = Electric\ Energy\ Consumed\ (kWh) \times Electric\ Price\ (£/kWh)$	Cheapest Domestic Electric Price August 2017: (1) standard fixed rate 12p/kWh; (2) economy 7 rate of 6.95p/kWh (night rate between 01:00 − 08:00 GMT) and 14.25p/kWh (day rate 00:00 − 01:00 and 08:00 - 00:00) (The Consumer Council NI, 2017a)
3-10	$Gas\ Cost\ (£) = Gas\ Consumed\ (kWh) \times Gas\ Price\ (£/kWh)$	Cheapest domestic gas price August 2017 = £0.04/kWh (The Consumer Council NI, 2017b)
3-11	$HP\ Price\ per\ kWh\ of\ Thermal\ (£/kWh) = \dfrac{Electric\ Price\ (£/kWh)}{COP\ HP}$	Electric price as above

Equation	Formulae	Notes
3-12	$Gas\ Boiler\ Price\ per\ kWh\ of\ Thermal\ (£/kWh) = \frac{Gas\ Price\ (£/kWh)}{COP\ Gas\ Boiler}$	Gas price as above
3-13	$Hybrid\ Price\ per\ kWh\ of\ Thermal\ (£/kWh)$ $= \frac{[Gas\ Consumed\ (kWh) \times Gas\ Price\ (£/kWh)] + [HP\ Electric\ Consumed\ (kWh) \times Electric\ Price\ (£/kWh)]}{Total\ Heat\ Delivered\ to\ House\ (kWh)}$	Gas price and electric price as above
3-14	$Thermal\ Store\ Price\ per\ kWh\ of\ Thermal\ (£/kWh) = \frac{Electric\ Price\ (£/kWh)}{COP\ Thermal\ Store}$	Electric price as above
3-15	$HP\ Carbon\ Intensity\ (kg\ CO_2e/kWh) = \frac{Electric\ GHG\ Factor\ (kg\ CO_2e/kWh)}{COP\ HP}$	Electric GHG factor + distribution losses = 0.3516 + 0.03287 = 0.38443 kg CO_2e/kWh (BEIS, 2017b)
3-16	$Thermal\ Store\ Carbon\ Intensity\ (kg\ CO_2e/kWh\ Thermal) = \frac{Electric\ GHG\ Factor\ (kg\ CO_2e/kWh)}{COP\ Thermal\ Store}$	Electric GHG factor as above
3-17	$Gas\ Boiler\ Carbon\ Intensity\ (kg\ CO_2e/kWh\ Thermal) = \frac{Natural\ Gas\ GHG\ Factor\ (kg\ CO_2e/kWh)}{COP\ Thermal\ Store}$	Natural Gas GHG factor (gross calorific value) = 0.18416 kg CO_2e/kWh (BEIS, 2017b)
3-18	$Hybrid\ Carbon\ Intensity\ (kg\ CO_2e/kWh\ Thermal)$ $= \frac{[Gas\ Consumption\ (kWh) \times Gas\ GHG] + [HP\ Electric\ Consumption\ (kWh) \times Electric\ GHG\ Factor]}{Total\ Heat\ Delivered\ to\ House\ (kWh)}$	Electric GHG factor and natural gas GHG factor as above

Table 3-12 List of the power, energy, and COP calculations to assess system performance.
[1]*Sensor reference refers to those illustrated in Figure 8-1 used to calculate heat transfer.*

Ref	Calculation Description	Unit	Sensor Reference[1]		
			Flow Meter	Temperature	
				Flow	Return
1	HP electric power consumption	kW	NA	NA	NA
2	HP thermal power delivered house	kW	DT:20	DT:7	DT:8
3	HP electric energy consumption	kWh	NA	NA	NA
4	HP thermal energy delivered house	kWh	DT:20	DT:7	DT:8
5	Gas boiler thermal power delivered	kW	DT:20	DT:7	DT:8
6	Gas boiler thermal energy delivered	kWh	DT:20	DT:7	DT:8
7	Thermal store: thermal power HP storing	kW	DT:22	DT:10	DT:9
8	Thermal store: thermal energy stored	kWh	DT:22	DT:10	DT:9
9	Thermal store: thermal power discharging	kW	DT:21	DT:11	DT:12
10	Thermal store: thermal energy discharging	kWh	DT:21	DT:11	DT:12
11	DHW tank: thermal power storing	kW	E:12	E:7	E:8
12	DHW tank: thermal energy stored	kWh	E:12	E:7	E:8
13	DHW tank: thermal power discharging	kW	E:11	E:6	E:5
14	DHW tank: thermal energy discharging	kWh	E:11	E:6	E:5
15	COP HP	NA	NA	NA	NA
16	COP thermal store	NA	NA	NA	NA
17	COP gas boiler	NA	NA	NA	NA
18	COP DHW tank	NA	NA	NA	NA
19	Gas boiler thermal power delivered hybrid series	kW	DT:20	DT:7	DT:10
20	Gas boiler thermal energy delivered hybrid series	kWh	DT:20	DT:7	DT:10
21	Combined thermal power delivered hybrid series	kW	DT:20	DT:7	DT:8
22	Combined thermal energy delivered hybrid series	kWh	DT:20	DT:7	DT:8
23	COP hybrid series	NA	NA	NA	NA
24	Cost to run HP	£	NA	NA	NA
25	Cost to run gas boiler	£	NA	NA	NA
26	HP price per kWh of thermal energy	p/kWh	NA	NA	NA
27	Gas boiler price per kWh of thermal energy	p/kWh	NA	NA	NA
28	Thermal store price per kWh of thermal energy	p/kWh	NA	NA	NA
29	Hybrid price per kWh of thermal energy	p/kWh	NA	NA	NA
30	HP carbon intensity per kWh of thermal energy	kg CO_2e / kWh	NA	NA	NA
31	Thermal store carbon intensity per kWh of thermal energy	kg CO_2e / kWh	NA	NA	NA
32	Gas boiler carbon intensity per kWh of thermal energy	kg CO_2e / kWh	NA	NA	NA
33	Hybrid carbon intensity per kWh of thermal energy	kg CO_2e / kWh	NA	NA	NA

Table 3-13 Logic matrix used to filter calculations depending on DSM strategy.

Flowmeter Description	Boiler Room Flow (DT:20)	Tank Flow (DT:21)	HP Flow (DT:22)
Direct (heat from HP to house)	> 0	≤ 0	> 0
Indirect (heat from thermal store to house)	> 0	> 0	≤ 0
Storing (heat from HP to thermal store)	≤ 0	≤ 0	> 0
Gas boiler only	> 0	≤ 0	≤ 0

4 RESULTS & DISCUSSION

4.1 House Heating Demand

To provide an overview of the energy consumption of the test house, two complete years of thermal heat demand (space heating and DHW) for house 64 was recorded and is shown in Figure 4-1. The total demand is categorised by month for 2015 and 2016 so that each year can be compared to each other on a monthly basis. The graph also shows the average monthly outside temperature recorded on site.
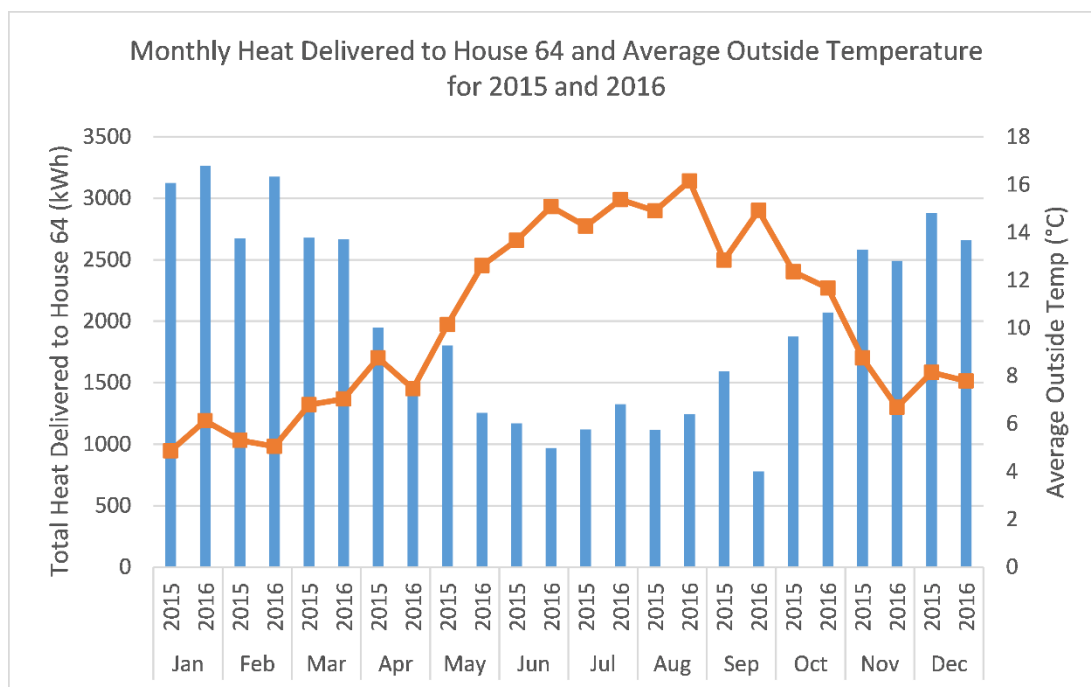
Figure 4-1 Total monthly heat demand for house 64 (space heating and hot water) for 2015 and 2016

For 2015 the total heat demand for the house was 24567 kWh and the average outside temperature was 10.1°C whereas in 2016 the total heat demand was 23323 kWh with an average outside temperature of 10.5°C. The house has an internal floor space of 97.0 m^2 (Figure 3-2) therefore the energy consumption per floor area for 2015 and 2016 is 253.3 kWh/m^2 and 240.0 kWh/m^2 respectively.

The energy demand data summarised in Figure 4-1 was also plotted as a scatter graph, illustrated as Figure 4-2. The figure plots the average daily outside temperature versus the total daily heat delivered to house 64 for 2015 and 2016. A linear trendline is also plotted on the graph. From the graph a strong negative correlation between daily house heat demand and outside temperature is evident i.e. as outside temperature increases the heat demand of the house decreases. It is clear from Figure 4-2 that even at relatively high outside

temperatures i.e. above 17°C, the heat demand of the house can still exceed 40 kWh per day. This is counter to what would be expected, as above this temperature it wold be intuitive to think that the only heat demand from the house would be for domestic hot water. Indeed, the value is higher than what would be expected even for domestic hot water only. It is noted however that one of the occupants of house 64 was unwell for the duration of much of the project and higher space and hot water demands may be attributable to this factor. There is also the possibility of the heating running for longer than required as a result of a pre-programmed timer in combination with a high thermostat setting for either or both the domestic hot water tank and space heating.
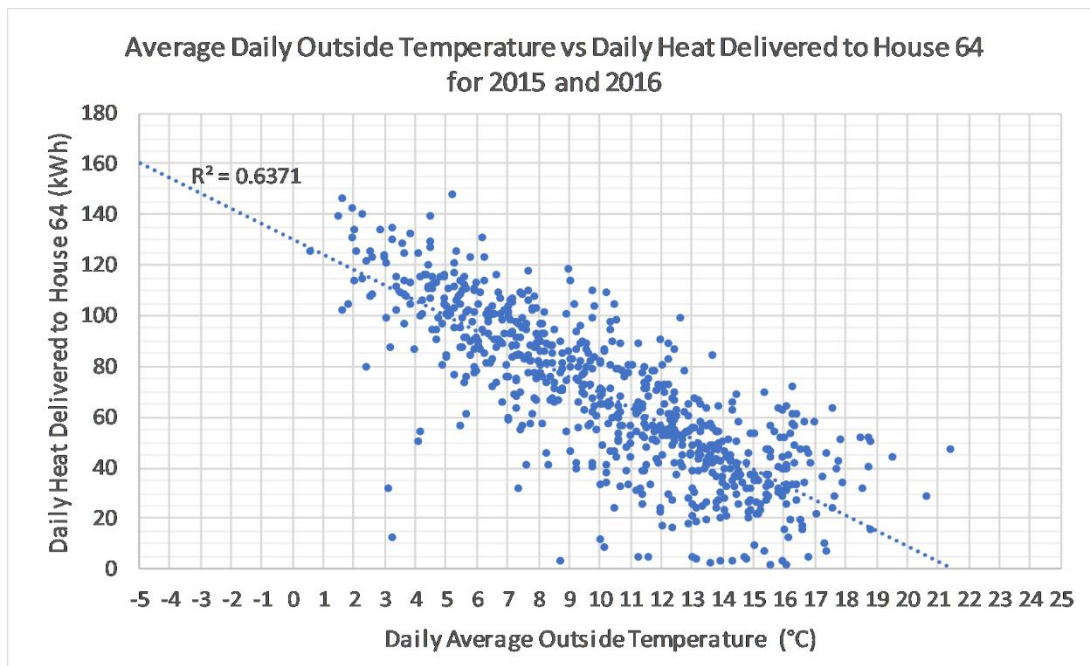
Figure 4-2 Average daily outside temperature versus daily heat energy delivered to house 64 for 2015 and 2016.

4.2 Baseline ASHP: Direct Mode

The heat pump was run in direct heating mode with no DSM between the 26/11/14 and 09/02/15. Figure 4-3 shows the total daily heat demand for house 64 along with average daily outside temperature. Across the period the daily thermal energy consumed ranged from a maximum of 146.1 kWh to a minimum of 50.4 kWh and averaging 105.7 kWh (values not including days with data loss). The outside temperature across the period ranged from a maximum of 11.2°C to a minimum of 0.8°C and averaging 5.4°C.
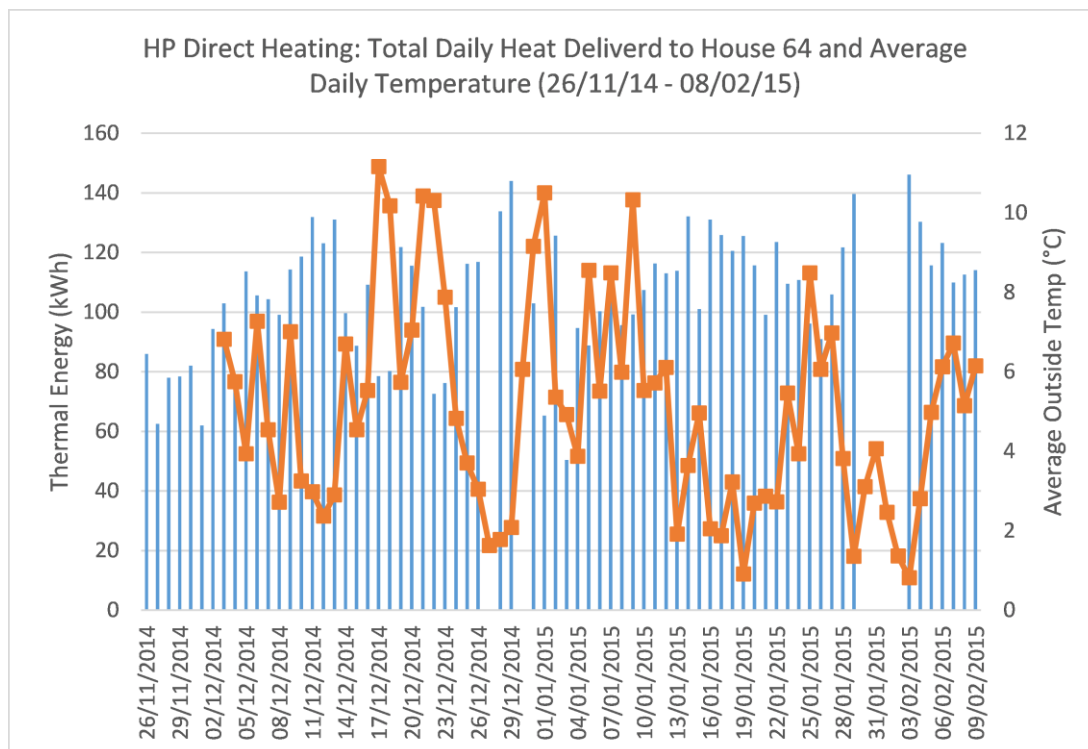
Figure 4-3 Total daily heat demand for house 64 (space heating and hot water) running in direct only mode with no DSM between 26/11/14 and 09/02/15. No heat demand data was available for 27th and 30th Dec 2014, 30th and 31st Jan 2015, and 1st and 2nd Feb 2015 due to data logger error. Temperature readings were available from 3rd Dec 2014 onwards only.

To provide an overview of how the heat pump operates in direct heating mode with no DSM intervention an example of the heat pump thermal output and electric power consumption is shown in Figure 4-4 for the 15th December 2014 between 05:30 and 11:30. In addition Figure 4-5 shows the flow temperature, return temperature, and volumetric flow rate for the same period. Average outside temperature for this specific time period was measured at 4.1°C. The graphs show the heating system at 1st call for heat on the 15th December i.e. the central heating system has cooled to balance with surroundings.

From Figure 4-4 it can be seen that it takes approximately 10 minutes to reach a thermal power output of 15 kW and from Figure 4-5 the set flow temperature of 76°C is reached in

approximately 56 minutes. By comparing the two graphs it can be seen that as the higher flow temperature is approached the ratio of the heat pump thermal power output to electric power consumption (COP) decreases to a value of approximately 1.61. This compares to a COP value of approximately 2.44 after 10 minutes from 1st start-up.

At around 06:40 and 07:50 the thermal power output and electrical power consumption drop as do the flow and return temperatures for a period of about 10 minutes each time. This is a result of the heat pump entering defrost operation to remove condensation and prevent frost build up on the outdoor unit. The heat pump uses some of the heat from the central heating system to perform this operation and this can be seen as negative thermal power output at these times. At 08:41, 10:26, and 11:11 the flow rate drops to zero indicating the room thermostat has been satisfied and this is discernible from a defrost operation by this fact and the fact that the flow and return temperatures decrease gradually as opposed to a sudden sharp drop seen with the defrost operation.

The daily COP of the heat pump for the period is shown in Figure 4-6 versus the daily average ambient temperature. Across the period the COP ranges from a maximum daily average of 2.41, minimum daily average of 1.82, and averages 2.10. The values correspond to daily average outside temperatures of maximum 11.2°C, minimum of 0.8°C, and averaging 5.4°C. There is a good spread of measured COP values across the outside temperature range showing a strong positive linear correlation between the two parameters. The data therefore gives a good baseline indication of the heat pump operational performance installed in house 64 and heating the house directly without any thermal storage or DSM control.

Using the COP data, the daily average cost per kWh of thermal energy supplied to the house was also calculated based on the cheapest domestic electricity price of £0.12/kWh in Northern Ireland in August 2017 (The Consumer Council NI, 2017b). The calculated data is plotted versus daily average outside temperature (Figure 4-7) to give an indication of the actual cost of heating the house with variation in outdoor temperature. The relationship between the two parameters is a negative linear relationship. The cost per kWh of thermal ranges from a maximum of £0.066/kWh, minimum of £0.050, and averaging £0.058/kWh for the previously stated temperature ranges. For comparison the cheapest domestic gas price was £0.04/kWh in August 2017 (The Consumer Council NI, 2017b) so for example a gas boiler at 80% efficiency would cost roughly £0.050/kWh thermal energy. For the HP to be cheaper to run than a gas boiler in this instance the HP would need to achieve a COP of greater than 2.4 (electric price per kWh divided by gas thermal cost per kWh). The average cost of heating

oil in August 2017 for comparison was £0.044/kWh, based on purchasing 300 litres and a conversion of 1 litre equal to 10.35 kWh (The Consumer Council NI, 2017c), so for example an oil boiler at 80% efficiency would cost roughly £0.055/kWh thermal energy. For the HP to be cheaper to run than an oil boiler in this instance the HP would need to achieve a COP of greater than 2.18 (electric price per kWh divided by oil thermal cost per kWh). It should be noted however that heating oil prices are much more volatile than gas and electric prices and can have considerable seasonal variation with prices effected by demand i.e. oil prices may be higher in winter and therefore the HP could be cheaper to run even though HP COP will drop in colder periods also. An indication of oil heating prices has been included due to its high prevalence for domestic heating in Northern Ireland, the largest in Western Europe, with 68% of homes (82% in rural areas) using it as a primary heating source (The Consumer Council NI, 2013).

The COP data of the HP through this period has also been used to calculate the CO_2e intensity per kWh of thermal energy supplied to the house and this is plotted versus daily average outdoor temperature in Figure 4-8. Across the period the CO_2e intensity ranges from a maximum of 0.21 kg CO_2e/kWh thermal to a minimum of 0.16 kg CO_2e/kWh thermal, and averages 0.19 kg CO_2e/kWh thermal. For comparison a gas boiler at 80% efficiency would have an approximate CO2e intensity of 0.2302 kg CO_2e/kWh thermal based on natural gas intensity of 0.18416 kg CO_2e/kWh thermal (gross CV) taken from UK GHG factors for 2017 (BEIS, 2017b). Furthermore, an oil boiler at 80% efficiency would have an approximate CO_2e intensity of 0.3082 kg CO_2e/kWh thermal based on burning oil intensity of 0.24659 kg CO_2e/kWh thermal (gross CV) taken from UK GHG factors for 2017 (BEIS, 2017b). The basic examples illustrate the HP potential for a reduction on CO_2e intensity over both gas and oil heating even at relatively low operational COP. There is significant potential when displacing oil heating which as previously mentioned accounts for 68% of primary heating for homes in Northern Ireland.
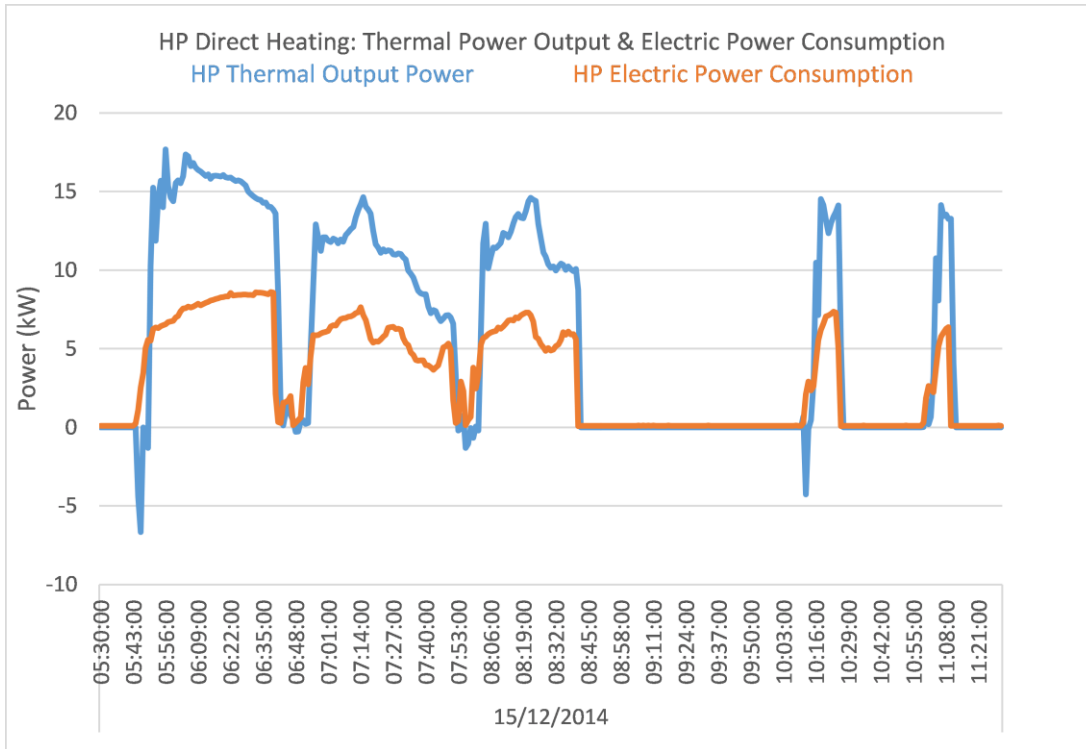
Figure 4-4 Example of HP thermal output power and electric power consumption running in direct heating mode between 05:30 and 11:30 on 15th December 2014.
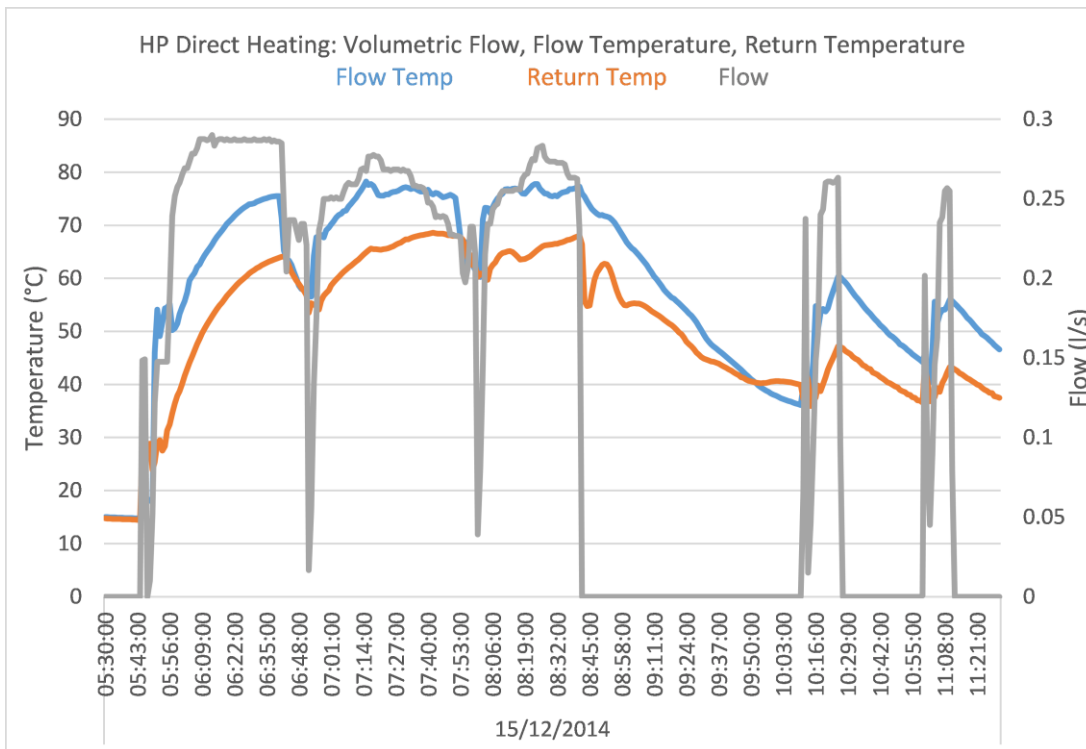
Figure 4-5 Example of HP central heating flow temperature, return temperature and volumetric flow running in direct heating mode between 05:30 and 11:30 on 15th December 2014. Sensor locations are indicated in Figure 8-1: flow temperature (DT:7), return temperature (DT:8), volumetric flow (DT:20).
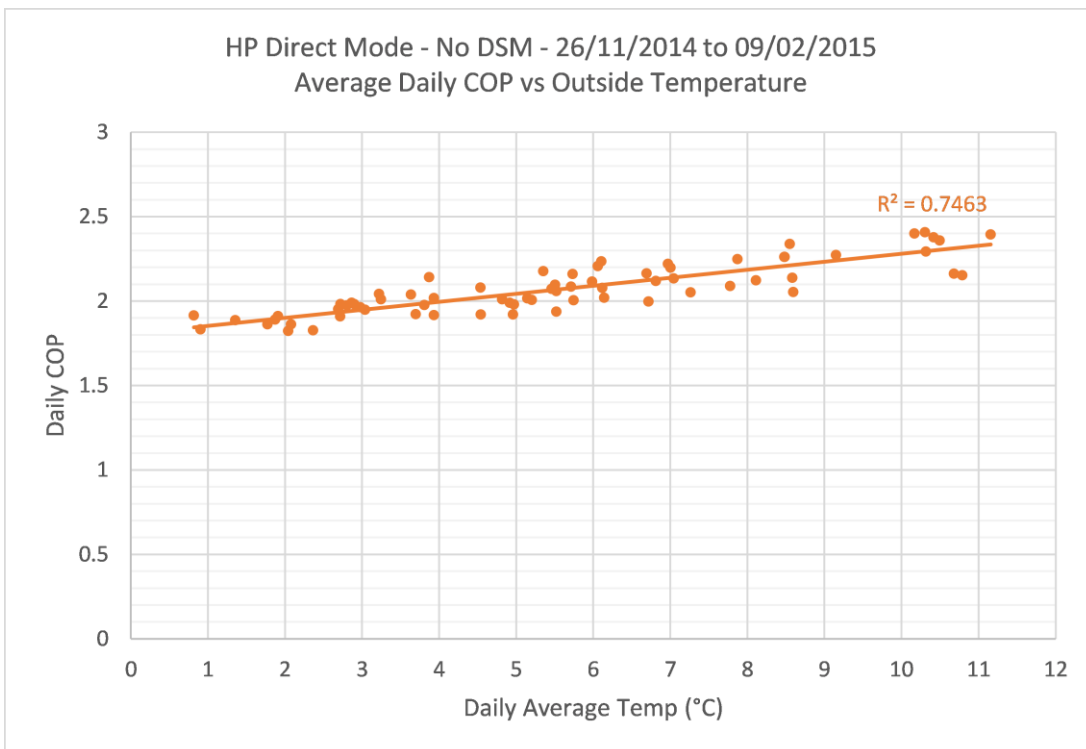
Figure 4-6 Daily COP vs daily average outside temperature for HP running in direct mode with no DSM controls between 26/11/2014 and 09/02/2015.
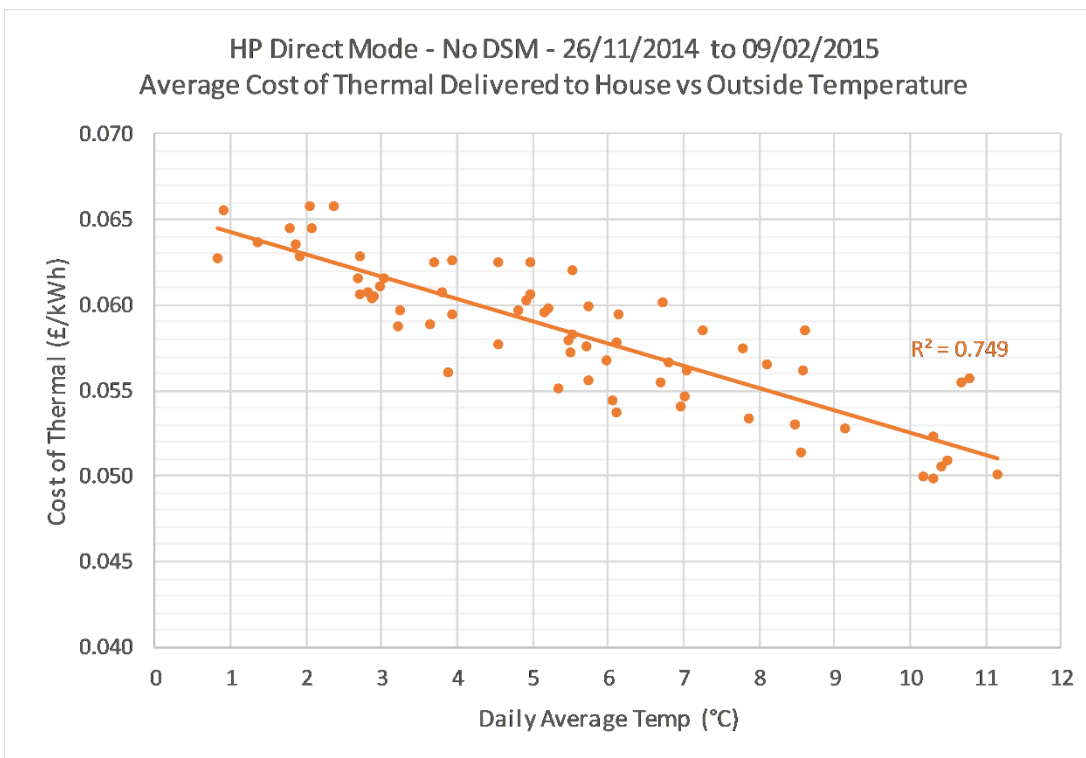
Figure 4-7 Daily average cost of thermal energy supplied by HP vs daily average outside temperature for HP running in direct mode with no DSM controls between 26/11/2014 and 09/02/2015. Thermal cost is calculated using domestic electricity price of £0.12/kWh based on cheapest domestic fuel prices (The Consumer Council NI, 2017b).
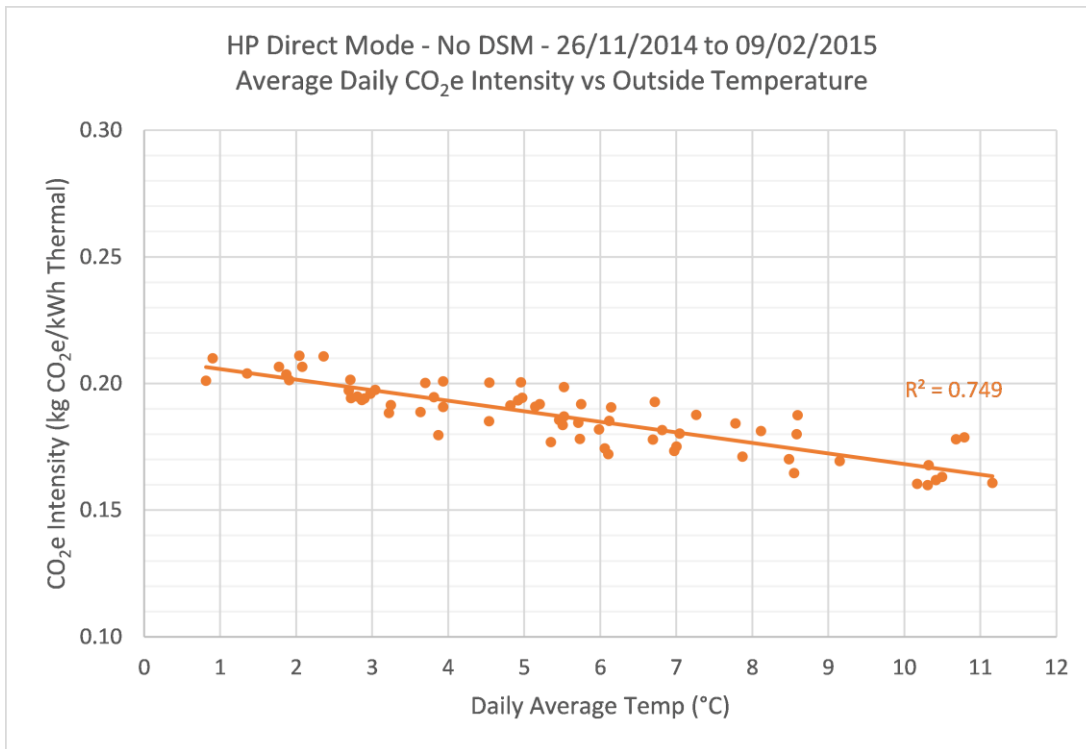
Figure 4-8 Daily average CO₂e intensity of heat supplied by HP vs daily average outside temperature for HP running in direct mode with no DSM controls between 26/11/2014 and 09/02/2015. The calculation uses UK GHG factors for 2017 (BEIS, 2017b). Electricity GHG factor is inclusive of transmission and distribution GHG factor.

4.3 Baseline Thermal Store: Heat Loss Analysis

In order to get a better understanding of the thermal store performance in terms of thermal losses compared to theoretical losses a simple heat loss test was conducted which consisted of heating the installed thermal store up to 75°C using the HP and observing the tank temperature drop for a period of 10 days. The test was conducted post the experiments listed in Table 3-8 between the 21st and 31st January 2019. The average outdoor air temperature across the period was 3.9°C and the average indoor shed temperature (where the thermal store and HP are housed) was 18.3°C. The shed temperature was maintained by thermostatically controlled electric radiators and the indoor temperature was measured by two PT100 sensors located in the centre of the shed at ceiling height.

Figure 4-9 shows the measurements from the seven tank temperature sensor probes installed in the thermal store. The temperature sensors are approximately equidistant apart along the height of the tank with "Tank 1" sensor located at the top and "Tank 7" sensor located at the bottom.
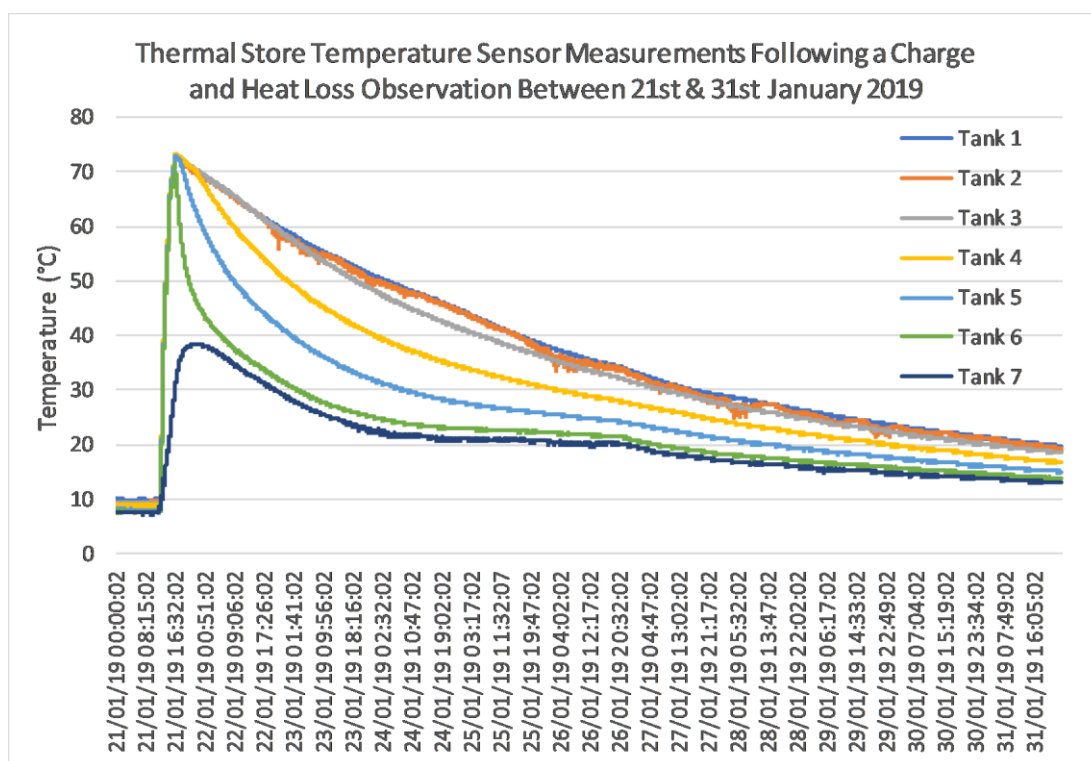
Figure 4-9 Measured thermal store temperature from 7 temperature probes placed along the height of the tank following charging to 75°C by the HP and no subsequent charging for a period of 10 days between 21st and 31st January 2019.

From Figure 4-9 it is observed that the temperature of the tank begins to rise at 12:21 on the 21/01/2019 from an average of 8.3°C until 16:43 on the 21/01/2019 to a temperature of

approximately 75°C. Following this the HP was turned off and no further heating of the tank occurred for a period of 10 days. Sensors 1,2 and 3 cool at a similar rate following approximately the same curve with sensors 4, 5, 6, and 7 cooling faster. The separation of the sensor cooling curves is a result of thermal stratification occurring in the tank. Sensor number 7 does not achieve the charge temperature of 75°C instead only reaching a peak temperature of 38.5°C approximately 5 hours after thermal charging by the HP stops. This is due to the location of sensor 7 which is very close to the base of the tank and below the HP charging coil. It is likely that a small volume of water at the base of the tank is not effectively heated due to the charging coil position. To counteract this to a certain degree, the flow from the HP could be adjusted to enter at the bottom of the tank rather than higher up i.e. the flow direction in the charging coil could be reversed. However, the volume of water not effectively heated is likely to be small as sensor 6, which does achieve the charging temperature, is less than 10cm above sensor 7.

In addition to measuring the temperature drop of the thermal store the theoretical thermal loss was calculated using the tank specification details outlined in Table 3-6. A simple calculation, Equation 4-1, considering conduction as the primary energy loss and full mixing in the tank was used (Clean Energy Regulator, 2017). A thermal conductivity of 0.03 W/mK and 0.04 W/mK was used for the tank spray polyurethane foam and glass fibre loft wool respectively (Engineering ToolBox, 2003). The heat loss was calculated in 1-minute time steps for a duration of 10 days using 75°C as T_{store} initial and 17°C for $T_{ambinet}$ producing an initial heat loss of 108W. T_{store} and hence Q was calculated at each subsequent timestep. A factor of 1.3 was applied to Q to account for insulation imperfections and thermal bridging (Clean Energy Regulator, 2017). In addition a heat loss due to pipe connections and sensor probes was estimated to take account for 7 22mm pipe connections, 7 temperature sensor pockets, and 3 immersion heater cuts to the insulation using the method outlined by Clean Energy Regulator (2017). This amounted to a further initial 56W of heat loss and therefore a total thermal store heat loss of 164W at 58°C ΔT (T_{store} - $T_{ambinet}$). The total theoretical heat loss was converted to an energy heat loss in kWh for each time step.

The measured temperature values, illustrated in Figure 4-9, were also used to calculate the actual energy heat loss at 1-minute intervals, using Equation 4-2, for comparison to the theoretical energy heat loss. The mass of water in the tank was taken as 600 kg and a value of 4,191 J/kg °C was used for the specific heat capacity of water. The heat loss was then converted to energy loss in kWh. The results of the actual and theoretical calculations are illustrated in Figure 4-10.

Equation 4-1 Heat loss calculation theoretical

$$Q = \frac{k}{\Delta x} \times A \times (T_{store} - T_{ambient})$$

Where:

Q	*Heat Loss (W)*
k	*Thermal Conductivity (W/mK)*
Δx	*Material Thickness (m)*
A	*Effective cross-sectional area of tank (includes insulation thickness (m²))*
T$_{store}$	*Thermal store initial temperature after charging (°C)*
T$_{ambinet}$	*Ambient shed temperature (°C)*

Equation 4-2 Actual heat loss calculation using measured values

$$Q = m \times C \times (T_{store\ (n)} - T_{store\ (n+1)})$$

Where:

Q	*Heat Loss (W)*
m	*Mass of water contained in tank (kg)*
C	*Specific heat capacity of water (J/kg °C)*
T$_{store\ (n)}$	*Thermal store temperature at time n (°C)*
T$_{store\ (n+1)}$	*Thermal store temperature at time n + 1 (°C)*
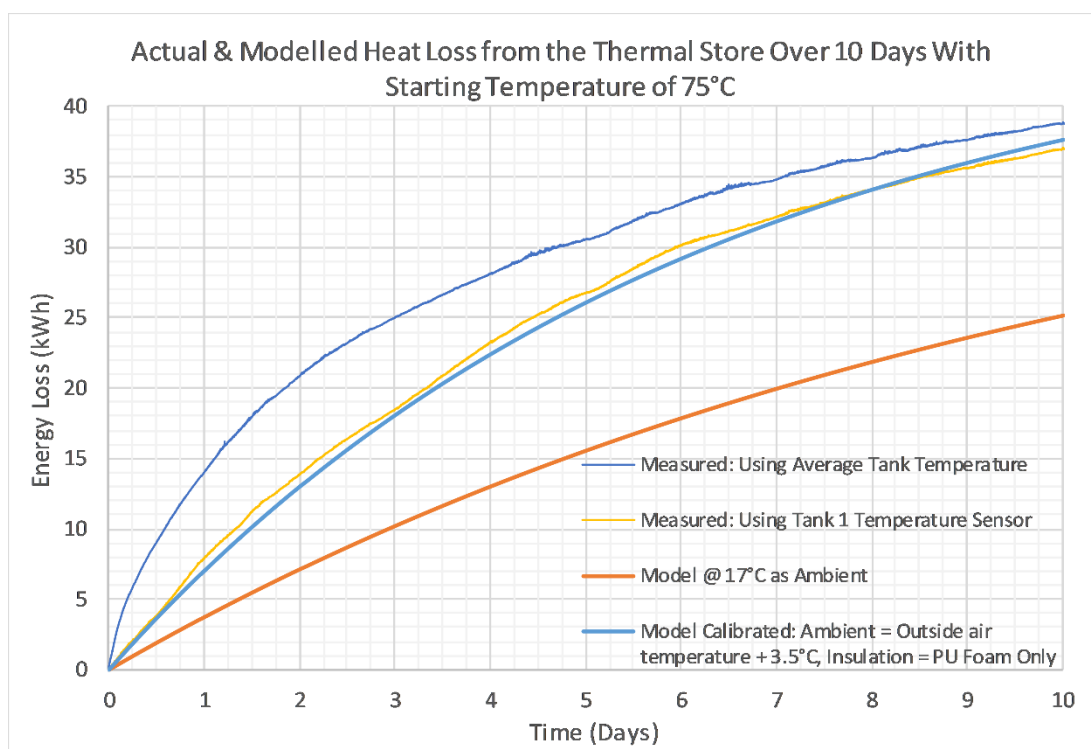
Figure 4-10 Comparison of actual (measured) and modelled heat loss energy from the thermal store for a 10-day period at initial store temperature of 75°C. Model assumes fully mixed tank and conduction as primary heat loss.

In addition to the measured heat loss using the average tank temperature from all temperature sensors, the measured heat loss using the highest temperature sensor in the tank, "Tank 1" is also included in Figure 4-10. Temperature sensor 1 cools the slowest because of thermal stratification in the tank. For the modelled heat loss, a model using an average indoor shed temperature of 17°C is shown. The measured heat loss is equal to 14kWh/day and 8kWh/day for the average and "Tank 1" tank temperatures respectively. The heat loss is considered high considering the useful heat that can be supplied to the house is between 75°C and 55°C approximately 14 kWh maximum i.e. no heat loss (Table 3-6). After 12 hours a heat loss of around 9 kWh has occurred (based on average tank temperature) and this will have obvious consequences for the effectiveness and efficiency of shifting thermal energy from the early morning to the evening time (approximately a 12-hour shift).

An attempt to calibrate the model to the observed heat loss has been made by using an ambient temperature equal to the measured outdoor air temperature plus 3.5°C (7.5°C average over 10 days) and neglecting the loft wool insulation on the tank. The result is shown on Figure 4-10. The calibrated model shows a good fit with the measured heat loss matching temperature sensor 1 on the tank. For the calibration the ambient temperature was changed as it was believed the shed air temperature sensors may be reading higher than the air temperature surrounding the thermal store due to their positioning (centre of shed at ceiling height). By reducing the insulation of the tank, a better fit between the modelled and measured "Tank 1" was also seen. To accurately check if these changes are justified in the model, more air temperature sensors should be placed in the vicinity of the tank. Reducing the insulation also helped to calibrate the heat loss curve, although a factor of 1.3 had already been applied to Equation 4-1 to consider insulation ineffectiveness. Either the insulation does not perform as expected in terms of expected thermal conductivity or there is another heat loss which is occurring that is unaccounted for in the model.

After studying the tank design, an additional possible heat loss was identified. Figure 4-11 shows a 22mm copper overflow pipe positioned at the top of the tank approximately 14cm above the water surface exiting a short distance through the shed wall running horizontally to the outside. It is possible at higher temperatures evaporation from the water surface occurs and the overflow pipe acts as type of Liebig condenser, were the evaporated water from the tank flows through the overflow pipe and condenses at the cooler outdoor side were the condensed water is lost. This would agree with a direct observation of water loss from the tank at the end of the study with no apparent leaks present. The overflow pipe should be changed so that it is inclined upwards at an angle, so that any evaporated water

will run back into the tank. In addition, the overflow pipe should run vertically down the side of the tank (inside the shed – to reduce thermosyphon effect) through a self-closing waste valve with tundish adapter and exit the shed at a low level. The inclusion of the self-closing waste valve and tundish adapter (air break) should reduce the effect of cool outdoor air blowing across the end of the overflow pipe and therefore reduce the risk of heat loss via evaporation from the tank.

Figure 4-11 Left picture: Inside of thermal store (view from top) with overflow indicated. Right picture: 22mm overflow pipe exiting shed - connected horizontally to thermal store.

Further work could be carried out to improve the modelled heat loss to consider the possibility of evaporation in the manner described above as well as the effect of stratification in the tank with regards to heat loss. To consider stratification in the model, the tank could be divided into sections or nodes corresponding to the installed temperature sensor positions and calculation performed for each node. However due to time constraints the extra work was not possible for this research project. If the heat losses could be identified and quantified accurately from the thermal store, then simple improvements might greatly reduce the thermal losses that have been measured. The impact of the tank being in an outdoor shed may also have a greater effect than previously thought. Extra air temperature sensors inside the shed would confirm the exact air temperature and if the mitigation (electric radiators) are performing sufficiently enough to maintain a constant air temperature in the shed. If this is not the case, extra insulation could be added to the shed walls in order to sufficiently maintain the shed at a constant air temperature.

4.4   ASHP & Thermal Store DSM

4.4.1   Store at Low Demand & Use at High Demand

The heat pump was run using demand-based DSM in conjunction with the thermal store between 11 June 2015 and 1st December 2015. The DSM consisted of storing energy to the thermal store at the lowest daily system demand and using it at peak system demand as detailed in section 3.4.3.1 and summarised in Table 3-8.

One week of actual data recorded by the controller is illustrated in Figure 4-12 showing the forecast electricity demand retrieved from the system operator, the calculated 85th and 10th percentile of the forecast demand, and the periods of time when the HP was storing to the thermal store and when the thermal store was discharging to the house. When the forecast electricity data is below the calculated 10th percentile the controller will initiate the HP to store thermal energy up to 75°C and maintain it until the forecast demand data is above the 10th percentile. When the forecast electricity demand is greater than the 85th percentile the heating system will discharge from the thermal store if there is a call for heat from the house.

When observing the HP storing lines in Figure 4-12 it is evident that on some days, for example the 9th November, the HP begins to store heat and stops when the storage temperature of 75°C is reached and then starts again to reheat the store back to 75°C. Ideally the HP should not reheat the thermal store, instead the window of when the HP stores, below the 10th percentile of forecast electricity demand, should be more dynamic to take into account the starting temperature of the thermal store and from historical measurements the heating time to reach the target temperature of 75°C. This was difficult to apply in practise because the forecast electricity demand is available in half hourly windows and the heating windows can therefore only be accurate to a half hour resolution. Another method could be to add a counter to the program so that once the target temperature of the store is met no reheat will occur within that specific window, with the counter resetting for subsequent windows. However, there would still need to be a reasonably accurate estimate of the low percentile window size to ensure the storage mode was activated as close as possible to the lowest system demand i.e. too large a window and the storage will begin too early increasing standing losses, too small and the target temperature of store will not be reached.

Further to the analysis of the storage window size, it can be observed in Figure 4-12, the effect of a significant drop in daily electric demand on the calculation of the 10th percentile. This can be seen on Friday 13th November were system demand drops on Friday and over the weekend when compared to higher daily demand from Monday through Thursday. The 10th

percentile can be seen to drop in the morning low demand of the 13th resulting in a reduced storage window and the thermal store not reaching the target temperature of 75°C, reaching 70°C instead. The percentile calculation was calculated on 24 hours ahead basis meaning the lower demand on the morning of the 14th compared to the morning of the 13th causes the when-to-store window on the 13th to be shorter due to the overlap i.e. lower forecast demand on the 14th reduces the calculated 10th percentile on the 13th. The calculation was adjusted to calculate the percentile on a daily basis for the hybrid experiments using market price as a signal (see Table 3-8 for when the change was applied).

Examining the store discharging lines in Figure 4-12, two observations can be made on the timing of the discharge with respect to peak daily forecast demand. Firstly, a tendency for the discharge to begin and sometimes end before peak electricity is noticed. Secondly, the early discharges on the 13th and 14th at 11:30 to 12:00 and 10:30 to 11:00 respectively. The first observation is a result of the when-to-use window being calculated using the 85th percentile meaning the window is larger than the thermal storage available for discharge. The window size was based on the thermal storage that would be available but also had to take into consideration the likelihood there would be a call for heat within that window so that the stored energy would get utilised within that day and therefore the window was made slightly wider. A simple solution to this would be to size the window for the thermal energy that would be available and if there is no call for heat within this period just use the thermal energy at any subsequent call for heat from the household. This would be achievable by the appropriate modification of the controller software. With regards to second previously mentioned early discharges, this appears to be a result of a higher morning demand at the weekends, Saturday and Sunday, with respect to the weekdays, in addition to the when-to-use window being slightly oversized. A combination of the solutions previously mentioned: reducing the when-to-use window size; and calculating the percentiles based on the in-day forecast demand would avoid this situation. Ultimately this would maximise the avoidance of the HP impacting on peak system demand whilst maximising the efficiency of a thermal storage demand side management system within this aim.

An example of the system operating on the 12th November 2015 is shown in Figure 4-13. The figure compares: the thermal power output of the HP when storing to the thermal store; the thermal power output of the HP when heating the house directly; the thermal power output of store to the house when discharging; the thermal store temperature; and the electrical power input to the HP. The HP is activated for storage at 01:35 and runs for 2 hours 10 minutes until 03:45 raising the thermal store temperature from 51.6°C to 75°C. The HP

reaches a thermal maximum power output of 15.0kW at 1:55, 20 minutes after start up, at which point the thermal store temperature has increased to 58.7°C. Thermal power output then decreases steadily to a constant thermal power output of approximately 2.7kW which is reached at 2:40 at which point the thermal store has increased to a temperature of 69.7°C. As the thermal power output of the HP begins to decrease so too does the COP of the HP as evident by the electrical power consumption line. In fact the COP between 02:40 and 3:45 when the HP is outputting around 2.7kW the COP of the HP is on average just 1.27, this compares with an average COP of 1.84 between start time of 01:35 and 02:40. The drop in COP is likely a result of reduced heat transfer between the HP heating circuit and the thermal store as the thermal store temperature increases. The HP flow temperature was set at a target of 76°C and the HP controls the temperature difference between the flow and return pipes by modulating the flow rate, with an aim to maintain a delta T of 7°C between the two. As the store temperature reaches around 69°C the HP reduces the flow rate down to approximately 4.2 l/min compared to peak flow rate of 17.4 l/min, almost a factor of 4 reduction. In summary it seems more logical that the upper set-point of the thermal store might be better set at around 69°C as opposed to 75°C to avoid the significant drop-off in HP COP at higher storage temperatures. Although this decreases the storage capacity of the store by approximately 4.2 kWh (considering reduced maximum storage temperature of 6°C, tank size of 600 litres and storage medium of water).

Referring to Figure 4-13, the thermal store discharge to the house central heating system can also be analysed compared to the HP operation in direct heating mode. The average thermal power discharge from the store between the discharge start time of 15:35 and end time of 16:45 was 3.1 kW accounting for approximately 3.62 kWh of thermal energy, compared to the HP thermal power input in direct mode of an average 11 kW. During the thermal store discharge period the dining room temperature of house 64, where the heating thermostat is located, dropped from 21.7°C to 21.4°C (-0.3°C). It is evident that the thermal store was providing inadequate thermal power to heat the house in this example. The likely reason is an under sized heat exchanger coil in the thermal store or a possible drop in the water volume in the tank (discharge coil is positioned at the top of the tank).

Analysing the thermal losses of the tank based on the store temperature in Figure 4-13, a heat loss of 9°C was observed between end of storage (03:45) and start of discharge (15:35) equating to approximately 6.3 kWh of thermal energy in 11 hours and 50 minutes. With the initial heat storage input into the tank of 11.4 kWh and discharge of around 3.6 kWh, the storage efficiency is approximately 32% for this example. The heat loss is high and has a major

impact on the thermal store efficiency and practicality, couple this with the fact that the COP of the HP drops significantly when storing at temperatures above 69°C, the thermal store in this form would not be a suitable energy or cost efficient solution. This however does not detract from the smart controller functionality and generally reliable performance in providing a dynamic demand shift capable of operating to various signals which could aid in improving the electric grid balance and efficiency. A redesigned thermal store with much reduced heat loss and improved heat power output would however be required for this type of DSM methodology.
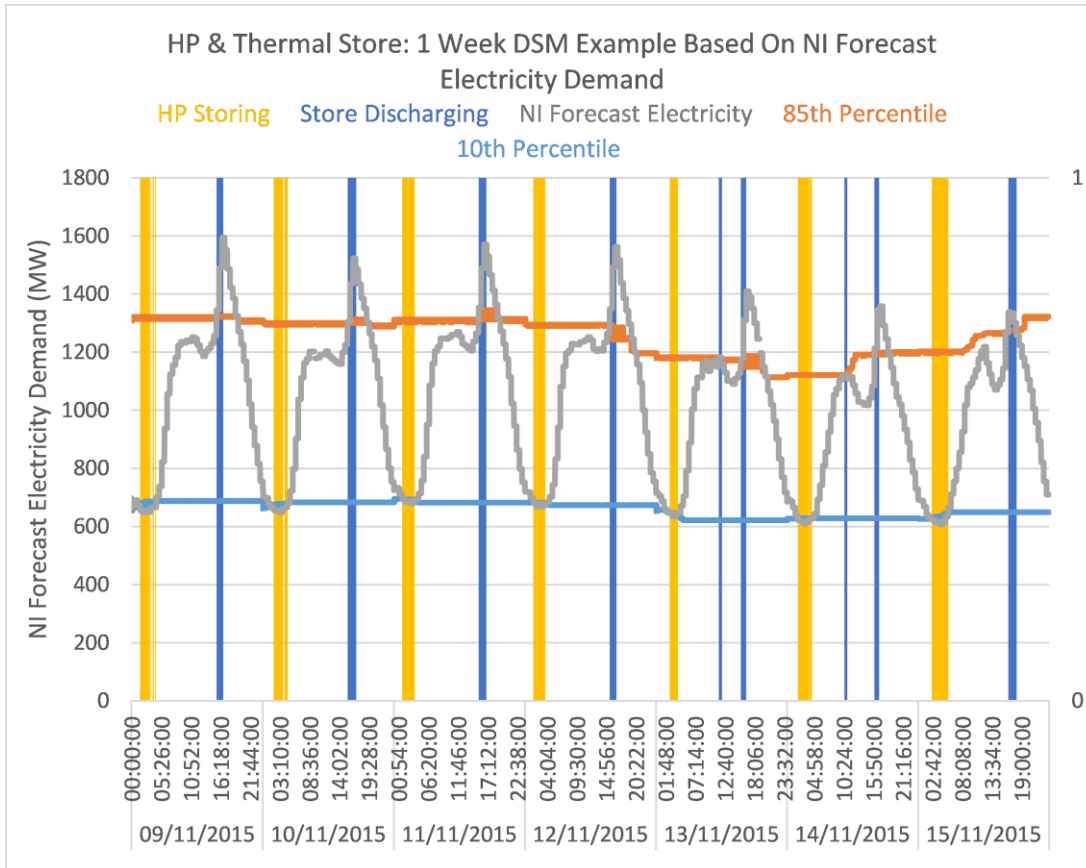
Figure 4-12 HP and thermal store: 1 week example of DSM control (09/11/15 to 15/11/15). Shown is the forecast electricity demand for NI, the controller calculated 85th percentile and 10th percentile of the forecast electricity demand, and the HP storage and thermal store discharge times.
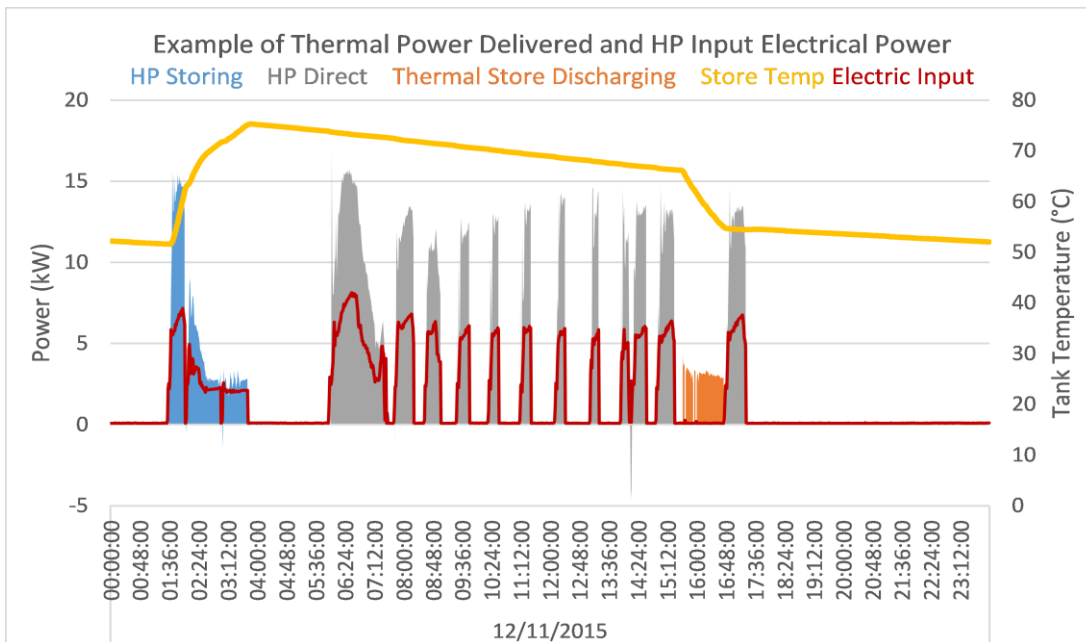
Figure 4-13 HP and thermal store thermal power comparison when storing heat in thermal store, heating house directly, and when discharging thermal store (12/11/2015). Also shown is thermal store temperature (sensor DT:15, Figure 8-1) and HP electric power consumption.

To assess the long term performance of the storage mode, Figure 4-14 was plotted showing total weekly thermal energy stored to the thermal store from the HP and the thermal energy discharged from the HP to the house. The DSM controller malfunctioned between week 42 and 45 hence the low values and weeks 24 and 49 are partial weeks hence the comparatively lower values in comparison to full weeks. It is immediately obvious from the graph that much of the thermal energy stored to the tank is lost and not utilised efficiently to heat the house. There are two elements to this: first is the high standing heat loss of the tank; and second, the DSM schedule that is used. Both have been analysed in the previous paragraphs.

Figure 4-15 shows the stacked thermal energy supplied to the house from the thermal store and from the HP directly. It is evident from the graph the relatively small proportion of heat supplied from the store compared to the total daily house heat demand. As would be expected, the heat demand increases as the outside temperature drops. The proportion of heat delivered to the house from the thermal store also becomes smaller with the extra demand being delivered direct from the HP to the house.

Table 4-1 provides a summary of energy use in each of the individual components of the heating system as to ascertain the impact of the thermal storage and DSM schedule on the overall COP. The highest COP is achieved when the HP delivers heat directly to the house (COP: 2.27). As highlighted previously, the COP in storage mode drops to 2.00, as a result of the high storage temperature and reduced heat transfer to the store at higher temperatures. When the COP of the HP providing heat to the house via the thermal store (indirect heating) is considered on its own, the COP of the system drops to 0.71. The drop in COP is a combination of firstly, the reduced COP of the HP when storing heat; secondly the standing heat loses of the thermal store from charge to discharge i.e. the physical properties of the tank; and thirdly the DSM schedule which defines the amount of time between charge and discharge of the tank. An improvement in COP could therefore be provided by improvement in the thermal store by reducing heat loss and optimising the storage temperatures of the tank and by optimising the DSM schedule (although this would be limited by the goals of the DSM itself). Looking at the heat stored to the thermal store and the heat discharged to the house, the calculated thermal efficiency of the tank is 0.35 across the testing period. It is clear that the store thermal efficiency has great potential for improvement and would have the largest impact on the indirect heating COP. Although impractical due to the size of the tank, locating the store within the heated areas of the house with good air circulation, would be a simple method of recovering this lost energy. If the heat lost from the tank provided a proportion of the space heating demand, the tank size could be reduced possibly to a size

more suited to being positioned within the home, whilst providing the same net space heating capacity as the larger tank situated outside the home.

The overall combined COP of the system, which is simply the total heat delivered to the house divided by the total electric consumption of the HP across the testing period, was calculated as 1.91 and is shown in Table 4-1. The value compares to the direct heating COP of the HP of 2.27 i.e. the impact of the thermal storage and DSM as a combined system causes a COP drop of 0.36. With this drop the system achieves a household heat demand shift of 8.68% from the lowest 10th percentile electric system demand to the highest 85th percentile system demand. To put the shift into context, if all the energy stored to the thermal store was delivered to the house i.e. 100% thermal store efficiency, a maximum demand shift of 25% of the house heating demand would have been achievable across this testing period. The combined COP is dependent on the proportion of the total house heating demand delivered by the HP in direct mode or delivered by the HP via the thermal store i.e. the greater the proportion of heat delivered directly by the HP the higher the combined COP or the greater the proportion delivered via the thermal store the lower the combined COP.

The effect of improving the thermal store efficiency on the combined system COP and demand shift potential achievable was investigated by altering the indirect COP from the measured value of 0.71, with associated tank thermal efficiency of 35%, in steps up to a tank thermal store efficiency of 100% which would equate to the indirect COP equalling the storing COP of 2.00. The calculation was applied to the house heat demand summarised in Table 4-1 and assumes as the thermal efficiency of the thermal store increase the proportion of heat supplied directly by the HP will be reduced as it is replaced by heat from the store which is lost at lower thermal efficiencies. The assumption is also made that the COP when storing will remain constant as the thermal efficiency of the store changes and that the HP COP in direct mode will also remain constant even though the HP would be running for a shorter duration in direct mode. The results are plotted in Figure 4-16. The plot provides an indication of the demand side shift potential with regards to the thermal efficiency required to achieve it when considering the installed 600 litre tank. The thermal efficiency could be improved by physically improving the tank but also by reducing the time between charge and discharge. By plotting the thermal efficiency of the thermal store versus elapsed time from discharge the effect of varying the DSM schedule (i.e. reducing or extending time shift) could be derived by comparing to Figure 4-16.
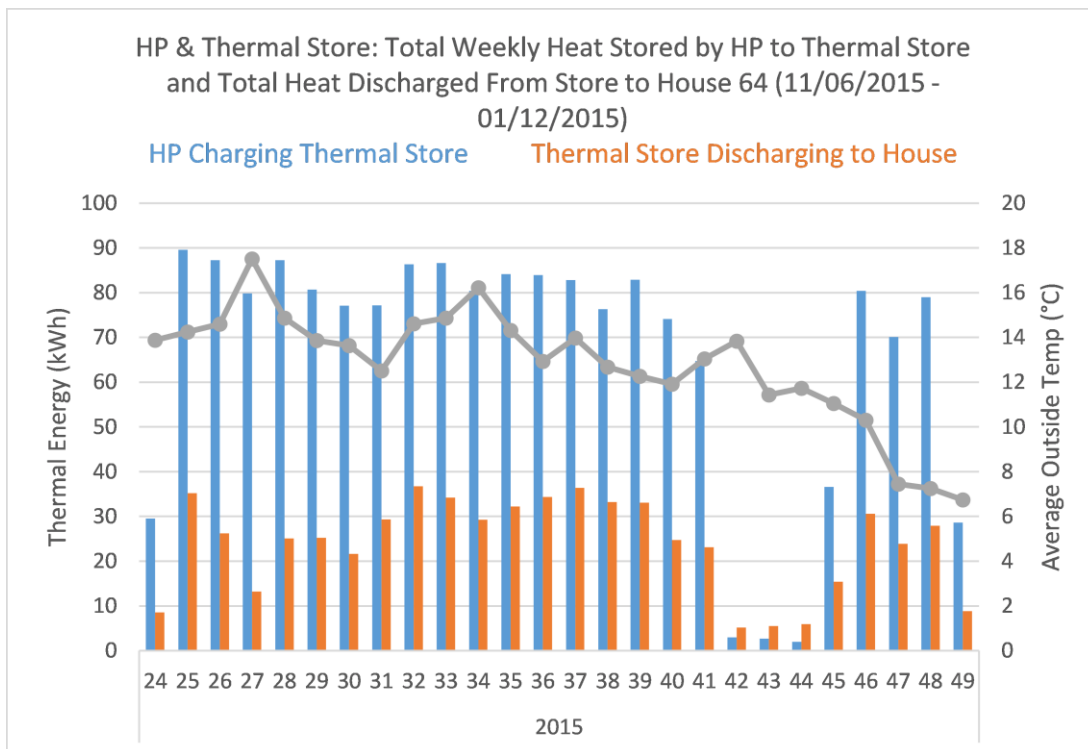
Figure 4-14 HP and thermal store weekly total heat stored by HP and weekly heat discharged to house 64 from thermal store for the period 11/06/15 – 01/12/15. Time axis is labelled week number from the start of the year. The Raspberry Pi DSM controller malfunctioned between 09/10/15 and 04/11/15 (week 42, 43, 44 and partial week 45).
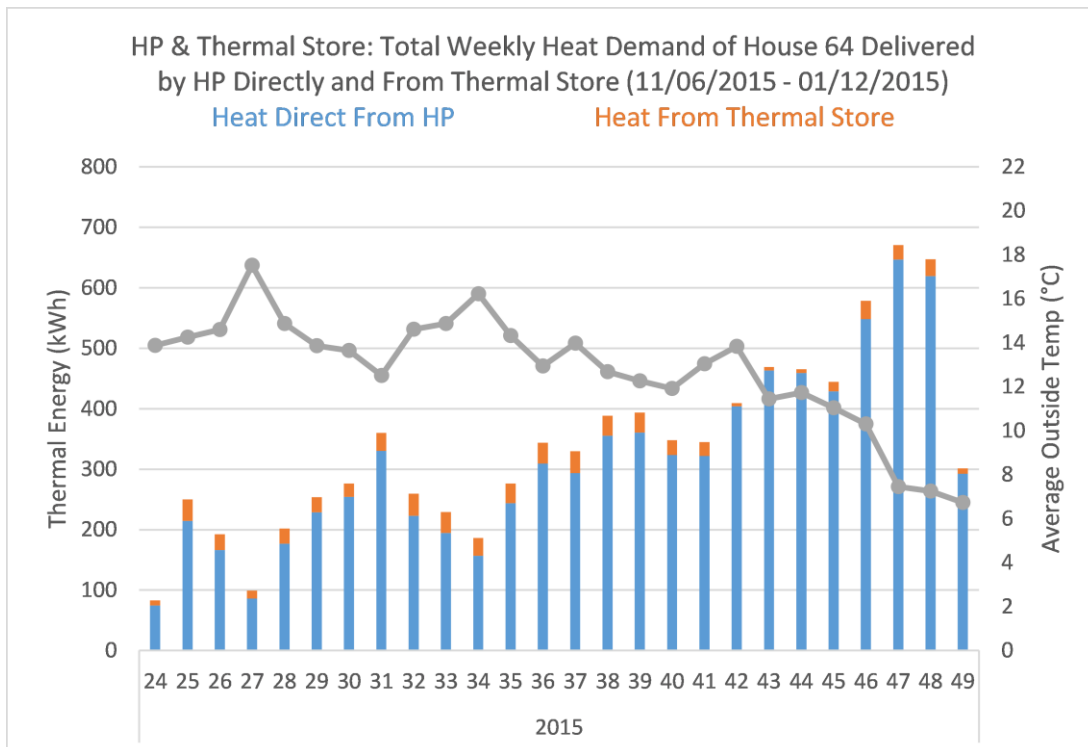
Figure 4-15 HP and thermal store weekly total heat delivered to house 64 from the HP directly or from the thermal store (stacked column) for the period between 11/06/15 – 01/12/15. Time axis is labelled week number from the start of the year. The Raspberry Pi DSM controller malfunctioned between 09/10/15 and 04/11/15 (week 42, 43, 44 and partial week 45).

Table 4-1 Summary of HP electric energy consumption and thermal energy production for the period 11/06/15 – 01/12/15 (less the period 09/10/15 – 04/11/15 when the Raspberry Pi DSM controller malfunctioned).

System Mode	HP Elec. (kWh)	HP Heat (kWh)	Heat to House (kWh)	Heating COP	Notes
Direct	2766.88	----	6291.33	2.27	HP COP when providing heat directly from HP
Storing	847.35	1692.92[1]	----	2.00	HP COP when storing heat to thermal store only
Indirect	----	----	597.86[2]	0.71	COP is heat provided from store to house/electric used by HP storing
Sum	3614.22	----	6889.19	1.91	COP is total combined system (all heat to house/all HP electric consumption)
% from store	*8.68*				
% direct	*91.32*				

*Using these values; [1]heat to store and [2]heat from store the efficiency of the thermal store is calculated as 0.35 across the testing period.
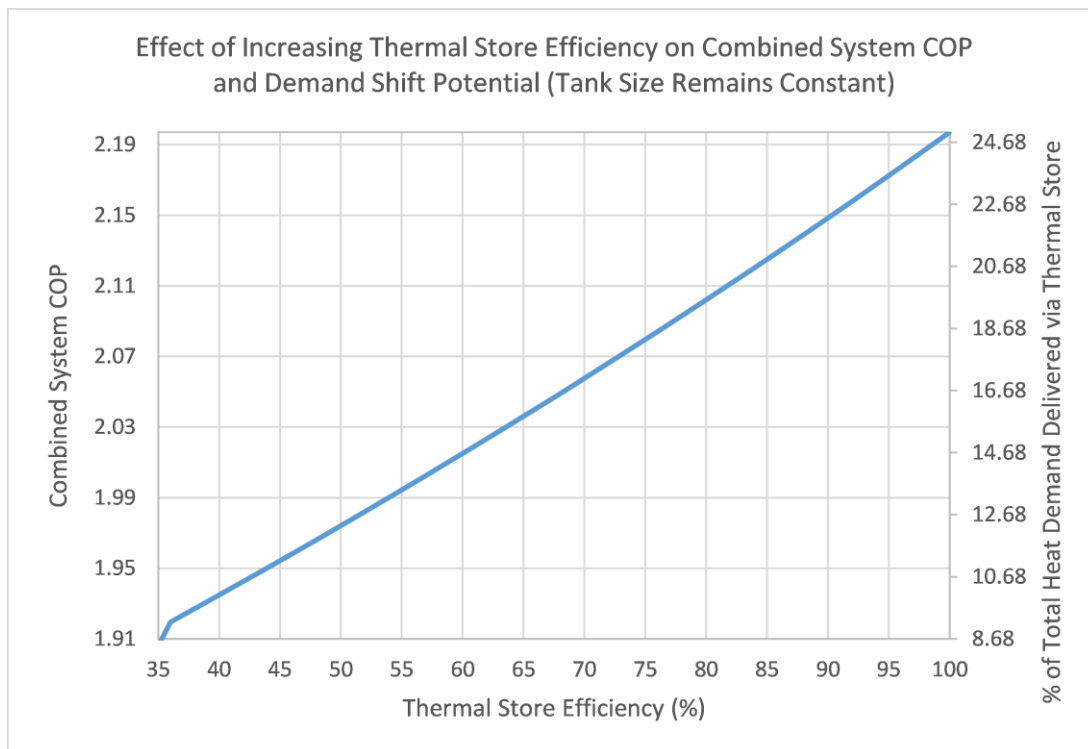
Figure 4-16 Calculated effect of increasing the thermal store efficiency (tank size remains constant) on the combined COP of the system and the percentage of total house heat demand shift that would be achievable. The calculation is based on the test period and house heat demand data summarised in Table 4-1 varying indirect COP between measured (0.71) and theoretical maximum (indirect COP = storing COP = 2.00).

The system performance across the testing period was compared to average daily outside temperature. The daily average COP of the HP in direct mode, storing mode, indirect mode (heat to house via thermal store), and overall combined system performance was plotted and is shown in Figure 4-17. The average COP of each mode has been previously summarised in Table 4-1. Comparing HP in direct mode and HP in storing mode there is a clear difference in COP performance when plotted versus the daily average temperature. The difference is a result of the lower COP when storing at higher temperatures, as discussed previously, but also as a result of storage occurring at night time and therefore lower outdoor temperatures, the impact of which is masked by plotting against a daily average temperature. In other words, the HP appears to underperform in storing mode more than it does in reality. To investigate this further the average COP of the HP in direct mode and HP in storing mode was plotted versus the outside average temperature when active in each of the respective modes i.e. if the HP was storing between 02:00 and 04:00 on any given day the storing COP was plotted against the calculated average outdoor temperature between these times and similarly for the direct mode. The results, shown in Figure 4-18, provide a truer reflection of the HP performance in each of the respective modes and it can be seen that the COP in storing mode is not as pronounced as Figure 4-17. The COP in storing mode in Figure 4-18 is however still slightly lower on average and it is believed that this is most likely due to the high temperature set-point of the thermal store and drop-off in HP COP as the set-point is approached. Reducing the set-point might improve the COP of the HP in storing mode. In addition, the COP of the two modes appear to diverge as the outside temperature increases and this may be down to how the Raspberry Pi controller heats the thermal store in a 'benefit to store' window. At higher outdoor temperatures the time taken to heat the tank will be shorter as the HP COP is higher however the 'benefit to store' window is fixed at approximately 2 hours. When the tank reaches the controller set point it will maintain the set point within the window i.e. the HP will come back on when the temperature of the store drops for a short duration to heat the tank back up to the set-point. This is more likely to happen and more frequently happen at higher outdoor temperatures. The on/off short duration nature of this cycling may explain the divergence in COP at higher outdoor temperatures. If this is the case, then the software on the controller could be modified to either switch off storage mode when the store set-point is reached and not maintain the temperature or the 'benefit to store' window could be narrowed based on historical heat up times at measured outdoor temperatures. The prior would be the simplest solution and the latter would require a database of measurements (time, tank temperature, outdoor

temperature) that could be queried based on the current measured outdoor temperature to calculate the necessary reduction in the 'benefit to store' window.

Referring to Figure 4-17 and the thermal store series (heat provided to house via thermal store), a highly variable COP with changing outside temperature is observed. The COP when delivered via the thermal store is most influenced by the heat loss between storage and discharge rather than the outside temperature, hence the low R^2 value for the series. The variability is increased on several days were the thermal store is charged but does not discharge to the house, resulting in average daily calculated COP of zero. This variability increases at higher outdoor temperatures when there would be a lower heat demand from the house. Hence the most likely reason for the thermal store not discharging to the house is that the call-for-heat from the house and the Raspberry Pi controller 'benefit-to-use' window do not coincide on these days. This in turn will have an effect on subsequent days as slightly less heat will be required to increase the store up to set point temperature resulting in a higher than average COP on these days and therefore further exacerbating the variability of the thermal store series in Figure 4-17. Modification to the controller software to reduce this issue could involve changing the 'benefit-to-use' window for example: making it larger resulting in greater likelihood of call-for-heat and the window coinciding, although this would be detrimental on days of high heat demand; adding code to ensure the thermal store discharges after the 'benefit-to-store' window closes if the store still has charge i.e. window extended until midnight of that day; or develop the controller software further so that a learning database can be queried to reduce or prevent storage based on historical heat demand at measured outside temperatures and forecast day ahead weather temperatures. The latter would prove most difficult, but the controller would effectively be able to adapt to individual households by learning from historical data.

The final series plotted on Figure 4-17 is the overall combined system COP versus the daily average outdoor temperature. Like the thermal store plot, a high degree of variability can be seen. The variability seen in the thermal store plot previously discussed carries through to this series and results in dragging the COP correlation negative with respect to daily average temperature. In addition, the COP of the combined system tends to reduce with higher daily average temperatures as a result of the increased proportion of the total heat demand delivered via the thermal store. The proportional change of heat delivered directly versus via the thermal store is illustrated in Figure 4-19.
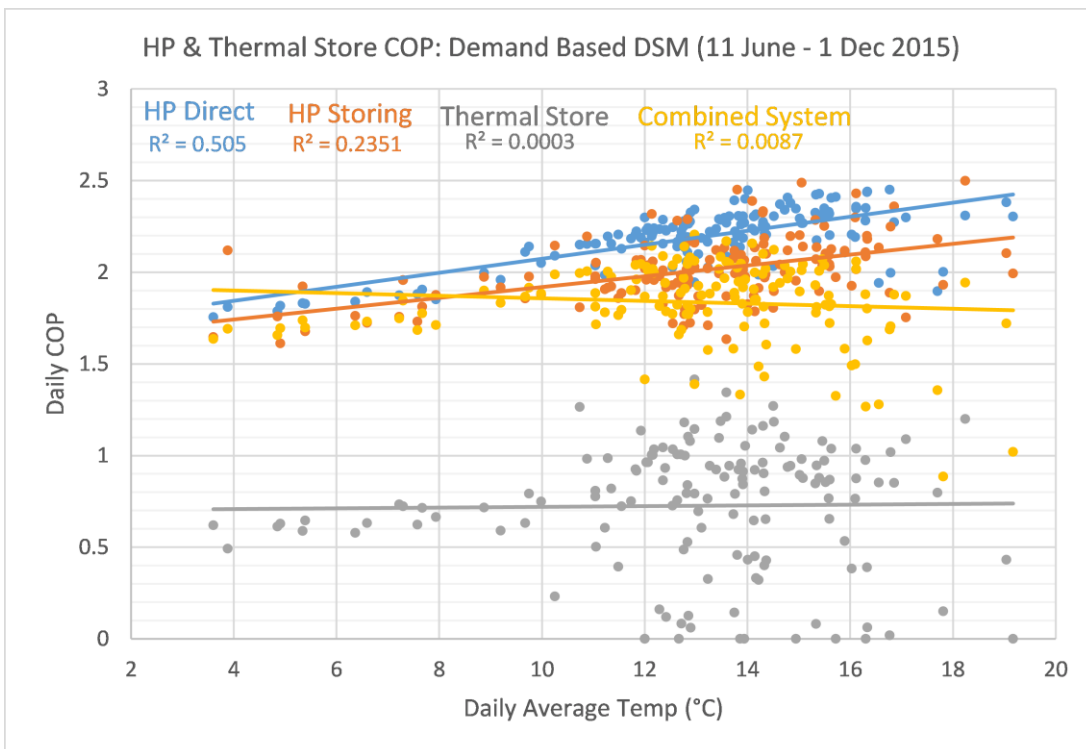
Figure 4-17 Daily average HP COP for HP in direct mode, storing mode, indirect mode (heat to house via thermal store), and overall combined system versus daily average outside temperature for demand based DSM testing period between 11/06/2015 and 01/12/2015.
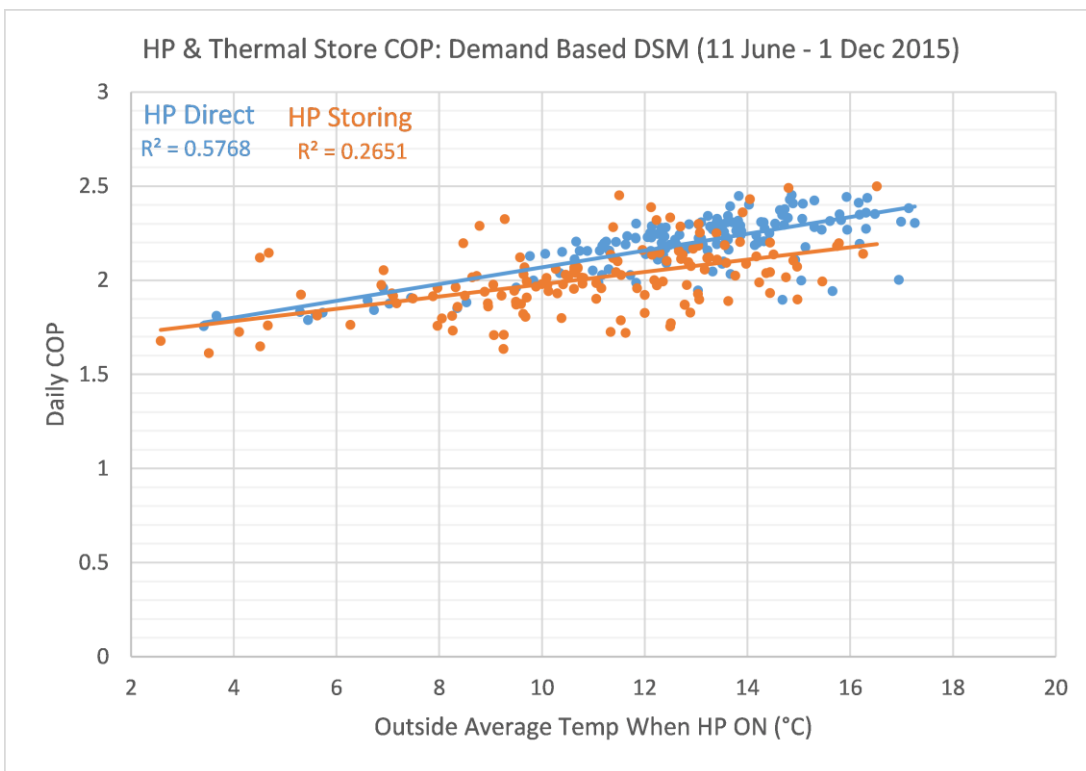
Figure 4-18 Daily average HP COP for HP in direct heating mode and HP in storing mode. The data series are plotted against the average outside temperature when each respective mode was active as opposed to daily average outside temperature used in Figure 4-17.
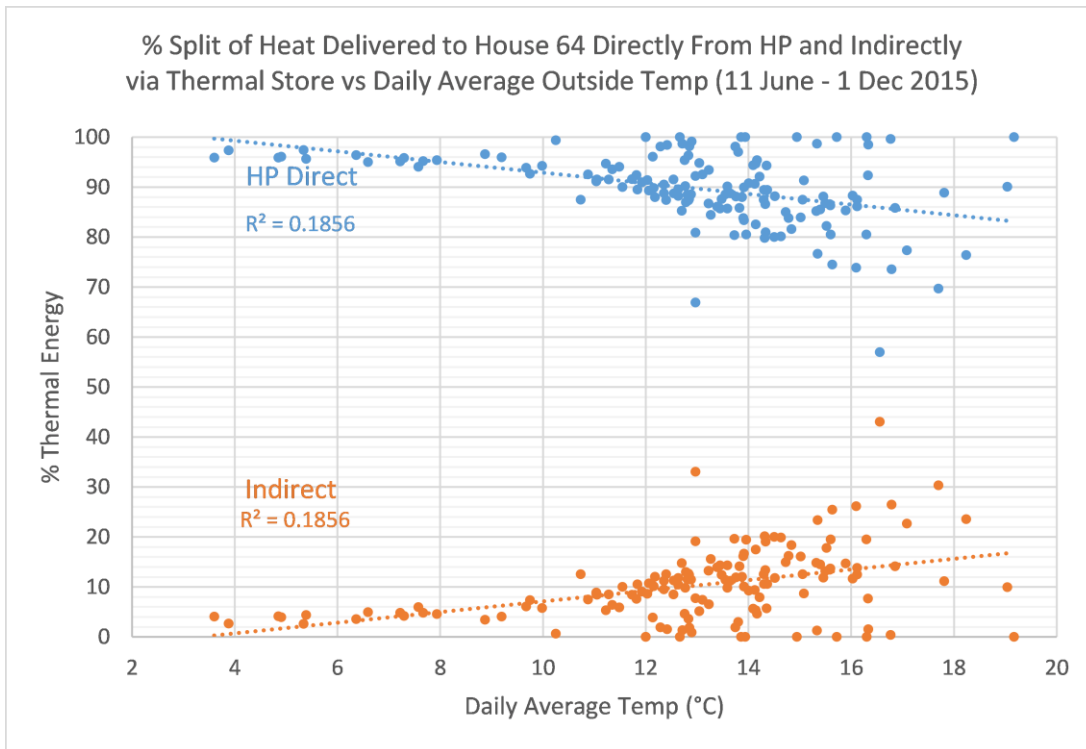
Figure 4-19 Percentage split of heat delivered to house directly from the HP and via thermal store versus daily average outside temperature for demand based DSM testing period between 11/06/2015 and 01/12/2015.

The calculated COP for each of the modes plotted in Figure 4-17 were used to calculate the cost of thermal energy (Figure 4-20) to provide a comparative assessment in subsequent testing regimes. In addition, the cost of thermal using the Economy 7 domestic electricity tariff was also calculated and is presented in Figure 4-21.

The cost of thermal at the standard domestic price varies in line with daily average COP as they are a direct ratio of one and other. The poor COP of the thermal store mode results in the thermal energy costing more than the unit rate of electric to produce it, 12 p/kWh electric, compared to an average of 16 p/kWh thermal. The combined mode compared to the HP in direct mode results in an average increase of 1.2 p/kWh of thermal energy delivered to the house. To put the value into context using the annual heat demand of house 64 detailed in section 4.1 for 2015 and 2016, an increase of 1.2 p/kWh thermal would increase the annual heating bill by £294.80 and £279.88 respectively.

Comparing Figure 4-20 and Figure 4-21 it can be seen that the cost of storing to the thermal store is reduced significantly below the HP in direct mode for the Economy 7 tariff. In addition, the HP in direct mode is cheaper in the Economy 7 tariff at higher ambient temperatures but at lower temperatures it starts to become more expensive compared to the standard tariff. The reason for this is the higher demand at lower outside temperatures and therefore greater proportion of heat required at the higher Economy 7 day rate. Conversely, at higher outside temperatures a greater proportion of heat is provided at the lower night time rate. The trend of lower cost of thermal at higher outside temperatures is also dependant on the heating schedule of the house i.e. for house 64 the heating tends to come on in the morning and therefore takes advantage of the lower tariff before 08:00 GMT. However different consumers may tend to use there heating predominately in the evening and therefore be disadvantaged by the higher day time rate resulting in a higher cost of thermal in direct heating mode even at higher outside temperatures compared to a standard tariff rate. The effect on the combined mode of using the Economy 7 tariff is a clear reduction in thermal cost with increasing outside temperature compared to the standard tariff.

A statistical comparison of the cost of thermal energy using the two tariffs is summarised in Table 4-2. Analysing Table 4-2 there are a number of points to make regarding the comparison of the two tariffs which include:

- The Economy 7 tariff reduces the cost of thermal across all modes with the most significant reduction for the HP storing and thermal store mode as this has the greatest proportion within the night time tariff. This greatly increases the feasibility of the thermal

store even with the efficiency issues previously identified although the thermal store mode is still considerably above the HP direct fixed tariff price.

- The average HP direct fixed tariff price is equal to the average combined economy 7 tariff price. With the potential efficiency improvements possible for the thermal storage, there is an opportunity for reducing the combined cost of thermal energy using the DSM model.

- However, it should be noted that the cost of thermal energy with the HP in direct mode on the Economy 7 tariff is also reduced to a price of 5.0 p/kWh thermal. It is difficult to assess whether there is great enough financial incentive considering the current system efficiency and increased capital cost and floor space that would be required with the thermal storage system to encourage significant uptake. In addition, all other domestic electric consumed at the day rate in the house is subject to a higher cost of 2.25 p/kWh electric which may have the effect of cancelling out any financial benefit gained from shifting thermal loads.

Table 4-2 Statistical summary comparison of cost of thermal energy (£/kWh) of HP and thermal store demand based DSM across testing period 11th June – 1st December 2015. The tariffs compared are cheapest domestic electricity tariffs for Northern Ireland as of August 2017: (1) standard fixed rate 12p/kWh (The Consumer Council NI, 2017b); (2) economy 7 rate of 6.95p/kWh (night rate between 01:00 – 08:00 GMT) and 14.25p/kWh (day rate 00:00 – 01:00 and 08:00 - 00:00) (The Consumer Council NI, 2017a).

Mode:	HP Direct		HP Storing		Thermal Store		Combined	
Tariff:	Fixed	Econ 7	Fixed	Econ 7	Fixed	Econ 7	Fixed	Econ 7
Average	0.055	0.050	0.060	0.036	0.160	0.096	0.067	0.055
Median	0.054	0.048	0.060	0.035	0.140	0.082	0.064	0.053
Lower Quartile	0.052	0.045	0.057	0.033	0.120	0.071	0.060	0.050
Upper Quartile	0.056	0.052	0.063	0.037	0.184	0.110	0.069	0.059
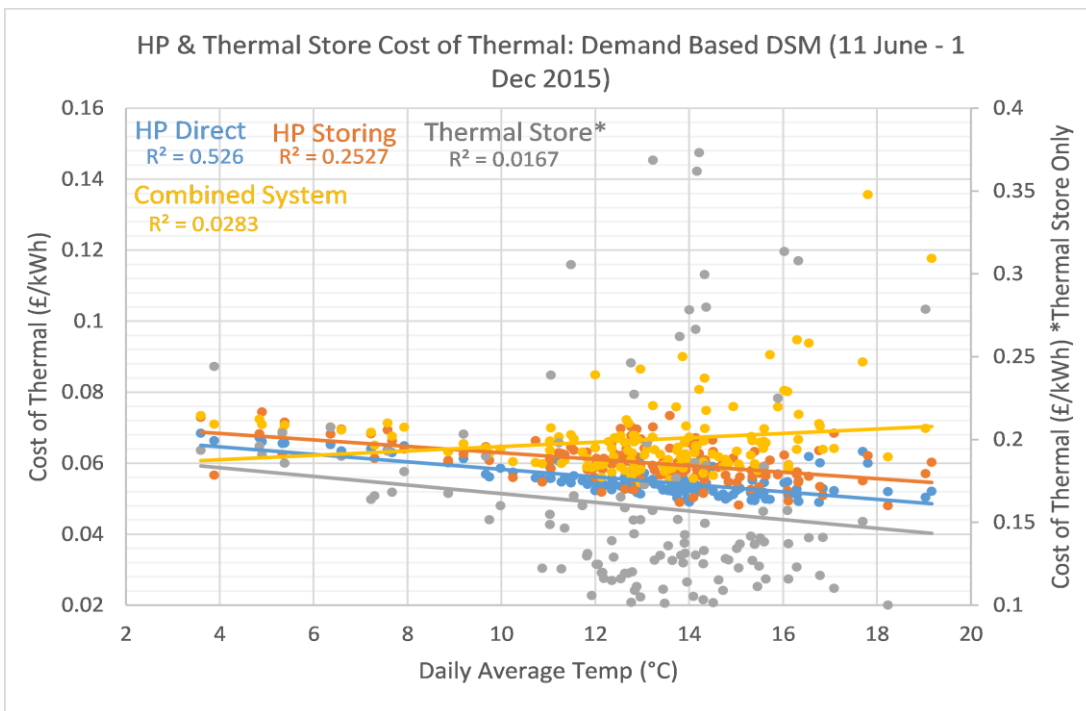
Figure 4-20 Daily average cost per kWh thermal energy versus daily average outdoor temperature for HP in direct, storing, indirect (thermal store), and total combined system mode using demand based DSM strategy. Thermal cost is calculated using domestic electricity price of £0.12/kWh based on cheapest domestic fuel prices (The Consumer Council NI, 2017b).
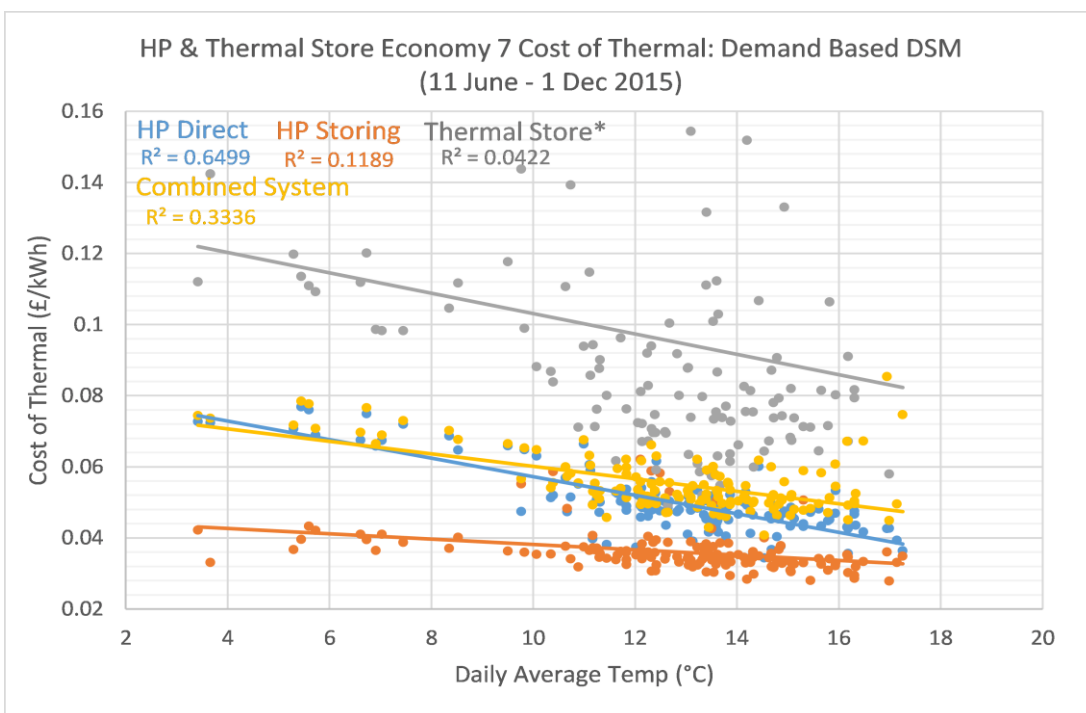
Figure 4-21 Daily average cost per kWh thermal energy versus daily average outdoor temperature for HP in direct, storing, indirect (thermal store), and total combined system mode using demand based DSM strategy. Thermal cost is calculated using domestic electricity Economy 7 rate of 6.95p/kWh (night rate between 01:00 – 08:00 GMT) and 14.25p/kWh (day rate 00:00 – 01:00 and 08:00 - 00:00) (The Consumer Council NI, 2017a).

The calculated COPs for each of the modes plotted in Figure 4-17 were used to calculate the CO_2e intensity per kWh of thermal energy (Figure 4-22). The CO_2e intensity varies in line with daily average COP as they are a direct ratio of one and other. The intensity values are calculated using the UK GHG factors for 2017 which provides an average factor for the year dependant on the mixture of generation sources within that year. However, to provide a better context of how CO_2e intensity varies across the day for Northern Ireland, Ireland, and on a combined All-Island basis, Figure 4-23 has been included. The data for the graph is sourced from the system operator EirGrid (EirGrid Group, 2017). The graph shows the average CO_2 intensity of the electricity generated by hour of day for 2017. The most obvious observation from the graph is the high CO_2 intensity of Northern Ireland at night time (low system demand) peaking at an average of 1022 gCO_2/kWh electricity generated. The peak intensity corresponds approximately to the low system demand times used to calculate the best time to store window for the HP and thermal storage system. It is obvious then for Northern Ireland that the result of trying to avoid the HP impacting on peak system demand by shifting thermal energy from the low morning demand will theoretically result in the utilisation of electricity with a higher CO_2 intensity. The word theoretically is used because the CO_2 intensity of Northern Ireland tends to be on average greater at night, compared to for example Ireland, because of coal fired and higher intensity conventional generation providing most of the base-load generation at the time of low system demand. Limits on non-synchronous renewable generation penetration as a ratio of total generation exacerbate the predominance of the high intensity generation at night time also. Therefore, theoretically increasing the demand at night time will allow a greater proportion of wind energy to be utilised on the grid putting downward pressure on the CO_2 intensity of electricity generation to a profile similar to that of Ireland also shown in Figure 4-23. It is worth noting also that for Northern Ireland the issue will be somewhat alleviated by the construction of a North-South interconnector providing greater connection between the electricity grids of Ireland and Northern Ireland. In addition, the higher intensity coal burning generators in Northern Ireland will be forced to close due to increasing environmental standards by 2024 at the latest. It is therefore thought that increased utilisation of renewable energy that may otherwise have to be curtailed will have a net positive effect in reducing the carbon intensity of electricity generation in the longer term although it may not seem logical in the shorter term judging by Figure 4-23. Therefore, the demand shifting algorithm used is also justifiable however consideration could be given in future work with regards to real time or forecast CO_2 intensity as a demand shifting signal. The aim would be to provide a means of greater renewable energy penetration onto the electricity grid.
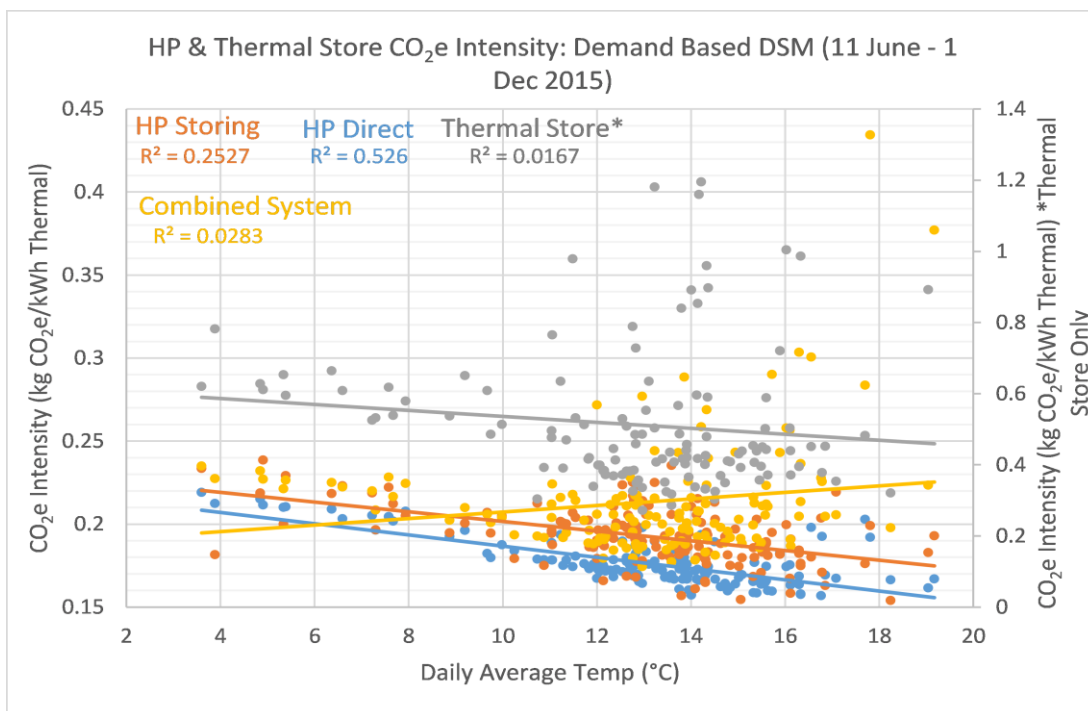
Figure 4-22 Daily average CO₂e intensity per kWh thermal delivered by HP versus daily average outdoor temperature for HP in direct, storing, indirect (thermal store), and total combined system mode using demand based DSM strategy. The calculation uses UK GHG factors for 2017 (BEIS, 2017b). Electricity GHG is inclusive of transmission and distribution GHG factor. Note thermal store plotted on secondary vertical axis.
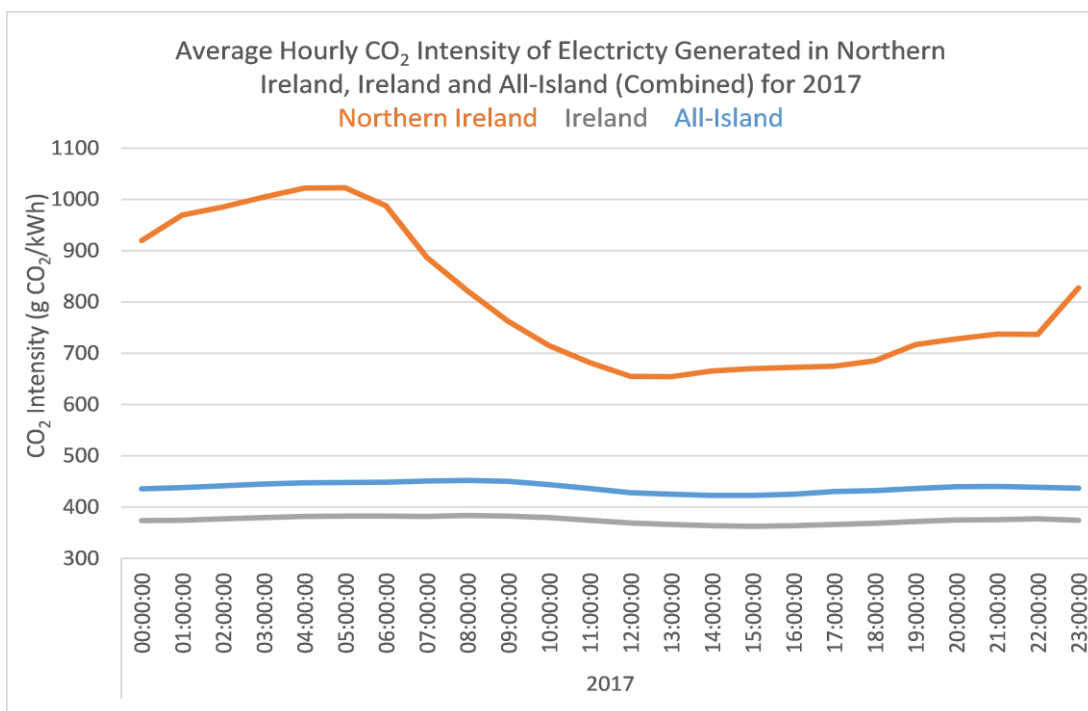
Figure 4-23 Average hourly CO₂ intensity per kWh of electricity generated in Northern Ireland, Ireland, and on an All-Island basis for 2017. Data source from the system operator EirGrid (EirGrid Group, 2017).

In summary the main impacts on the total combined COP (and subsequently cost of thermal per kWh and CO_2e intensity per kWh thermal) compared to direct heating mode are:

1. Heat loss from thermal store between charge and discharge and therefore increased reduction in combined COP as proportion of heat delivered via thermal store increases.
2. Impact of reduced COP as a result of storing at lower night time temperatures as opposed to providing heat directly when required.
3. Controller software reheating thermal store after set-point reached resulting in short cycling of HP.
4. Days when charged thermal store not utilised due to higher outside temperatures and therefore call-for-heat from house and 'benefit-to-use' window not coinciding. Controller software modification could avoid or at least reduce this impact.

4.4.2   Store at Low Demand & Use at 1st Call for Heat

The heat pump was run using demand-based DSM in conjunction with the thermal store between 1st December 2015 and 27 September 2016. The DSM consisted of storing energy to the thermal store at the lowest daily system demand and using it at any call for heat after storage as detailed in section 3.4.3.2 and summarised in Table 3.8. On the 19/01/2016 an extra 100mm glass fibre mineral wool was added to the thermal store to improve the thermal efficiency of the tank (shown in Figure 3-8), the DSM algorithm was unaltered.

One week of actual data recorded by the controller is illustrated in Figure 4-24 showing the forecast electricity demand retrieved from the system operator, the calculated 85th and 10th percentile of the forecast demand, and the periods of time when the HP was storing to the thermal store and when the thermal store was discharging to the house. When the forecast electricity data is below the calculated 10th percentile the controller will initiate the HP to store thermal energy up to 75°C and maintain it until the forecast demand data is above the 10th percentile. The thermal store was discharged at the first house call for heat after storage until the thermal store temperature reached 55°C.

The only alteration to the algorithm compared to that discussed in section 4.4.1 and more specifically in relation to Figure 4-12, is the change in the discharge time of the thermal store, therefore discussion of Figure 4-24 is limited to this specific change to avoid repetition. The store discharging lines represent the time when there is no benefit to store, regardless of store temperature, and when there is available useful thermal charge in the store. From the figure it observed that there are days when the blue store discharging line falls between the HP storing line, for example on the 18th December 2017. As discussed in section 4.4.1, this is a result of how the algorithm assesses the benefit to store using system forecast demand 24 hours ahead rather than within day midnight to midnight. As a result, the low demand 24 hours ahead has an influence on the calculated low demand threshold in the current day which can cause the HP charging cycle to be disrupted for example which in turn may reduce the HP storing COP. This problem was alleviated in the market price-based hybrid system as indicated in the data source column of Table 3-8 by changing the DSM algorithm to use the in-day data from the system operator (midnight to midnight).

An example of the system operating on the 17th December 2015 is shown in Figure 4-25. The figure compares the: thermal power output of the HP when storing to the thermal store; thermal power output of the HP when heating the house directly; the thermal power output of store to the house when discharging; the thermal store temperature; and the electrical

power input to the HP. The HP is activated for storage at 01:35 and runs for 3 hours 14 minutes until 04:49 raising the thermal store temperature from 59.1°C to 75.1°C. The HP reaches a thermal maximum power output of 11.2kW at 1:45, 10 minutes after start up, at which point the thermal store temperature has increased to 51.6°C. Thermal power output then decreases steadily to a constant thermal power output of approximately 3.1kW which is reached at 2:30 at which point the thermal store has increased to a temperature of 59.6°C. As the thermal power output of the HP begins to decrease so too does the COP of the HP as evident by the electrical power consumption line. In fact, the COP between 02:30 and 04:49 when the HP is outputting around 3.1kW the COP of the HP is on average just 1.51, this compares with an average COP of 1.92 between start time of 01:35 and 02:30.

It was interpreted in section 4.4.1 that the drop in COP when storing was likely to be as a result of reduced heat transfer between the HP heating circuit and the thermal store as the thermal store temperature increases. This was particularly evident in Figure 4-13 as the thermal store temperature approached 69°C at which point the HP modulated the thermal output by reducing the flow rate in order to maintain a constant delta T of 7°C between the flow and return (HP flow temperature was set at a target of 76°C). In this instance the HP appears to have modulated the thermal output down earlier i.e. as the thermal store approached 60°C. It was noted in the log of controller changes that the HP was set to run on weather compensation mode from 1st December 2015 onwards and this is the likely explanation for the difference in the peak thermal output when storing on 17th December 2015 and 12th November 2015 (Figure 4-13) and for the HP reducing thermal output earlier (weather compensation reduces flow set-point based on outdoor temperature). The fact that the average outdoor temperature on the 11th November 2015 when storing was 8.3°C as opposed to 12.1°C on the 17 December 2015, supports this. In addition, the reduction in thermal power output earlier on 17th December 2015 leads to a longer time to reach the thermal store set-point programmed on the Raspberry Pi DSM controller compared to the 11th November 2015.

Referring to Figure 4-25, the thermal store discharge to the house central heating system can also be analysed compared to the HP operation in direct heating mode. The average thermal power discharge from the store between the discharge start time of 05:58 and end time of 06:48 was 7.96 kW accounting for approximately 6.76 kWh of thermal energy, compared to the HP thermal power input in direct mode of an average 9 kW. During the thermal store discharge period the dining room temperature of house 64, where the heating thermostat is located, increased from 19.8°C to 20.4°C (0.6°C). This compares to the DSM example outlined

in section 4.4.1, Figure 4-13, in which the thermal store was discharged at peak system demand in the evening providing an average of 3.1 kW from the thermal store and an observed temperature drop in the dining room of 0.3°C. The thermal output is higher from the store for two reasons, firstly the central heating system is cold and therefore there is a much better heat transfer from the thermal store to it, and secondly there is only one hour between the thermal store reaching the set-point store temperature of 75°C and the first call for heat from the house and therefore standing heat loss from the tank is greatly reduced.

Analysing the thermal losses of the tank based on the store temperature in Figure 4-25, a heat loss of 1.1°C was observed between end of storage (04:50, 75.4°C) and start of discharge (05:58, 74.3°C) equating to approximately 0.77 kWh of thermal energy in 1 hour and 8 minutes. With the initial heat storage input into the tank of 12.17 kWh and discharge of around 6.76 kWh, the storage efficiency is approximately 56% for this example. The energy loss and storage efficiency compares to values of 6.3 kWh and 32% respectively for the evening based DSM in section 4.4.1, Figure 4-13.

Although the heat loss is greatly reduced by discharging the thermal store at the first call-for-heat after storing, the storage efficiency, although it significantly increases, is still affected by the starting temperature of the store when it is being charged. In other words, after the store is fully discharged (55°C and below) the store will continue to drop in temperature below 55°C and therefore energy content until it is next charged. The longer the time between discharge and charge the greater the difference will be and therefore the greater the amount of energy that will be required to charge the tank up above 55°C above which is defined as useful stored energy. Therefore, it is realised that it is not only the time between charge and discharge which affects the tank storage efficiency but also the time between discharge and charge.

In summary by using the thermal storage at the first call-for-heat after storage compared to evening discharge:

- Improves the thermal power output of the tank due to higher temperature difference between the central heating system fluid and the store.
- Increases thermal energy transferred to the house due to reduced standing heat loss to the environment. Thermal energy transferred almost doubles and therefore storage efficiency increases.
- Continued temperature drop after discharge and increased time until next charge impacts the efficiency of the thermal store.
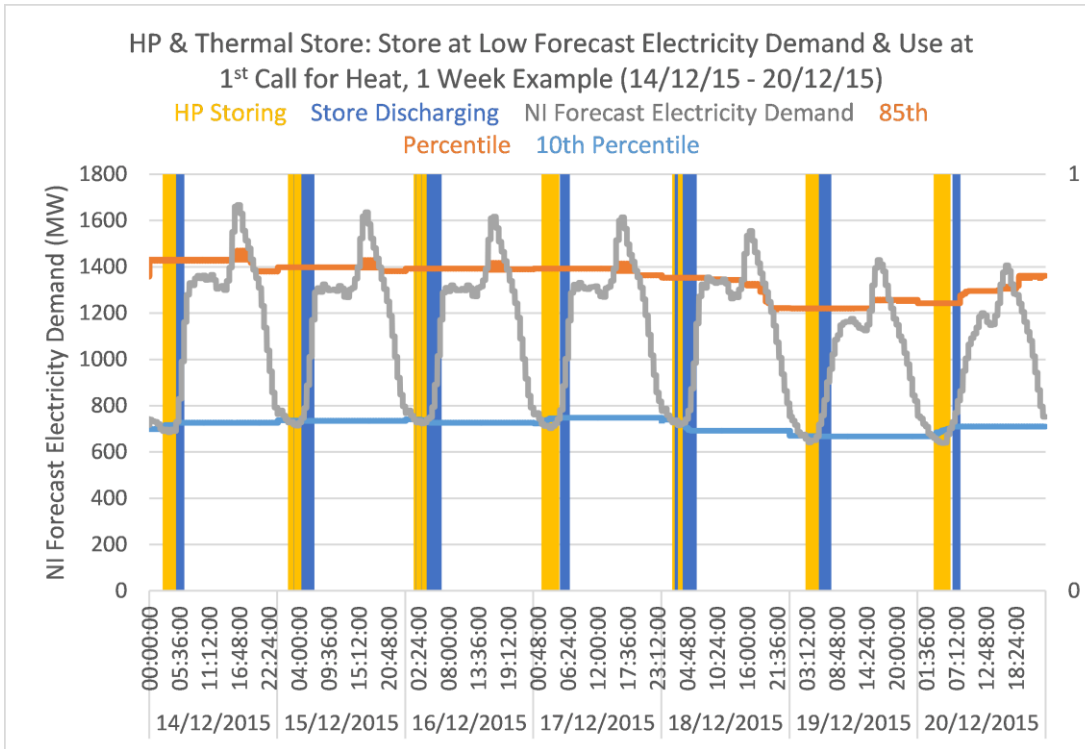
Figure 4-24 HP and thermal store 1 week example of DSM control (14/12/15 to 20/12/15). Shown is the forecast electricity demand for NI, the controller calculated 85th percentile and 10th percentile of the forecast electricity demand, and the HP storage and thermal store discharge times.
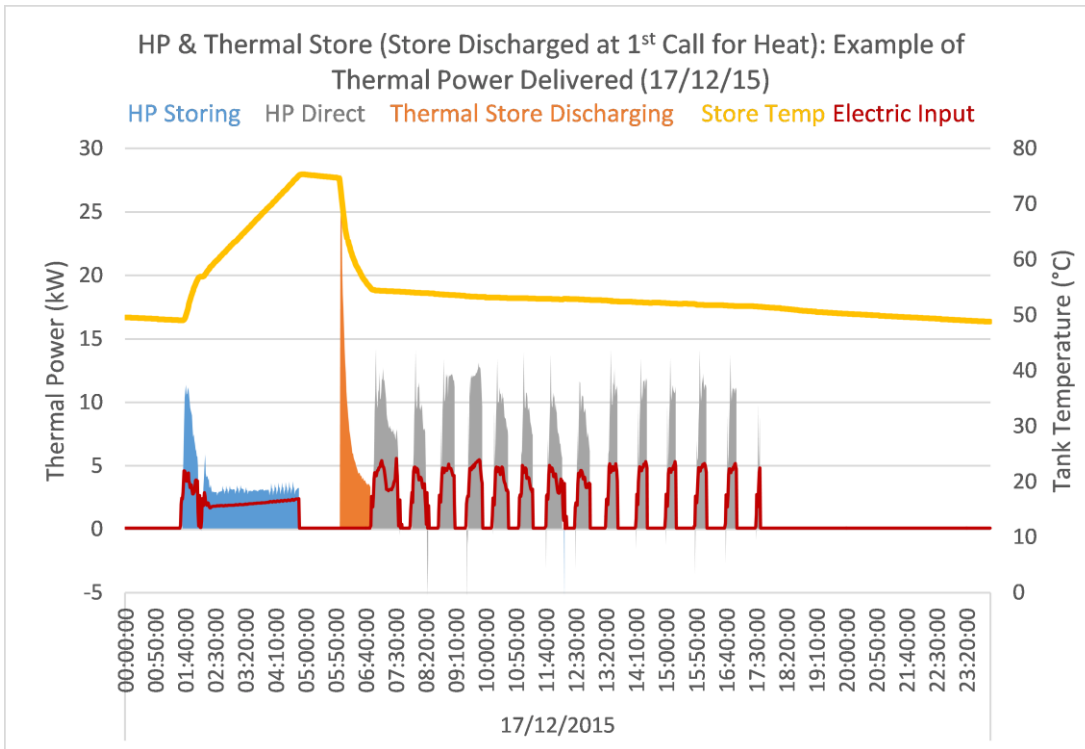
Figure 4-25 HP and thermal store thermal power comparison when storing heat in thermal store, heating house directly, and when discharging thermal store (17/12/2015). Also shown is thermal store temperature (sensor DT:15, Figure 8-1) and HP electric power consumption.

The remainder of this section will assess the long-term performance of the storage mode. Analysis identified several dates of which flow meter readings were inaccurate and this is evident in Figure 4-26 and Figure 4-27. Subsequently the erroneous data has been removed from the figures and tables which follow within this section after Figure 4-27. The dates include 28/08/16 – 02/09/16 (week 38) and 07/09/16 – 19/09/16 (partial week 37, week 38, partial week 39) inclusive. The malfunction was a result of a bad voltage supply to two of the flowmeters pulse output switches resulting in clearly erroneous data. The error was spotted at the time and rectified. An error with the data logger downloading files to the networked computer occurred between 15/04/2016 – 28/04/2016 (partial week 16, week 17, and partial week 18) as a result of network problems, that data was unfortunately lost. There was also an increase in the number of times (although still infrequent) that the EirGrid website, from which the electricity system data was sourced, became unreachable due to the site being offline. On these days there was therefore no data from which the controller could calculate the benefit-to-store and benefit-to-use windows and sometimes this resulted in the thermal store not being charged or discharged or in some cases interrupted during a charge or discharge event. Further iterations of the controlling software in subsequent tests reduced the impact of this by modifying the software so that the impact of intermittent network errors lasting less than 10 minutes had no effect on the DSM.

To assess the long term performance of the storage mode, Figure 4-26 and Figure 4-27 were plotted showing total weekly thermal energy stored to the thermal store from the HP and the thermal energy discharged from the HP to the house. In addition, the data is statistically summarised in Table 4-3 to give the total heat delivered, daily average and daily median to the store, indirectly from the store to the house, and directly from the HP to the house. Also included are the daily average and daily median of the outside temperature. Even though the time of discharge was moved forward to the first call-for-heat, for example on the 17/12/2015 the time between end of charge and start of discharge was only 50 minutes, the ratio of energy stored to tank to energy discharged to the house (Figure 4-25) is still low and this is clearly evident in Figure 4-26. The controlling factor of the tank efficiency is therefore the standing heat loss of the tank and although reducing the time between charging and discharging will improve this efficiency, because the tank will be at a lower temperature for longer compared to evening discharge, there is still on average 24 hours between each charge cycle irrespective of the discharge time.

Figure 4-27 shows the stacked thermal energy supplied to the house from the thermal store and from the HP directly. It is evident from the graph the relatively small proportion of heat

supplied from the store compared to the total daily house heat demand. As would be expected, the heat demand increases as the outside temperature drops. The proportion of heat delivered to the house from the thermal store also becomes smaller with the extra demand being delivered direct from the HP to the house. This is more clearly illustrated in Figure 4-28.

To provide further analysis by drilling down into the data used to create Figure 4-26 and Figure 4-27 a statistical summary was provided in Table 4-3. Firstly, comparing the HP storing energy before and after the thermal store insulation was added, a drop of 2.29 kWh is observed between the daily averages after the insulation was added, for which the outside average temperature was 6.9°C and 11.4°C respectively. The tank was charged and discharged to the same set-points and the shed where the thermal store was housed was maintained at a constant temperature using thermostatic electric heaters. Therefore, although there is a significant difference between the outdoor temperatures before and after the insulation was added it is more likely that the extra insulation resulted in less heat being required to heat the store up to the high set-point due to reduced heat loss. Secondly, comparing the thermal energy provided from the thermal store to the house before and after the extra insulation was added to the tank, a drop of 0.55 kWh is observed between the daily averages after the insulation was added, for which the outside average temperature was 6.9°C and 11.4°C respectively. The drop, although small, is contrary to what would be expected. It would be logical to think that as the thermal insulation is increased, the standing heat loss to the surrounding environment would decrease, and therefore the thermal energy available to the house from the store would increase. It is possible that over time some of the water content of the store has been lost through evaporation as it is a vented cylinder. If this were to be the case this would also contribute to a reduction in thermal energy being stored to the tank over time, however the ratio of thermal energy discharging to thermal energy charging, the efficiency, should remain fairly constant assuming the store is fully charged and discharged each day. Finally, a considerable drop of 34.7 kWh in average daily thermal energy supplied to the house directly from the HP is observed which is also clearly illustrated in Figure 4-27 before and after the insulation is added. The drop is in line with increasing daily average outside temperature from 6.9 °C to 11.4°C and unrelated to the insulation improvement of the tank. As a result however the thermal store provides an increased proportion of the total house heat demand as it reduces in line with increasing outside temperature. This is clearly illustrated in Figure 4-28.
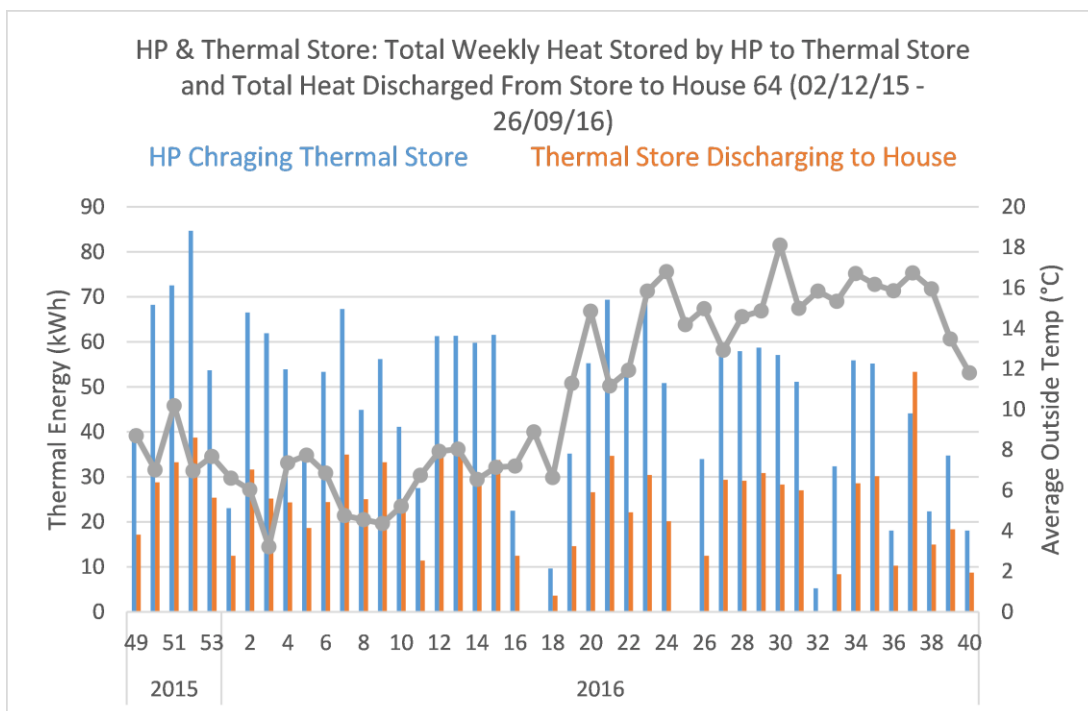
Figure 4-26 HP and thermal store weekly total heat stored by HP and weekly heat discharged to house 64 from thermal store for the period 02/12/15 – 26/09/16. Time axis is labelled week number from the start of the year. Also included is average outside temperature.
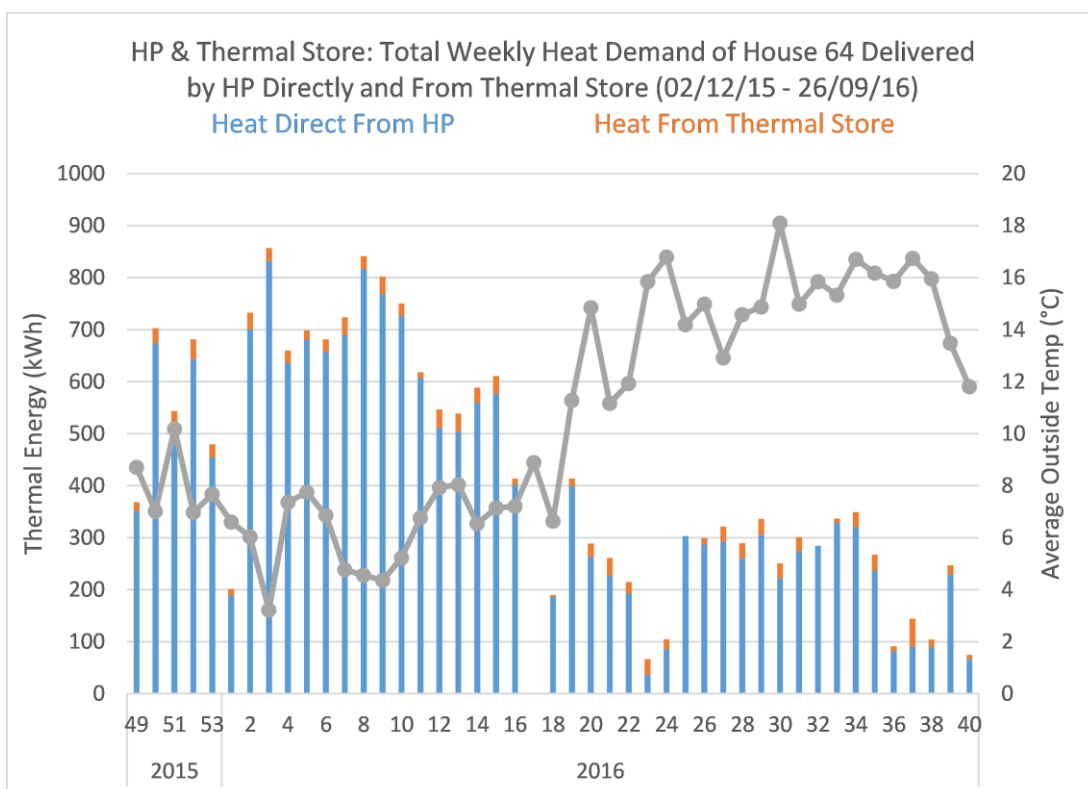
Figure 4-27 HP and thermal store weekly total heat delivered to house 64 from the HP directly or from the thermal store (stacked column) for the period between 02/12/15 – 26/09/16. Time axis is labelled week number from the start of the year. Also included is average outside temperature.

Table 4-3 Statistical summary of thermal energy delivered to the thermal store, from the thermal store to the house (indirect), and directly from the HP to the house for the DSM testing period between 02/12/2015 and 26/09/2016. The data is split between two dates between 02/12/2015 – 19/01/2016 before extra tank insulation added and between 20/01/2016 – 26/09/2016 after additional 100mm mineral wool added to thermal store.

Date	Statistic	HP Heat Storing (kWh)	House Heat Indirect (kWh)	House Heat Direct (kWh)	Outside Temp (°C)
02/12/2015 - 19/01/2016	Sum	507.18	229.56	4630.10	----
20/01/2016 - 26/09/2016	Sum	1514.67	746.28	12736.20	----
02/12/2015 - 19/01/2016	Daily Average	10.57	4.99	94.49	6.9
20/01/2016 - 26/09/2016	Daily Average	8.28	4.44	59.79	11.4
02/12/2015 - 19/01/2016	Daily Median	11.33	5.36	94.17	6.9
20/01/2016 - 26/09/2016	Daily Median	9.52	5.05	53.90	12.1
02/12/2015 - 19/01/2016	Count	48	46	49	49
20/01/2016 - 26/09/2016	Count	183	168	213	218
02/12/2015 - 26/09/2016	Total Count	231	214	262	267
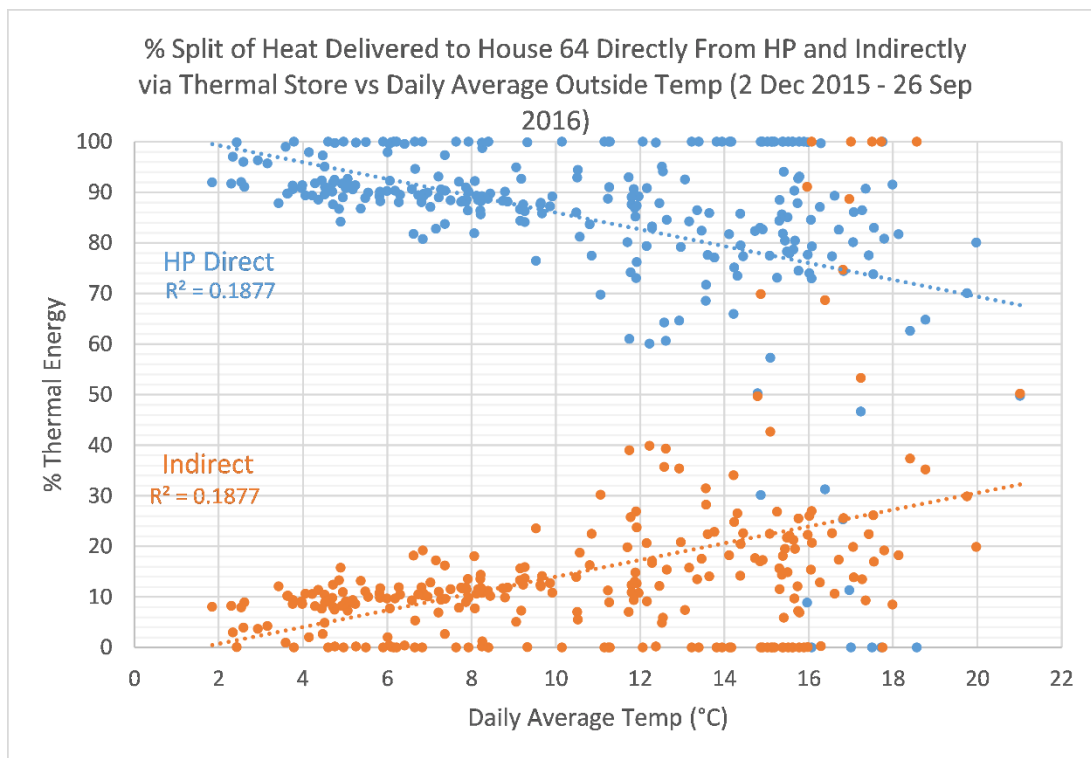
Figure 4-28 Percentage split of heat delivered to house directly from the HP and via thermal store versus daily average outside temperature for demand based DSM and thermal store discharging at first-call-for-heat for testing period between 02/12/2015 and 26/09/2016.

Table 4-1, Table 4-4 and Table 4-5 provide a summary of energy use in each of the individual components of the heating system as to ascertain the impact of the thermal storage and DSM schedule on the overall COP before and after the extra insulation was added to the thermal store respectively. The calculated COP in each of the two tables is not directly comparable as the system was operating under different outdoor temperature conditions, however the thermal store efficiency noted below each table is.

The highest COP is achieved when the HP delivers heat directly to the house (COP: 1.97, Table 4-4, and 2.01, Table 4-5). The COP in storage mode drops to 1.89, Table 4-4, and 1.94, Table 4-5, as a result of the high storage temperature and reduced heat transfer to the store at higher temperatures. The difference between the direct heating COP and storing COP before and after the insulation is added to the tank reduces which may indicate an improvement in storing COP with the increased insulation. When the COP of the HP providing heat to the house via the thermal store (indirect heating) is considered on its own, the COP of the system drops to 0.85, Table 4-4, and 0.96, Table 4-5. The drop in COP is a combination of firstly, the reduced COP of the HP when storing heat; secondly, the standing heat loses of the thermal store from charge to discharge i.e. the physical properties of the tank; and thirdly the DSM schedule which defines the amount of time between charge and discharge of the tank. This was noted in previous testing were the thermal store was discharged at high forecast electricity demand (section 4.4.1) as opposed to the first call-for-heat after charging. In an attempt to improve the COP, the DSM was changed so that the thermal store discharged at the first call-for-heat and then the thermal store was improved by adding an additional 100mm of mineral wool to the thermal store. Looking at the heat stored to the thermal store and the heat discharged to the house, the calculated thermal efficiency of the tank was 0.45 and 0.49 across the testing period before and after the insulation was added respectively. The values compare to a thermal store efficiency of 0.35 in section 4.4.1. Therefore, altering the DSM improved the thermal store efficiency from 0.35 to 0.45 and adding additional insulation resulted in a further increase from 0.45 to 0.49. Although there is a marked improvement it remains that the standing heat loss between charging, approximately 24 hours, must still have a significant impact on the efficiency of the store and therefore the indirect heating COP. Redesign of the existing thermal store is likely the best solution to reduce standing heat loss perhaps utilising different energy storage mediums.

The overall combined COP of the system, which is simply the total heat delivered to the house divided by the total electric consumption of the HP across the testing period, was calculated as 1.86, Table 4-4, and 1.89, Table 4-5. The value compares to the direct heating COP of the

HP of 1.97 and 2.01 respectively. The impact of the thermal storage and DSM as a combined system causes a COP drop of 0.11, Table 4-4, and 0.12, Table 4-5. This compares to a drop of 0.36 from section 4.4.1 when the store was discharged in the evening.

With this drop the system achieves a household heat demand shift of 4.72%, Table 4-4, and 5.54%, Table 4-5, from the lowest 10th percentile electric system demand to the first call-for-heat from the house. The demand shifts are reflective of the total house heat demand and are therefore not directly comparable, i.e. as outside temperature increases and house heat demand decreases the greater proportion of heat supplied from the thermal store. The DSM shift in this case was not the main priority for this testing period, whereas in section 4.4.1, the aim was to limit the impact of the HP on peak system demand by shifting heat from low system demand. In this testing period the aim was to try and maximise the efficiency of the thermal store by utilising heat from the lowest system demand only. The idea being, as in section 4.4.1, to increase system demand when demand is lowest to increase wind penetration onto the grid.

Table 4-4 Summary of HP electric energy consumption and thermal energy production for the period 02/12/2015 – 19/01/2016 (before extra tank insulation added to thermal store).

System Mode	HP Elec. (kWh)	HP Heat (kWh)	Heat to House (kWh)	Heating COP	Notes
Direct	2347.45	----	4630.10	1.97	HP COP when providing heat directly from HP
Storing	268.66	507.18[1]	----	1.89	HP COP when storing heat to thermal store only
Indirect	----	----	229.56[2]	0.85	COP is heat provided from store to house/electric used by HP storing
Sum	2616.11	----	4859.65	1.86	COP is total combined system (all heat to house/ all HP electric consumption)
% from store	*4.72*				
% direct	*95.28*				

*Using these values; [1]heat to store and [2]heat from store the efficiency of the thermal store is calculated as 0.45 across the testing period.

Table 4-5 Summary of HP electric energy consumption and thermal energy production for the period 20/01/2016 – 27/09/2016 (after additional 100mm mineral wool added to thermal store).

System Mode	HP Elec. (kWh)	HP Heat (kWh)	Heat to House (kWh)	Heating COP	Notes
Direct	6337.89	----	12736.20	2.01	HP COP when providing heat directly from HP
Storing	779.21	1514.67[1]	----	1.94	HP COP when storing heat to thermal store only
Indirect	----	----	746.28[2]	0.96	COP is heat provided from store to house/electric used by HP storing
Sum	7117.10	----	13482.48	1.89	COP is total combined system (all heat to house/ all HP electric consumption)
% from store	*5.54*				
% direct	*94.46*				

*Using these values; [1]heat to store and [2]heat from store the efficiency of the thermal store is calculated as 0.49 across the testing period.

The system performance across the testing period was compared to average daily outside temperature. The daily average COP of the HP in direct mode, storing mode, indirect mode (heat to house via thermal store), and overall combined system performance was plotted and is shown in Figure 4-29. For this the whole testing period 02/12/2015 to 27/09/2016 was plotted as one graph (i.e. before and after insulation not separated). The average COP of each mode has been previously summarised in Table 4-4 and Table 4-5.

Comparing HP in direct mode and HP in storing mode there is no clear difference in COP performance when plotted versus the daily average temperature. This is in contrast to the previous test run in section 4.4.1, Figure 4-17 were a much more defined difference can be observed. The difference in direct HP COP to storing COP was further investigated by looking at the COP of the HP in direct mode and HP in storing mode versus the outside average temperature when active in each of the respective modes i.e. if the HP was storing between 02:00 and 04:00 on any given day the storing COP was plotted against the calculated average outdoor temperature between these times and similarly for the direct mode. The results, shown in Figure 4-30, provide a truer reflection of the HP performance in each of the respective modes. It would appear that above approximately 7°C the storing COP begins to out-perform the direct heating COP.

Referring to Figure 4-29 and the thermal store series (heat provided to house via thermal store), it is clear there are a number of days when the daily COP of the system is zero. Of these days only 5 recorded energy storage of greater than 1 kWh (the values were: 1.33 kWh on 08/01/16, 2.91 kWh on 12/01/16, 1.49 kWh on 29/01/16, 5.39 kWh on 26/05/16, and 5.09 kWh on 05/08/16). On the 8th, 12th, and 29th January 2016 the low storage values were a result of simultaneous call-for-heat from the house i.e. the heat was running all night in the house. The house demand has priority over storage, so the HP was running in direct mode. When the thermostat in the house was satisfied the HP controller tried to store energy to the thermal store were the overlap existed. However, the thermostat was only satisfied for a short period and the storage mode was once again interrupted resulting in the low storage quantity. On the 26th May the tank charged for half an hour only which was due to the EirGrid website being down the previous day, the charge time was not sufficient to increase the tank temperature above 55°C. On the 5th August the controller crashed mid-charge due to a network glitch and was not rebooted until later that day. The charge lasted for 29 minutes only and below the useful temperature threshold of 55°C. Below 1 kWh the values are insignificantly small and are as a result of intermittent network issues causing on/off storage

signal to the system. The software was improved in subsequent versions to eradicate this bug.

The final series plotted on Figure 4-29 is the overall combined system COP versus the daily average outdoor temperature. The series diverges away from the HP Direct series at higher outdoor temperatures due to the decreased heat demand in the house and therefore greater proportion of heat delivered from the thermal store. Similarly, at low outdoor temperatures the combined system COP is almost the same as the HP Direct COP due to the high proportion of heat delivered from the HP in direct mode as a result in increased household heat demand. The thermal energy proportion from HP Direct to thermal store with changing outdoor temperature is illustrated Figure 4-28.
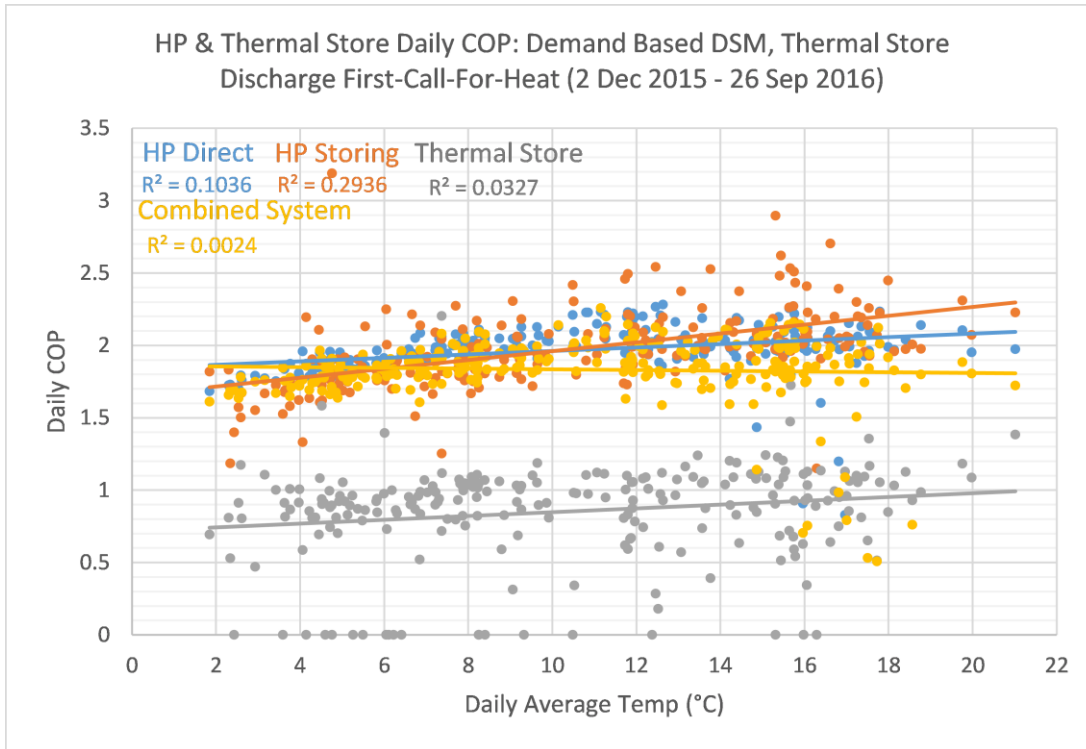
Figure 4-29 Daily average HP COP for HP in direct mode, storing mode, indirect mode (heat to house via thermal store), and overall combined system versus daily average outside temperature for demand based DSM and thermal store discharging at first-call-for-heat for testing period between 02/12/2015 and 26/09/2016.
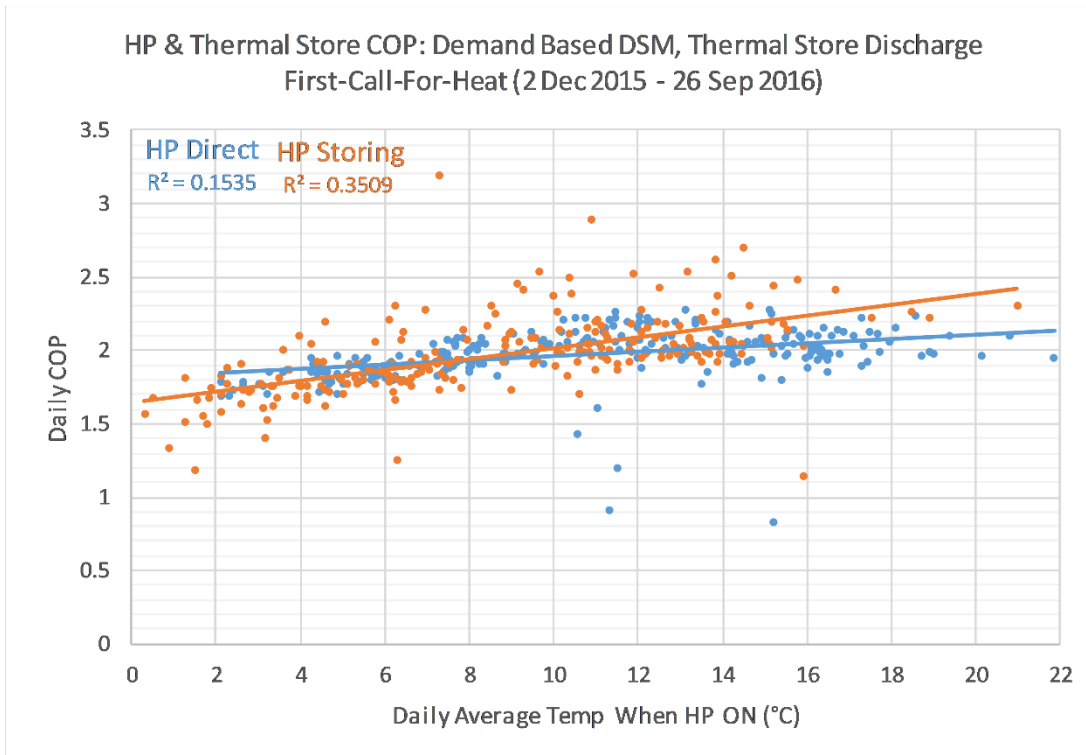
Figure 4-30 Daily average HP COP for HP in direct heating mode and HP in storing mode. The data series are plotted against the average outside temperature when each respective mode was active as opposed to daily average outside temperature used in Figure 4-29.

The calculated COP for each of the modes plotted in Figure 4-29 was used to calculate the cost of thermal energy (Figure 4-31) to provide a comparative assessment in subsequent testing regimes. In addition, the cost of thermal using the Economy 7 domestic electricity tariff was also calculated and is presented in Figure 4-32.

The cost of thermal at the standard domestic price varies in line with daily average COP as they are a direct ratio of one and other. The poor COP of the thermal store mode results in the thermal energy costing more than the unit rate of electric to produce it, 12 p/kWh electric, compared to an average of 14 p/kWh thermal. The combined mode compared to the HP in direct mode results in an average increase of 0.6 p/kWh of thermal energy delivered to the house. To put the value into context using the annual heat demand of house 64 detailed in section 4.1 for 2015 and 2016, an increase of 0.6 p/kWh thermal would increase the annual heating bill by £147.40 and £139.94 respectively.

Comparing Figure 4-31 and Figure 4-32 it can be seen that the cost of storing to the thermal store is reduced significantly below the HP in direct mode for the Economy 7 tariff. In addition, the HP in direct mode is cheaper in the Economy 7 tariff at higher ambient temperatures but at lower temperatures it starts to become more expensive compared to the standard tariff. The reason for this is the higher demand at lower outside temperatures and therefore greater proportion of heat required at the higher Economy 7 day rate. Conversely, at higher outside temperatures a greater proportion of heat is provided at the lower night time rate. The trend of lower cost of thermal at higher outside temperatures is also dependant on the heating schedule of the house i.e. for house 64 the heating tends to come on in the morning and therefore takes advantage of the lower tariff before 08:00 GMT. However different consumers may tend to use there heating predominately in the evening and therefore be disadvantaged by the higher day time rate resulting in a higher cost of thermal in direct heating mode even at higher outside temperatures compared to a standard tariff rate. The effect on the combined mode of using the Economy 7 tariff is a clear reduction in thermal cost with increasing outside temperature compared to the standard tariff.

A statistical comparison of the cost of thermal energy using the two tariffs is summarised in Table 4-6. Analysing Table 4-6 there are a number of points to make regarding the comparison of the two tariffs which include:

- The Economy 7 tariff reduces the cost of thermal across all modes except for the HP direct mode. The HP direct mode is on average 0.2 p/kWh thermal more expensive for the Economy 7 tariff. This is contrary to results seen in the previous section 4.4.1 (Table

4-2) were the cost per kWh thermal was cheaper across all modes using the Economy 7 tariff, including the direct mode. The reason the cost increases in this section for the direct mode is because the thermal store is discharged at the first call-for-heat which is in the morning and within the Economy 7 lower rate. As a result, this reduces the demand that would have otherwise been provided by the HP directly within the low rate Economy 7 tariff. In addition, the evening demand that was provided from the thermal store in the previous section is now met by the HP in direct mode.

- The most significant reduction occurs for the HP storing and thermal store mode as this has the greatest proportion within the night time tariff. This greatly increases the feasibility of the thermal store even with the efficiency issues previously identified although the thermal store mode is still considerably above the HP direct fixed tariff price.

- The average HP direct fixed tariff price is cheaper than the average combined Economy 7 tariff price. This is a result of using the store at first call-for-heat within the low tariff rate. This means the benefit of using the stored heat at a higher rate is lost and also the benefit of using the HP in direct mode for the morning heat demand within the Economy 7 low tariff rate is lost. This is obvious when Table 4-6 is compared to Table 4-2; there is a small improvement in the Thermal Store price (due to reduced heat loss by using heat closer to storage time) but all other prices are negatively impacted resulting in an increase in 1p/kWh thermal for the combined system using the Economy 7 tariff and the fixed tariffs are practically the same 0.068 p/kWh and 0.067 p/kWh respectively.

Table 4-6 Statistical summary comparison of cost of thermal energy (£/kWh) of HP and thermal store demand based DSM with thermal store discharged at first-call-for-heat across testing period 2nd December 2015 – 26th September 2016. The tariffs compared are cheapest domestic electricity tariffs for Northern Ireland as of August 2017: (1) standard fixed rate 12p/kWh (The Consumer Council NI, 2017b); (2) economy 7 rate of 6.95p/kWh (night rate between 01:00 – 08:00 GMT) and 14.25p/kWh (day rate 00:00 – 01:00 and 08:00 - 00:00) (The Consumer Council NI, 2017a).

Mode:	HP Direct		HP Storing		Thermal Store		Combined	
Tariff:	Fixed	Econ 7	Fixed	Econ 7	Fixed	Econ 7	Fixed	Econ 7
Average	0.062	0.064	0.062	0.037	0.140	0.082	0.068	0.065
Median	0.061	0.064	0.061	0.036	0.126	0.074	0.065	0.064
Lower Quartile	0.058	0.058	0.057	0.033	0.113	0.066	0.061	0.059
Upper Quartile	0.063	0.069	0.066	0.039	0.146	0.085	0.068	0.070

The conclusion is that there is no financial benefit in using the stored thermal energy at the first call for heat if using the Economy 7 tariff because the benefit of shifting energy from the low to high tariff is lost and the benefit of using the HP in direct mode to satisfy the morning heat demand within the low tariff is also lost. Looking at the fixed tariff, the combined system cost per kWh for the morning and evening DSM are practically the same, as the COPs are practically the same, therefore the benefit of using the stored thermal energy closer to the storage time (i.e. at the first call for heat) will be to maximise the thermal energy recovered from the store. To get the same amount of energy in the evening as in the morning there would be a need to increase the store size (for the same tank with same heat loss characteristics), therefore storage duration (and therefore heat loss) is a key consideration in sizing of the thermal store.
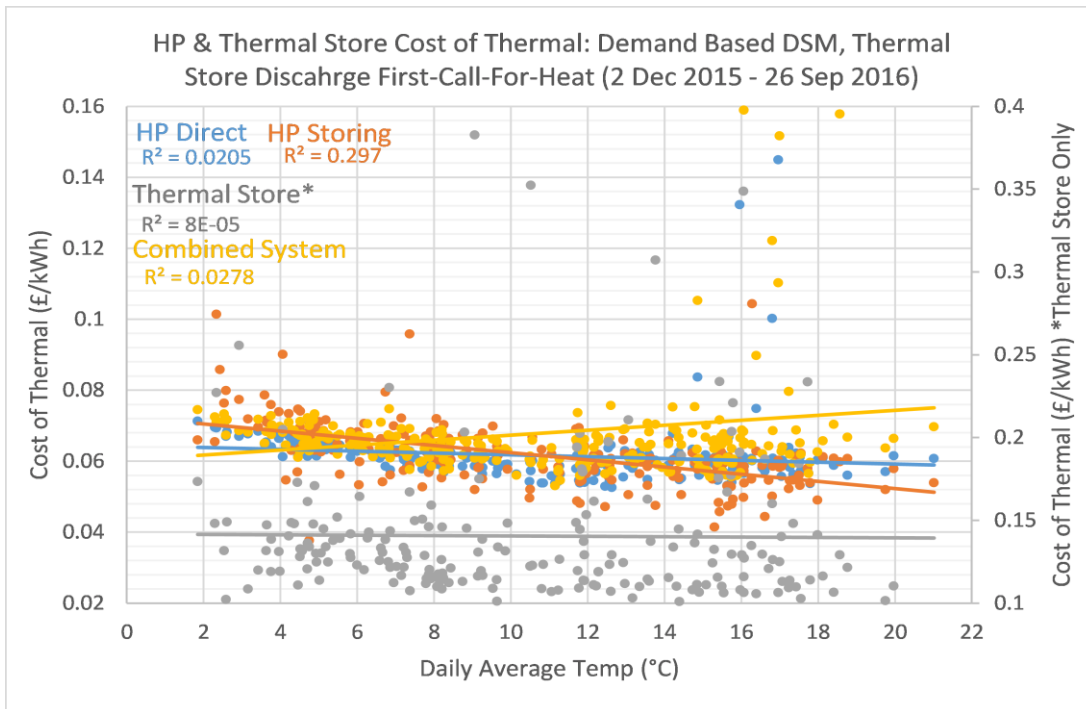
Figure 4-31 Daily average cost per kWh thermal energy versus daily average outdoor temperature for HP in direct, storing, indirect (thermal store), and total combined system mode using demand based DSM strategy with thermal store discharged at first-call-for-heat. Thermal cost is calculated using domestic electricity price of £0.12/kWh based on cheapest domestic fuel prices (The Consumer Council NI, 2017b).
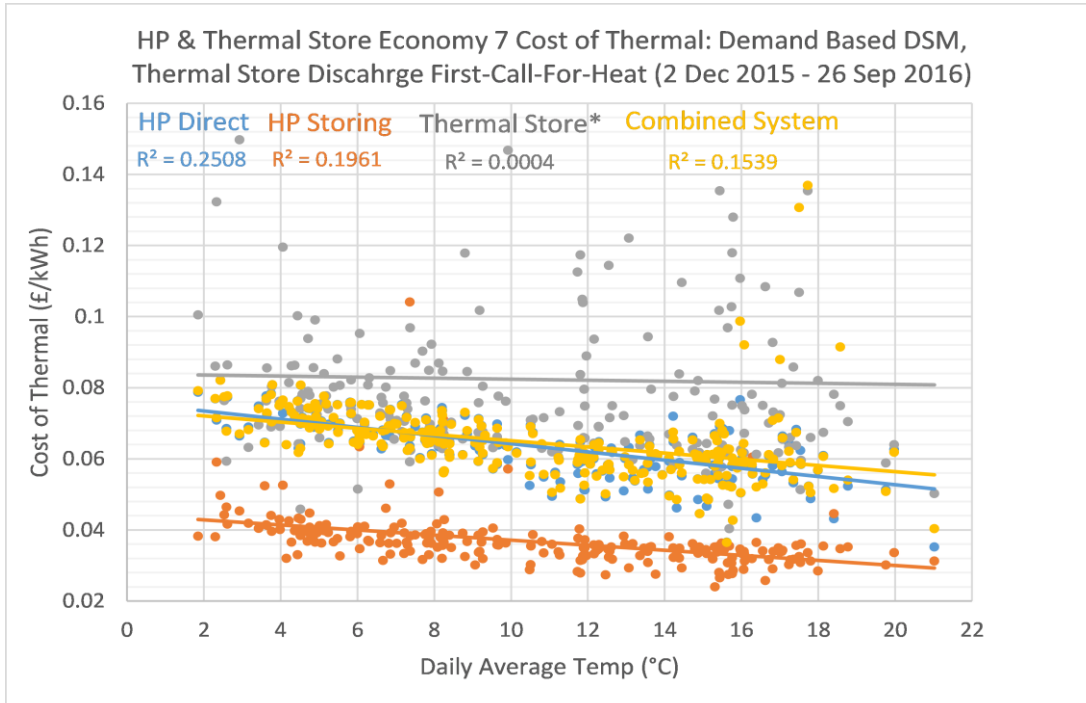
Figure 4-32 Daily average cost per kWh thermal energy versus daily average outdoor temperature for HP in direct, storing, indirect (thermal store), and total combined system mode using demand based DSM strategy with thermal store discharged at first-call-for-heat. Thermal cost is calculated using domestic electricity Economy 7 rate of 6.95p/kWh (night rate between 01:00 – 08:00 GMT) and 14.25p/kWh (day rate 00:00 – 01:00 and 08:00 - 00:00) (The Consumer Council NI, 2017a).

The calculated COPs for each of the modes plotted in Figure 4-29 were used to calculate the CO_2e intensity per kWh of thermal energy (Figure 4-33). The CO_2e intensity varies in line with daily average COP as they are a direct ratio of one and other. The intensity values are calculated using the UK GHG factors for 2017 which provides an average factor for the year dependant on the mixture of generation sources within that year. The thermal store CO_2e intensity is plotted on a second axis due the poor COP in this part of the system. The poor COP of the thermal store has the effect of increasing the CO_2e intensity of the combined system compared to the HP in direct mode. At higher outdoor temperatures the intensity increases for the combined system due to the increased proportion of heat provided by the thermal store to the house (due to lower house heat demand).
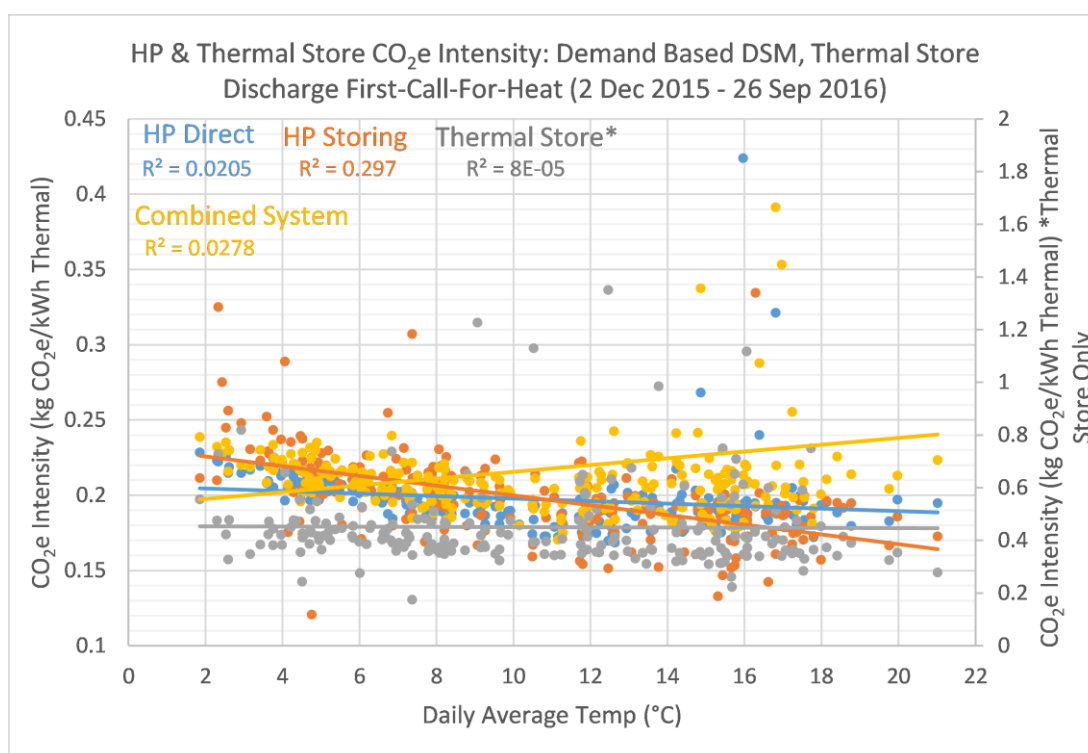
Figure 4-33 Daily average CO_2e intensity per kWh thermal delivered by HP versus daily average outdoor temperature for HP in direct, storing, indirect (thermal store), and total combined system mode using demand based DSM strategy with thermal store discharged at first-call-for-heat. The calculation uses UK GHG factors for 2017 (BEIS, 2017b). Electricity GHG is inclusive of transmission and distribution GHG factor. Note thermal store plotted on secondary vertical axis.

4.5   Gas Baseline

A short test was run to ascertain a baseline gas boiler efficiency when heating the house directly with no DSM intervention. As the gas boiler efficiency will be compared directly to the COP of the HP, the gas boiler efficiency will be referred to as a COP for the purposes of simplification. The baseline was to establish if the gas boiler COP is impacted by running the hybrid HP and gas boiler modes outlined in Table 3-8. The test was run between 28/10/2016 and 13/11/2016. The daily house heat demand and average outdoor temperature is shown in Figure 4-34. The average heat demand across the period was 74.6 kWh with a minimum of 54.1 kWh and maximum of 93.0 kWh. The average outdoor temperature was 8.5°C with a minimum of 5.3°C and maximum of 12.4°C.
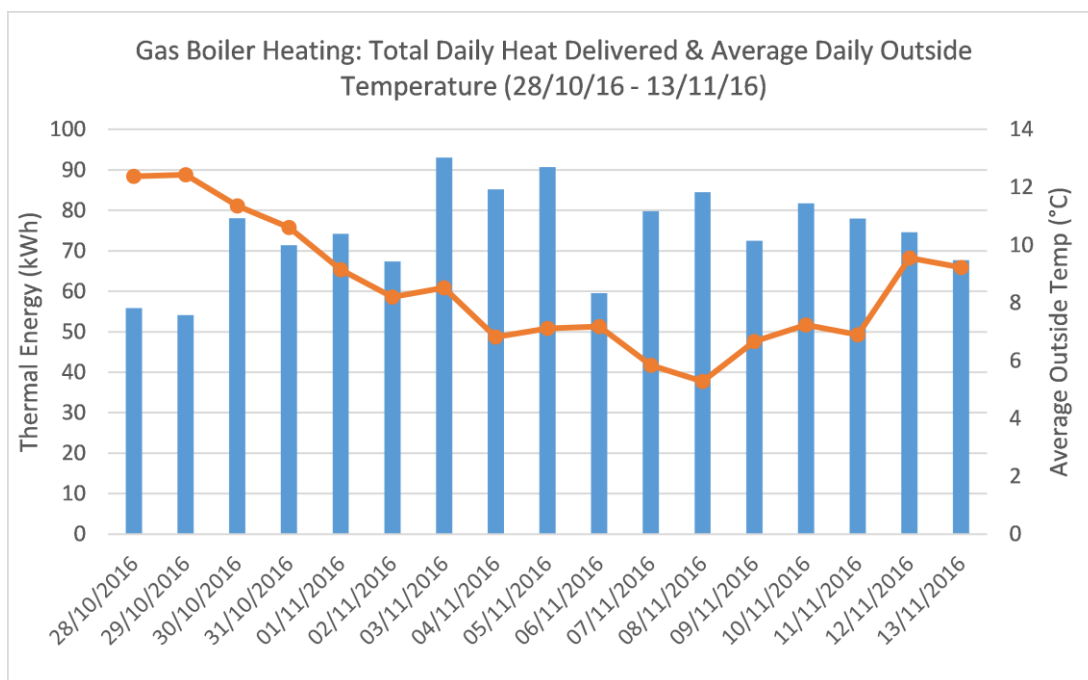
Figure 4-34 Gas boiler baseline (no DSM) total daily thermal energy delivered to house 64 between 28/10/16 and 13/11/16. Also shown is average daily outside temperature.

An example of the gas boiler running at the first call for heat in the morning on 30/10/2016 is shown in Figure 4-35 and Figure 4-36. Figure 4-35 shows the gas boiler gas power consumption and thermal power production for two heating cycles occurring between 07:00 and 12:00. The gas power consumption does not show as a smooth line due to the low measurement resolution of the gas meter. The measured maximum thermal power output is approximately 21.0 kW and modulates down to approximately 8.0 kW which compares to datasheet values of maximum 22.00 kW and minimum 9.14 kW at 70°C mean water temperature. Figure 4-36 shows for the same time period as Figure 4-35 the flow temperature, return temperature and volumetric flow of the central heating system. The

boiler takes approximately 30 minutes to reach a maximum flow temperature of 80.0°C and the boiler modulates based on maintaining the set flow temperature. Comparing Figure 4-35 and Figure 4-36 it can be seen that the thermal power output starts to reduce significantly as the high flow temperature is reached. The return temperature is not measured by the boiler but if the return temperature is higher, less power is required to maintain the set flow temperature i.e. the less thermal power required by the house. The delta T between flow and return temperature is on average 9.0°C after the set flow temperature is reached. It should be noted that the return temperature is a function of the heating load which is effectively three parallel circuits in house 64; (1) DHW circuit, (2) ground floor radiators, and (3) first floor radiators. Thus, if the delta T across the DHW circuit is small, the return temperature tends to be higher in this circuit, whereas the delta T across the radiator circuits tends to be larger and therefore the return temperature from these circuits tends to be lower. The return temperature at the boiler is therefore a weighted average of the three circuits. The boiler modulates to deal with the required load with no issues, however the higher return temperature, due to the small load over the DHW circuit, will result in reduced gas boiler efficiency due to reduced ability to condense and recover heat from flue gases. The issue is due to poor control design in house 64 which is illustrated in the central heating schematic in Figure 3-3. It can be seen that the control for the DHW uses a 3-port valve which switches based on a tank thermostat. When the thermostat is satisfied the circuit directs the flow straight over to the return pipework which will have the effect of increasing the return temperature i.e. there is effectively no delta T across this circuit. In addition, if the tank thermostat is set too high or positioned poorly i.e. close to 80°C or at the bottom of the tank the delta T will be very small across the DHW tank which will also cause a high return temperature on the DHW circuit and therefore a higher return temperature at the boiler. The 3-port valve should probably be a 2-port valve which would isolate the DHW circuit when the DHW load is satisfied. In addition, it is possible that the capacity control of the boiler may prematurely reduce resulting in less thermal power being provided to the central heating circuits and therefore a longer heat up time for the rooms in the house.
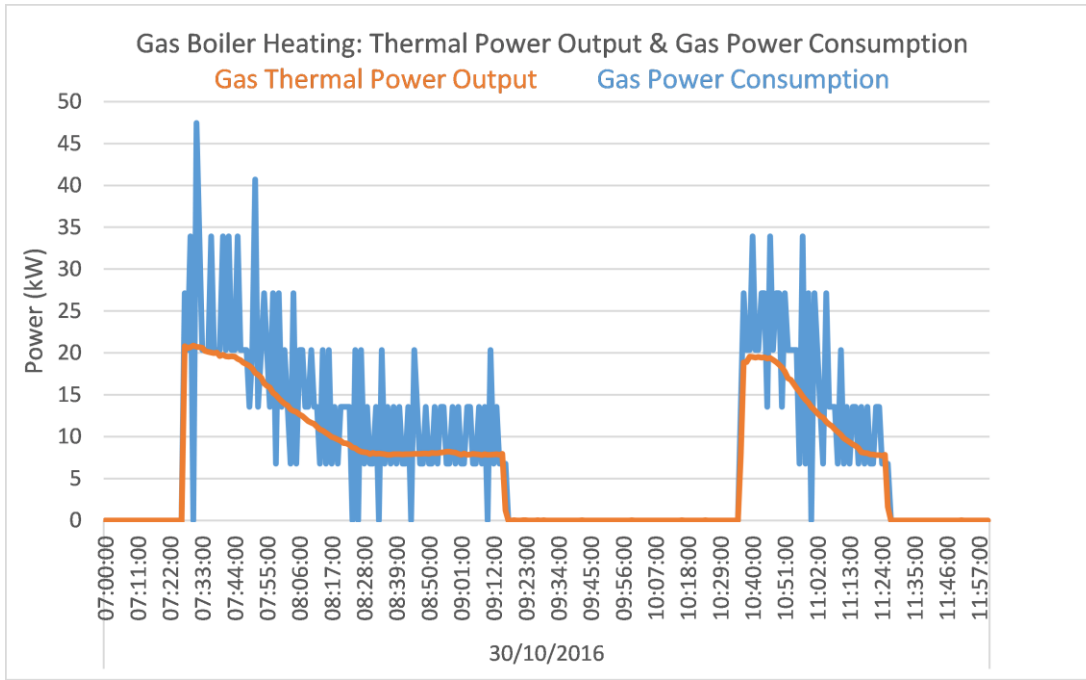
Figure 4-35 Gas boiler baseline (no DSM) thermal power delivered to the house and gas power consumption of gas boiler between 07:00 and 12:00 on 30/10/16. Gas power consumption does not show as smooth line due to low measurement resolution of the gas meter.
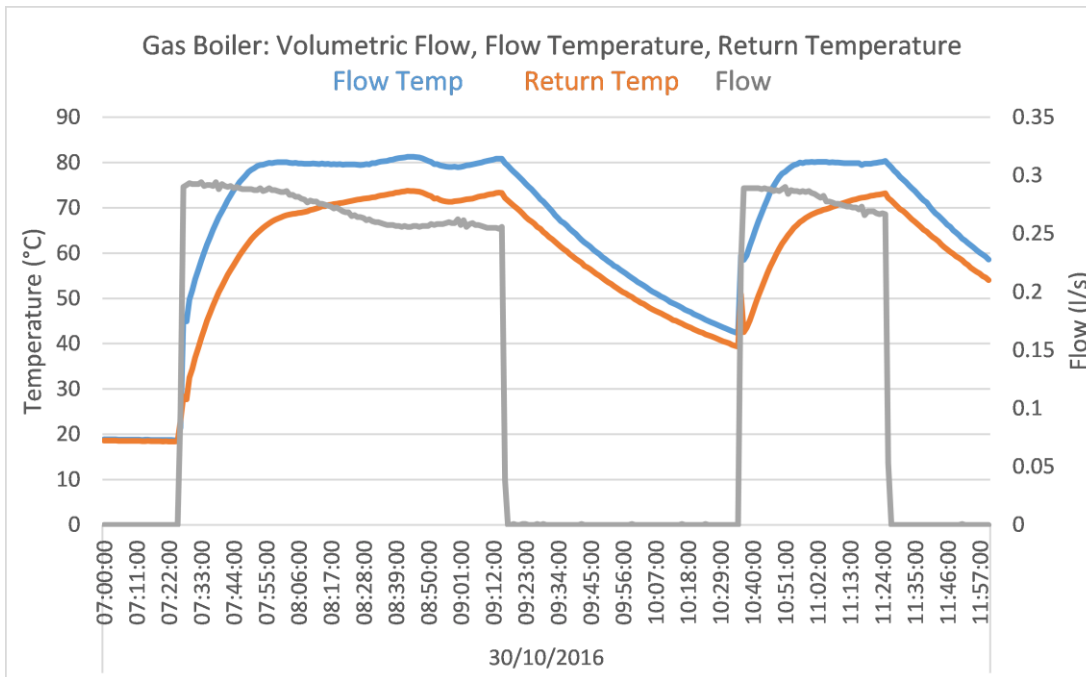
Figure 4-36 Gas boiler baseline (no DSM) flow temperature, return temperature, and volumetric flow rate between 07:00 and 12:00 on 30/10/16.

The measured daily average COP of the boiler is plotted versus daily average outdoor temperature in Figure 4-37. The calculated COP was then used to calculate cost of thermal per kWh delivered (Figure 4-38) and the CO_2e intensity per kWh thermal delivered (Figure 4-39). The average COP across the period was 0.80 with a minimum of 0.77 and maximum of 0.83. Across the period the average outdoor temperature was 8.5°C with a minimum of 5.3°C and maximum of 12.4°C. The COP compares to the manufacturer SEDBUK declared value of 90.9%. The low COP is likely a result of little or no condensing in the boiler due to the higher return temperatures detailed previously. The cost of thermal per kWh heat delivered, shown in Figure 4-38, averaged £0.050 per kWh. The CO_2e intensity averaged 0.23 kg CO_2e/kWh thermal.
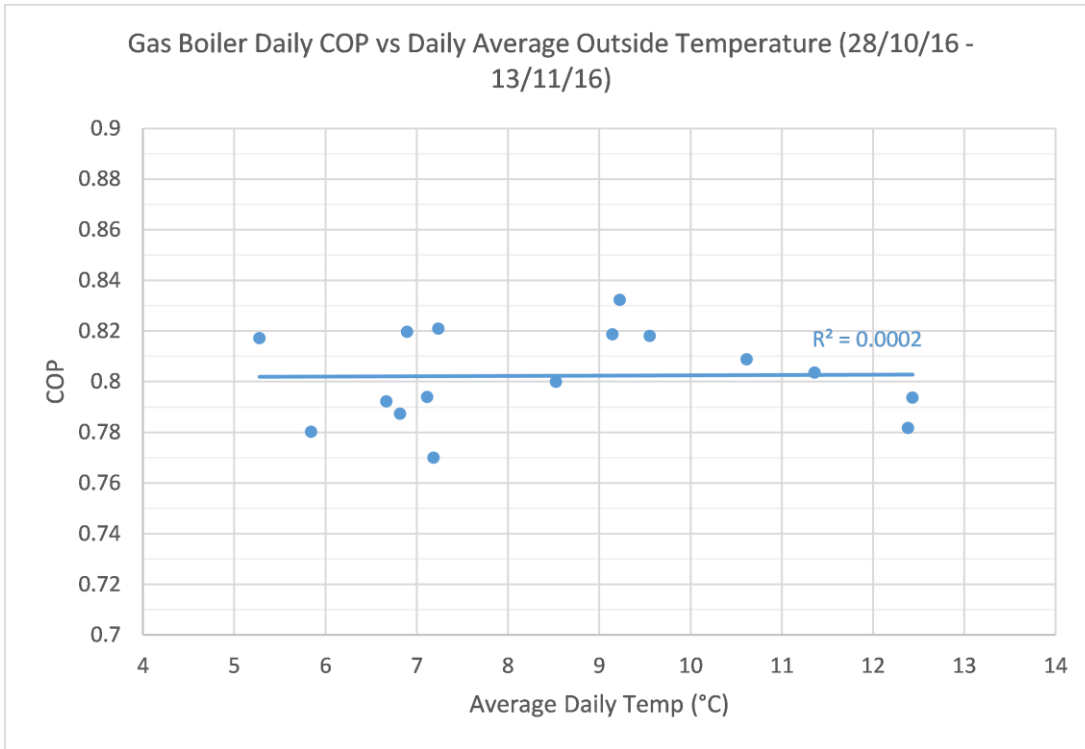
Figure 4-37 Gas baseline daily COP versus average daily outside temperature for period between 28/10/16 and 13/11/16.
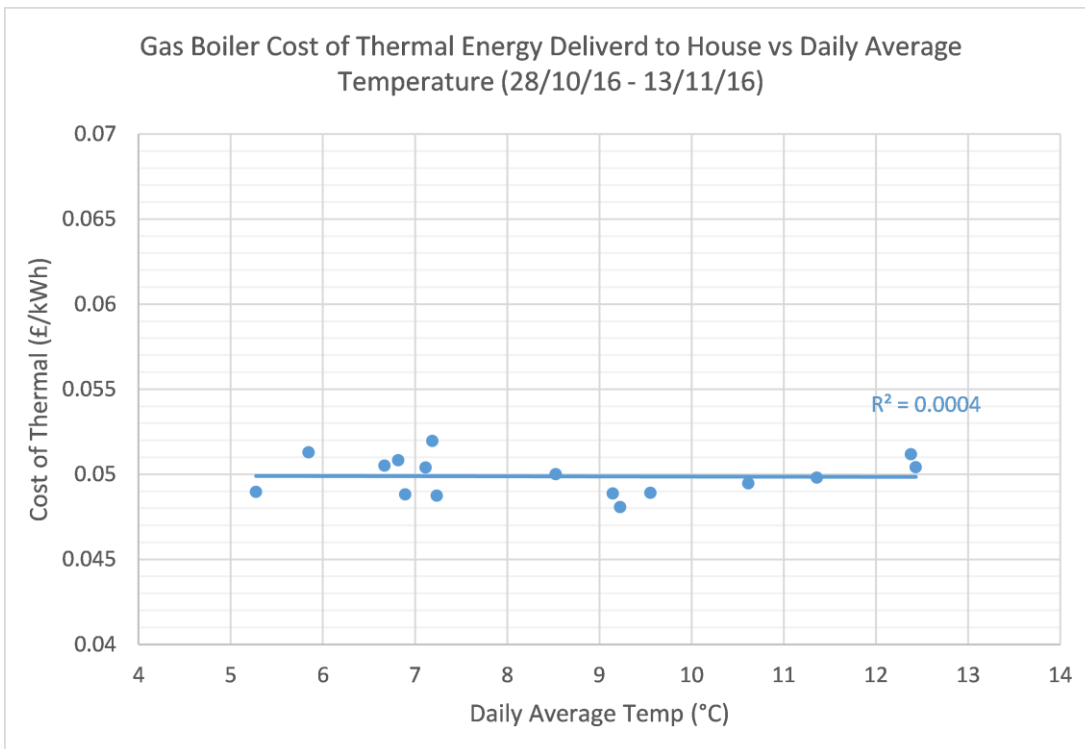
Figure 4-38 Gas baseline cost of thermal energy delivered to house 64 versus average daily outside temperature for period between 28/10/16 and 13/11/16. Thermal cost is calculated using domestic gas price of £0.04/kWh based on cheapest domestic fuel price (The Consumer Council NI, 2017b).
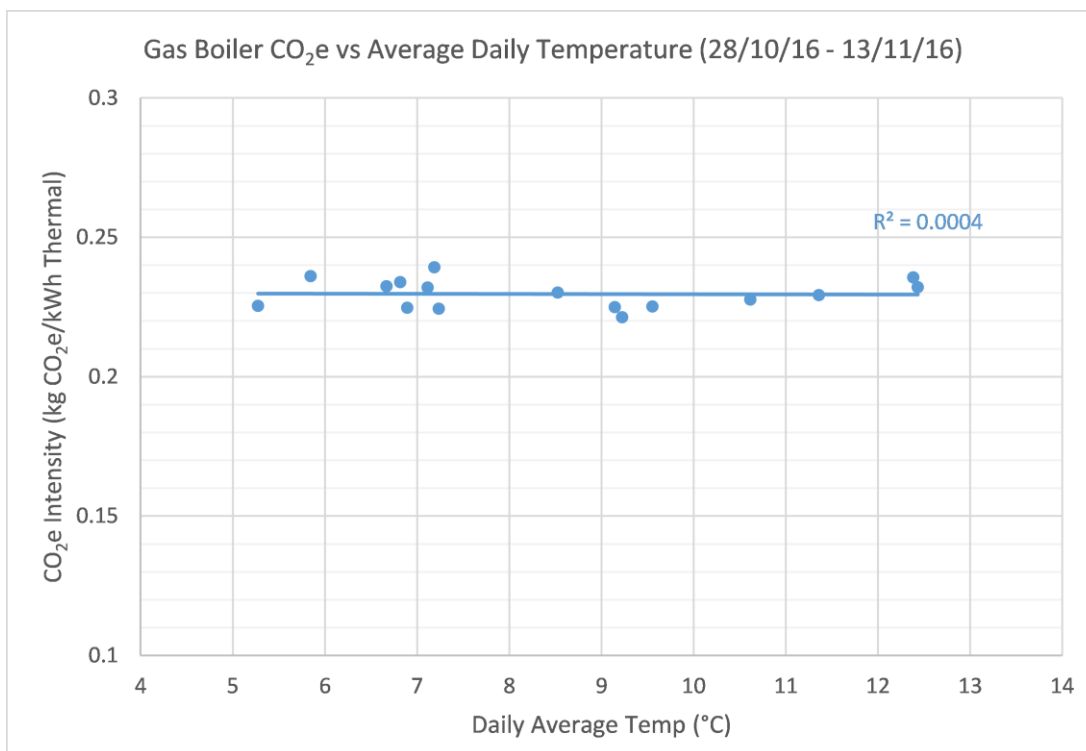
Figure 4-39 Gas baseline CO_2e intensity of thermal energy delivered to house 64 versus average daily outside temperature for period between 28/10/16 and 13/11/16. The calculation uses UK GHG factors for 2017 (BEIS, 2017b). Electricity GHG is inclusive of transmission and distribution GHG factor.

4.6   Gas & ASHP in Series

The gas boiler and HP were run in series (HP feeding the return of the gas boiler) without any DSM controls for 1 month in December 2016. The hydraulic schematic of this operation is illustrated in Figure 3-17. For reference the HP operates as a cascade system (see Figure 2-1) and the only alteration to its operation in this hybrid mode is a reduction in flow temperature which can be set on the HP controller. The objective was to test how the system would perform with minimal optimisation and lacking a common temperature modulation. The gas boiler modulates based on flow temperature which can only be approximately set. Flow temperature is modulated by varying fan speed and thereby the gas flow rate. If the flow temperature is above the set-point the gas valve is closed and spark ignition is off. The heat pump modulates by trying to maintain a constant delta T on the water side depending on user set flow temperature. Capacity control is via inverter control of compressors and water circulation pump. The gas boiler was set to heat the flow water to approximately 75°C and the HP 65°C flow temperature. With these settings it was hoped the gas boiler would provide around a 10°C temperature lift and the HP would try to maintain a delta T of 10°C giving an overall delta T of 20°C across the house.

Figure 4-40 shows the daily thermal energy delivered to the house across the month from the HP and gas boiler along with the average daily temperature. Figure 4-41 shows the percentage split of the thermal energy delivered to the house between the HP and gas boiler. Across the period the average daily temperature ranged from 3.9°C to 13.1°C with an average of 7.8°C. The HP delivered a total of 1124.2 kWh of heat using 576.8 kWh of electricity (SCOP: 1.95) and the gas boiler delivered 1559.6 kWh of heat using 2203.5 kWh of gas (SCOP: 0.71). The HP provided 42% of the heat on average across the period and the gas boiler 58%. Across the month the HP minimum daily heat contribution was 38% and maximum was 47% and the gas boiler minimum daily heat contribution was 53% and maximum 62%. Analysis showed that the greater the total heat delivered to the house in a day by the hybrid system the greater the proportion of that heat would be provided by the gas boiler.
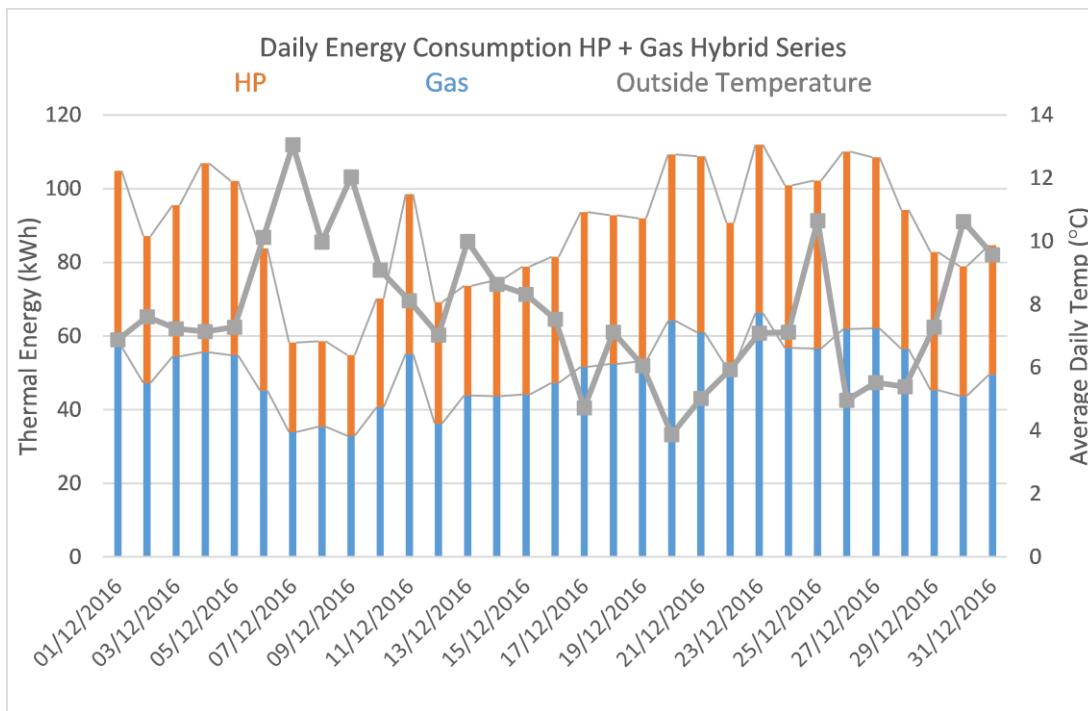
Figure 4-40 Hybrid series test December 2016: stacked daily thermal energy delivered to house 64 from the HP and gas boiler, also shown is daily average ambient temperature.
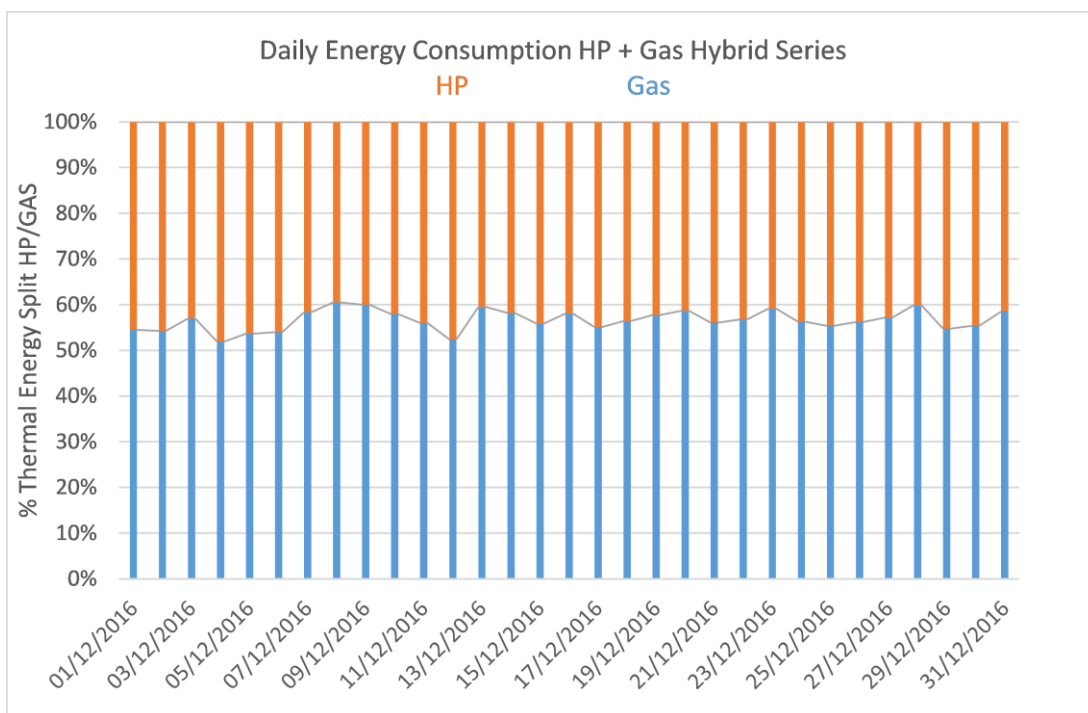
Figure 4-41 Hybrid series test December 2016: % split of daily thermal energy delivered to house 64 from the HP and gas boiler.

A sample day, 16th December 2016, was chosen to illustrate the typical running characteristics of the heating system. Figure 4-42 shows the in-line flow and return temperatures of the HP and gas boiler and also total system flow. Figure 4-43 shows the calculated thermal power output from the HP and gas boiler individually and also the combined total thermal power output to house 64. The time axis for Figure 4-42 and Figure 4-43 is the same, 06:00 to 09.20, and shows the first call for heat in that day.

For the series system the gas boiler central heating pump (external to gas boiler) and the HP circulating pump (built into HP) were both running at the same time. The gas boiler central heating pump is fixed speed and the HP is variable speed. The HP functions by maintaining a constant delta T between its flow and return temperatures by varying the speed of the circulation pump and therefore modulating the power input to the central heating system. In the series setup this will therefore have a modulating effect on the gas boiler also. Looking at Figure 4-42 the flow can be seen to rise sharply to a peak of 0.25 l/s corresponding to a HP flow temperature (gas return) of 67°C (HP flow set point: 65°C). The flow rate then decreases to maintain a constant delta T between the HP flow and return. At approximately 08:25 there is a spike in the flow rate and drop in flow temperatures which is likely a result of the HP going into a defrost cycle.

The gas boiler modulates based on trying to maintain a constant flow temperature (gas boiler set point: approximately 75°C) and does this by firstly modulating fan speed (and thereby gas rate) and then secondly by closing gas valve and switching of spark generator until flow temperature is below set point. The gas boiler flow temperature reaches the approximate set-point around the same point of peak flow rate. The flow temperature is steady for a period and then increases gradually to 80°C. During this period it is likely that the boiler is reducing the fan speed and therefore gas consumption to try and maintain a constant flow temperature although the low resolution of the gas pulse sensor means it is difficult to confirm this. The reducing flow rate will also increase the flow temperature measurement at the gas boiler as capability to dissipate heat into the central heating system will also reduce. After the gas boiler reaches a peak flow temperature of 80°C it goes into the second mode of modulation which involves turning the gas burner off and waiting for flow temperature to reduce below the set point before igniting the burner again. As Figure 4-42 shows the gas boiler begins to cycle in this mode and this will likely result in reduced efficiency of the boiler. Increasing the delta T between the flow temperature set point of the HP and the flow temperature set point of the gas boiler may reduce this on/off modulation.
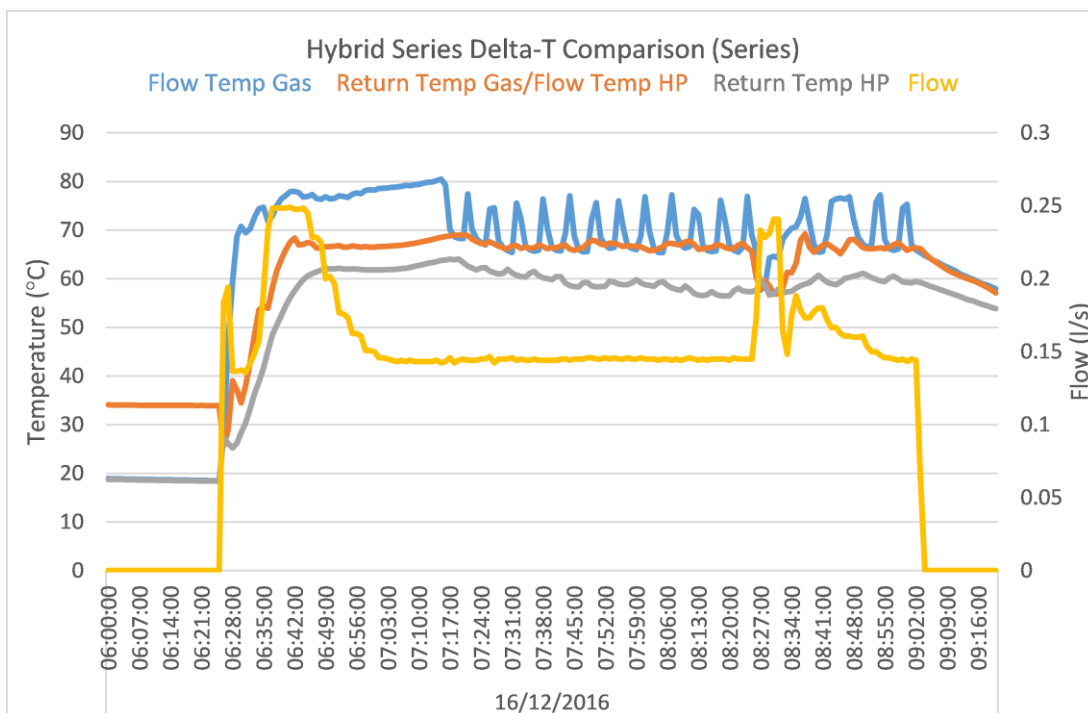
Figure 4-42 Example of running period of hybrid HP and gas running in series on 16th
December 2016. In-line pipe temperatures are shown along with the system flow.
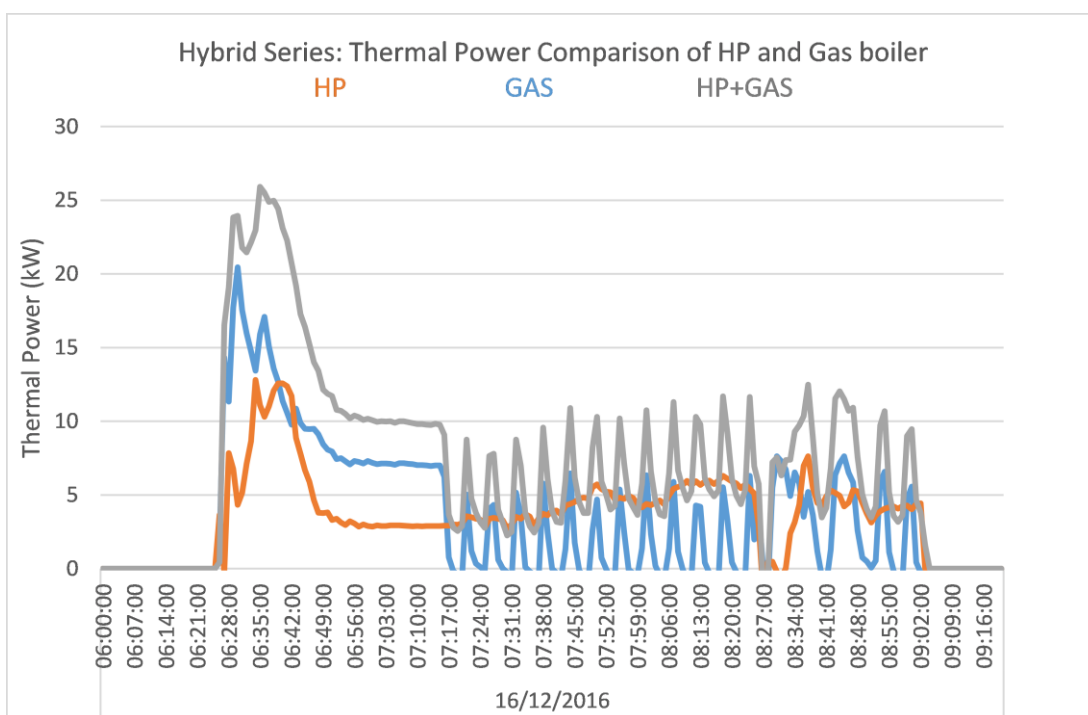
Figure 4-43 Example of running period of hybrid HP and gas running in series on 16th
*December 2016. Individual thermal power output of the HP and gas boiler is shown along
with a sum of HP and gas boiler thermal power (total thermal power output to house 64).*

Figure 4-44 shows the daily average COP of the HP, gas boiler and the combined hybrid system versus the daily average ambient temperature. An outlier analysis confirmed that all the calculated COP values lay within the lower quartile minus 1.5 times the inter-quartile range (IQR) and the upper quartile plus 1.5 times the IQR. The average daily temperature was 7.8°C with a minimum of 3.9°C and maximum of 13.1°C. The HP average daily COP across the month was on average 1.96 with a minimum of 1.77 and maximum of 2.11. The gas boiler average daily COP across the month was 0.71 with a minimum of 0.68 and maximum of 0.73. The overall hybrid heating system across the month had an average daily COP of 0.96 with a minimum of 0.90 and maximum of 1.01. The efficiency of the gas boiler was lower than expected based on baseline testing returning a daily average COP of 0.8. The lower COP could be a result of the gas boiler return being higher than it would be when running without the HP and as a result the boiler may not condense the flue gasses as efficiently and therefore recovers less heat. The increased cycling of the gas boiler may also result in an increase in unburned gas from the boiler exhaust as the burner ignites and extinguishes more frequently. It is more difficult to directly compare the HP baseline COP to the HP COP measured in the series test. The baseline HP COP value was on average 2.10 with corresponding daily average ambient temperature of 5.4°C compared to the series test COP values of 1.96 and 7.8°C respectively. The values suggest the COP of the HP in series may have been negatively impacted. This would be the expected result as the control of the gas boiler and HP are designed independent to each other and therefore not optimised to work together to maximise combined system COP. The ideal situation would be the HP providing low temperature heat to the gas boiler, maximum 55°C for example, to improve gas boiler condensing, and the gas boiler providing 65°-68°C flow temperature to ensure the radiators operate at high enough temperature to effectively heat the house. With a 20°C delta T across the house (radiators) the system might efficiently run with the HP maintaining 7°C delta T on the HP return i.e. gas flow 68°C, HP return 48°C, HP flow/gas return 55°C. The limiting factor is the ability of the radiators (which have not been altered) to achieve the 20°C delta T.

The cost of thermal energy delivered to the house was also calculated for the HP, gas boiler and combined hybrid system and is shown versus daily average ambient temperature in Figure 4-45. The average daily cost of heat delivered by the HP was £0.061/kWh, the gas boiler was £0.057/kWh, and combined was £0.059/kWh. The cost of heat from the gas boiler is increased as a result of the lower COP running the HP and gas boiler in series. The combined cost is less volatile to changes in ambient temperature compared to the HP in direct mode. The cost of the heat delivered from the HP would be cheaper than the gas if the HP COP was

greater than 2.10 which occurs above a daily average outside temperature of approximately 11.5°C.

The daily CO_2e intensity of the thermal energy delivered to the house is shown in Figure 4-46 and is dependent on the HP and gas boiler COP. The combined intensity varies dependant on the proportion of heat provided from the HP and gas boiler and the respective operating COP. The average daily CO_2e intensity of heat delivered by the HP was 0.197 kg CO_2e/kWh thermal, the gas boiler was 0.261 kg CO_2e/kWh thermal, and combined was 0.236 kg CO_2e/kWh thermal. As the HP has a COP greater than 1 the HP CO_2e intensity producing thermal energy reduces as the COP increases. Therefore, even though UK GHG factor for domestic electricity is much greater than for domestic gas, 0.38443 kg CO_2e compared to 0.18416 kg CO_2e respectively in 2016, the HP is much less carbon intensive. Improved COP of the HP provides greater potential for carbon savings over the gas boiler which can only have a maximum COP of 1 if it had no energy loss. In addition, decarbonisation of the electricity grid by increasing renewable penetration and improving grid efficiency further increases potential carbon savings for the HP.

Figure 4-44 Hybrid series daily average COP of HP, gas boiler and combined versus daily average ambient temperature for December 2016.
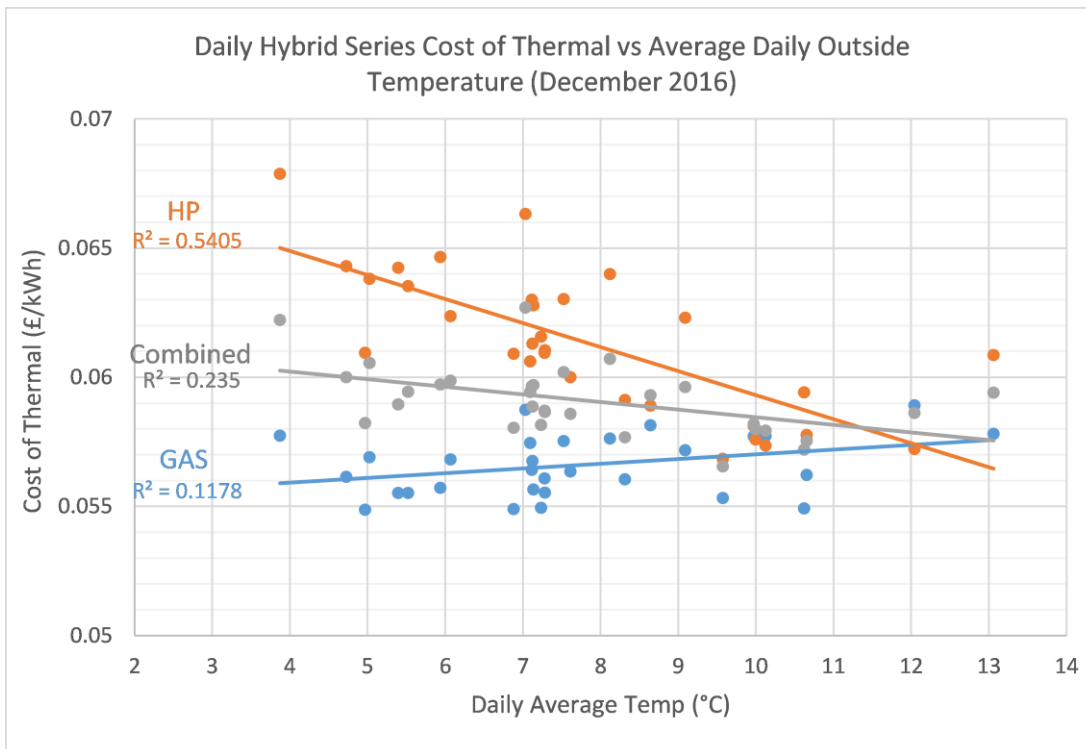
Figure 4-45 Hybrid series calculated cost of thermal based on daily average COP of HP, gas boiler and combined versus daily average ambient temperature for December 2016. Thermal cost is calculated using domestic gas price of £0.04/kWh and domestic electricity price of £0.12/kWh based on cheapest domestic fuel prices (The Consumer Council NI, 2017b).

Figure 4-46 Daily CO_2e intensity of thermal delivered to the house by the gas boiler, HP, and combined. The calculation uses UK GHG factors for 2017 (BEIS, 2017b). Electricity GHG is inclusive of transmission and distribution GHG factor.

4.7   Gas & ASHP in Parallel

The HP and gas boiler were run in parallel (one or the other) so that the gas boiler effectively replaces the thermal store. The DSM for the system was based on grid demand, the same as the thermal store DSM, and additional DSM using electricity market price as the DSM signal was also carried out.

4.7.1   HP/Gas Boiler Hybrid Mode: System Demand Signal

An example of how the HP and gas boiler was run is illustrated in Figure 4-47. The graph shows the data logged by the Raspberry Pi controller on the 1st April 2017. The forecast system demand was retrieved for 24 hours ahead (and repeated every minute) and the 85th percentile of the dataset was calculated. The gas boiler is activated when the forecast demand becomes greater than the 85th percentile as indicated by the red box. There may or may not be a call for heat from the house in this window, the controller is unconcerned with this. The controller's function is to avoid the HP impacting upon peak grid demand whilst maintaining a heating source for the house. The algorithm can be seen to perform precisely as intended. The gas boiler could be run at a greater proportion of peak system demand by simply reducing the percentile calculation variable, this would have the effect of lowering the blue line on the chart. The variable could be altered throughout the day, across the course of the week, or across the seasons in line with the system operator's requirements.
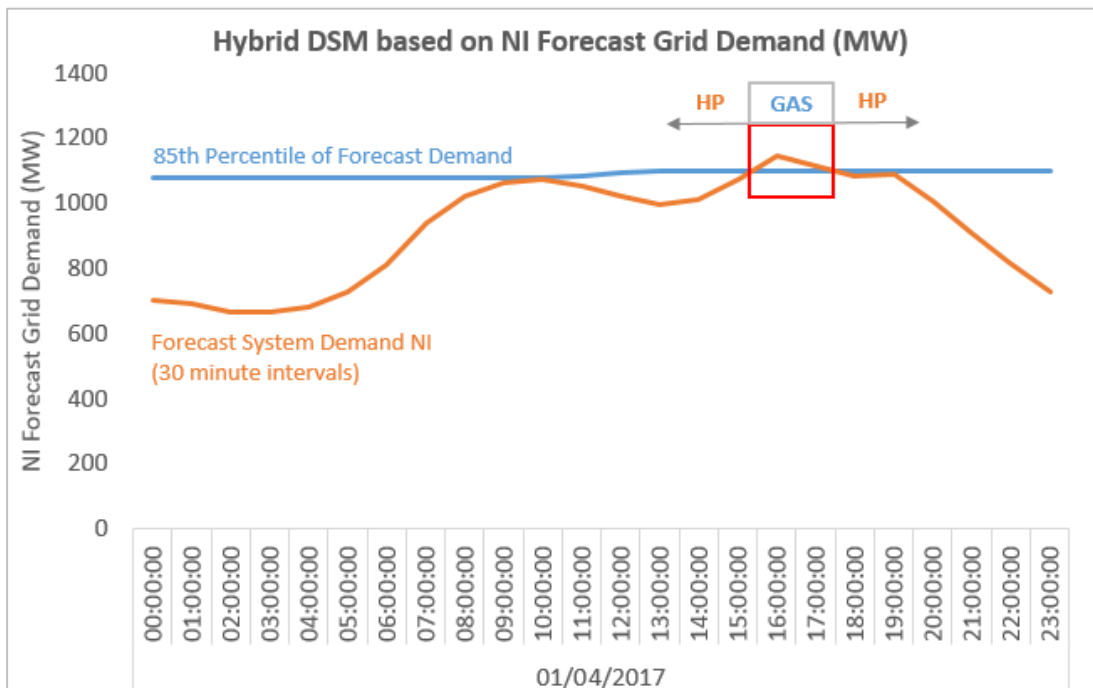
Figure 4-47 Logged data from Raspberry Pi HP controller 1st April 2017 running hybrid HP or gas boiler DSM based on grid forecast system demand signal.

The actual thermal energy produced by the gas boiler and HP in this DSM mode is shown in Figure 4-48 and the proportional use is shown in Figure 4-49. Figure 4-48 is included to provide an indication of the total daily thermal energy demand to the house and the quantities of energy provided by each heating source across the day. One day in particular stands out, the 09/04/2017. On this day the HP provides 82.6 kWh thermal, the largest across the period, and the gas boiler provides 0 kWh. With the large heat demand it was thought odd that the gas boiler was not activated due to the length of time the HP was probably running for. Drilling down into the data produced Figure 4-50 which shows the logged controller data for that day. The 85th percentile line rises across the day and this was found to be a result of how the data for the controller was retrieved. The forecast system demand data is retrieved rolling 24 hours ahead. If the forecast system demand is generally greater the next day the 85th percentile calculation value is pushed higher, and this can affect the time window for which the gas boiler will be active i.e. it will be smaller. The opposite can happen if the forecast system demand for the next day where to be generally lower i.e. the gas boiler will be activated for longer. This affect is generally undesirable as it can lead to this situation where no DSM occurs in a day due to a relatively larger forecast demand in the day ahead. This is illustrated further by Figure 4-51 which shows the forecast demand data and subsequent percentile calculation across the period. Paying particular attention to the 9th April, it can be seen that the demand for the 10th April is significantly greater, resulting in the undesirable effect. As a result, subsequent algorithms were modified to use the in-day forecast demand only i.e. 00:00 to 23:45.

In terms of the controller DSM performance Figure 4-49 provides greater insight by showing the percentage split between the gas boiler and HP. The percentage split varies across the period, with several days were there is a very large proportion of the heating provided by the gas boiler, and the majority of days were the heating is provided predominately by the HP. It should be reiterated that the gas boiler is only active for an approximate 2 hour window in the day and that the heat demand is entirely independently controlled by the occupant who is unaware of the heating system arrangement. From this we can gather that a significant amount of heating demand occurs in concurrence with peak electric system demand and therefore the controller does provide a useful function of avoiding the HP impacting upon peak system demand. As the controller is automated the system operator would therefore not have to rely on causing a behavioural change in the occupant and the occupant has the benefit of an uninterrupted and seamless heating source.
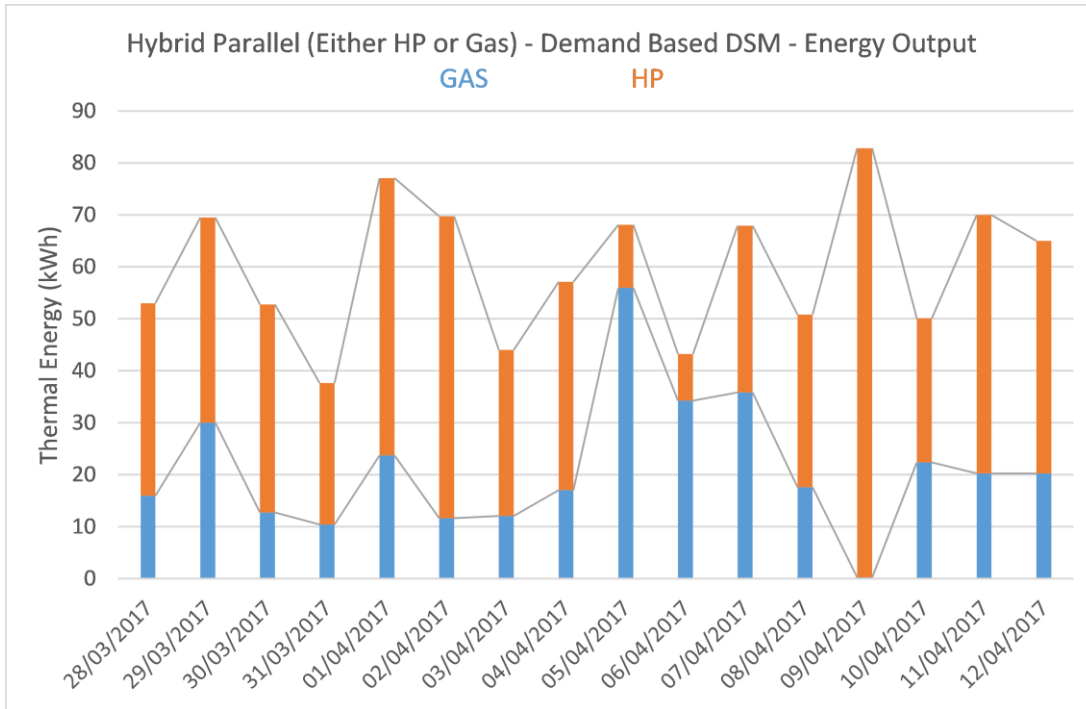
Figure 4-48 Comparison of total daily thermal energy delivered to house from the HP and gas boiler between 28th March 2017 and 12th April 2017. The gas boiler is used at peak system demand if the house calls for heat. In this mode the heating is provided by either the gas boiler only or the HP only (not on at the same time).
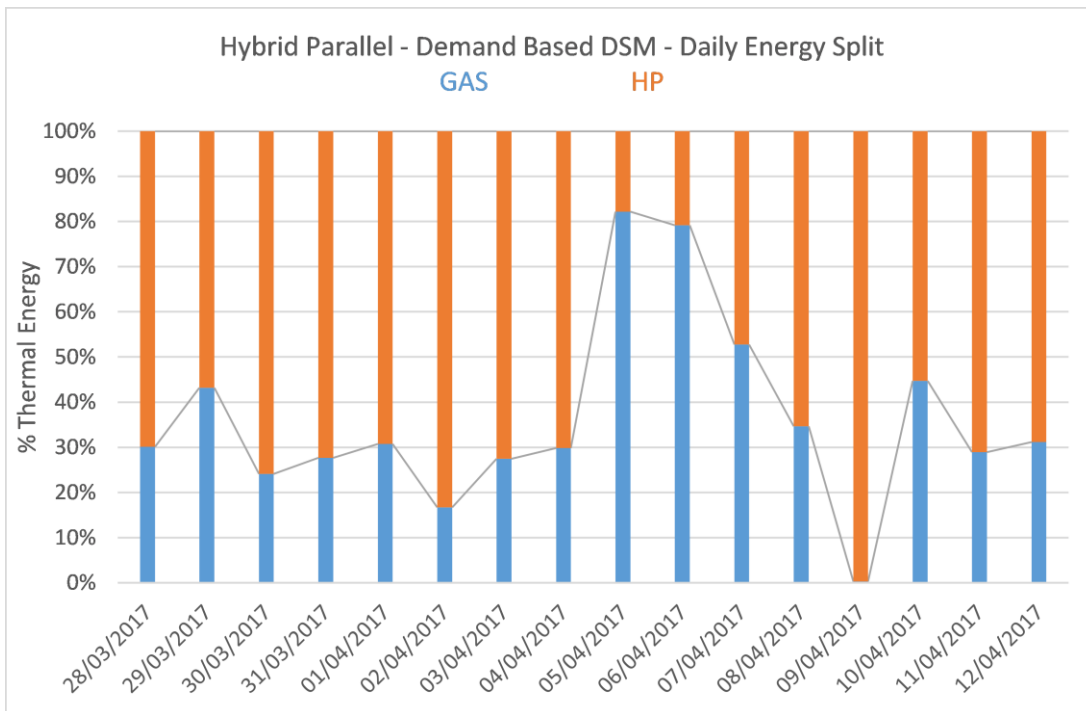
Figure 4-49 Percentage split of thermal daily energy delivered to the house by the gas boiler or HP using demand based DSM between 28th March 2017 and 12th April 2017.
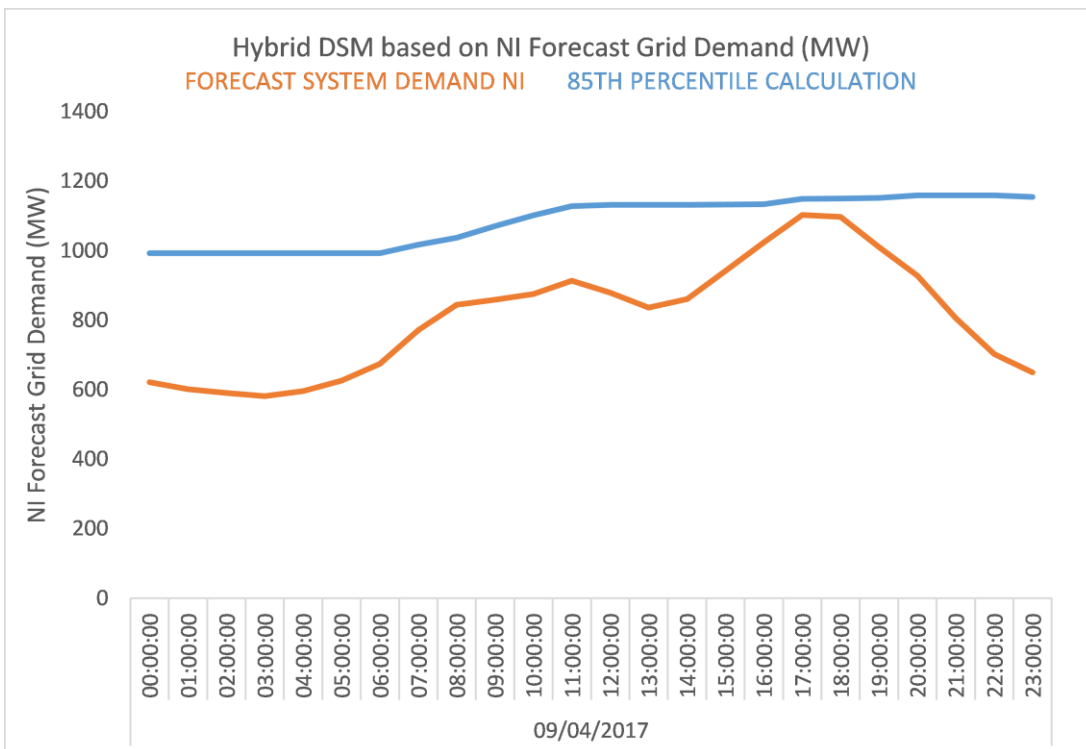
Figure 4-50 Logged data from Raspberry Pi HP controller 9th April 2017 illustrating artefact of data retrieval using rolling 24 hours ahead.
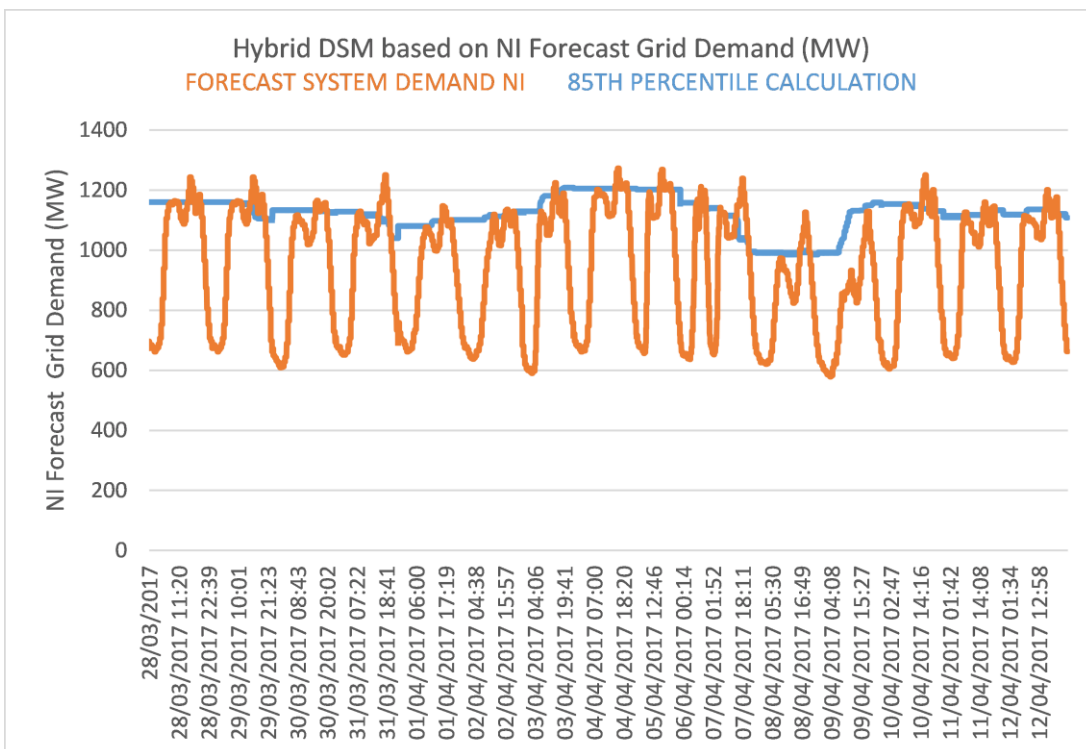
Figure 4-51 Logged data from Raspberry Pi HP controller between 28/03/2017 and 12/04/2017 running hybrid HP or gas boiler DSM based on grid forecast system demand signal.

The COP of the gas boiler and HP was calculated to compare performance using the DSM strategy. The results are shown in Figure 4-52 plotted against daily average temperature. Two outliers were identified for the HP calculations (circled in solid red) were the HP COP was unusually low for the given ambient temperature. The data points relate to the 5th and 6th of April 2017. Further investigation revealed the HP was running for a short period of time, switching to the gas boiler then switching back to the HP soon after and repeating the cycle. The cycling occurred across the 2 days. The issue was a result of how the Raspberry Pi controller software was programmed to deal with network faults such as no network connectivity or the EirGrid website being unavailable. In such an instance a network error exception would be thrown and the error handler would instruct the relays in the system to de-energise causing the heating system to revert to the default mode of gas boiler heating. The error handler would sleep for 5 seconds and the programme would try to reconnect to the website. If successful the controller program would begin to function normally again and the appropriate heating system would be chosen. If the connection was unsuccessful the error handler would continue to retry every 5 seconds until successful. This method worked without issue at the beginning of the controller design when using the HP and thermal store DSM strategies. However, as the project progressed the reliability of the EirGrid website began to reduce and connectivity errors became more frequent and sporadic. In this instance the controller was able to connect one minute but unable to connect the next (rather than long periods of no connectivity) and the relays were switching back and forward between the HP and gas boiler. This meant the HP would switch on for short periods of time and then switch off therefore resulting in greatly reduced COP on the 5th and 6th of April. Subsequent algorithms were modified to use an error counter in which a network connection was attempted and if successful the program loop could proceed, or else if the connection was unsuccessful 10 attempts would be made every 30 seconds before any action would be taken. If within 10 attempts a successful connection was made the error counter would reset to zero. After 10 attempts the relays would be de-energised and the default system of gas boiler heating would occur. This method alleviated sporadic short-term errors causing the HP and gas boiler to switch back and forth, however it was still effective at catching longer term more semi-permanent errors such as the website or network connection being down.

In order to give a better reflection of how the system could perform without the software errors in the controller the outliers identified for the HP COP calculation were removed and the revised graph is shown in Figure 4-53. The fit of the HP trend line is improved as a result

as indicated by the R^2 value. The average temperature across the period was 8.7°C and the COP of the HP averaged 1.91, with the gas boiler averaging 0.81.

The COP of the HP and gas boiler has been plotted against daily average temperature so that the performance of the HP and gas boiler can be fairly compared. The gas boiler will be largely unaffected by the ambient temperature and this is obvious from the low R^2 value of 0.1696 and the flat trend line i.e. the variables show no relationship to one and other. The efficiency of the ASHP on the other hand shows a positive relationship to increasing ambient temperature.
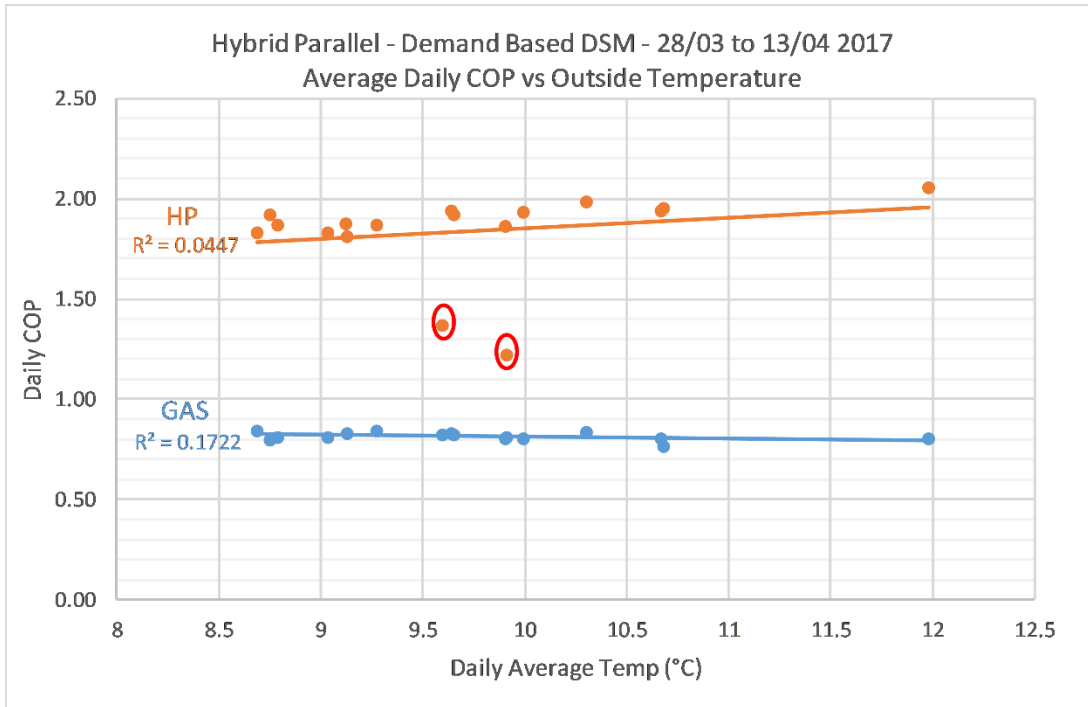
Figure 4-52 Graph of daily COP of the HP and gas boiler versus average daily temperature between the 28/03/2017 and 13/04/2017. The DSM running strategy of the heating system was hybrid parallel (either HP or gas on only) based on the forecast electricity demand on the grid (gas boiler used above 85th percentile system demand and HP used otherwise).
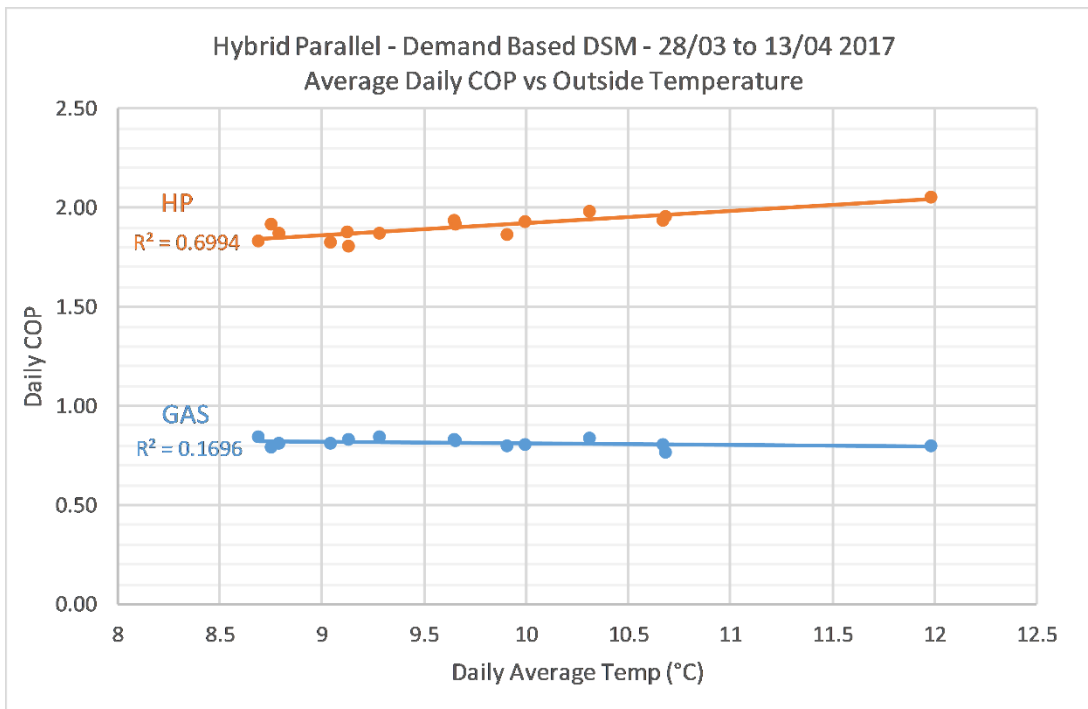
Figure 4-53 Graph of daily COP of the HP and gas boiler versus average daily temperature between the 28/03/2017 and 13/04/2017 (same as Figure 4-52 with HP outliers removed).

To gain an insight into the running costs of the hybrid system the daily COP data was used to calculate the average daily cost of thermal energy produced by the HP, gas boiler and the combined heating system. The results are shown in Figure 4-54.

Across the period the average cost of thermal provided by the HP, gas boiler, and combined was 6.3, 4.9 and 5.8 p/kWh and COP averaged 1.91, 0.81 and 1.37 respectively with average daily temperatures ranging from 8.7 to 12.0 °C. The HP remains more expensive than the gas boiler throughout the trial period due to the low COP despite the relatively mild ambient temperatures. At the given domestic fuel prices and average gas boiler COP of 0.81 the HP would need to achieve a COP of 2.45 (electric cost divided by gas thermal cost) to reach parity with the cost of producing thermal energy with the gas boiler.

Combining the HP and gas boiler using the parallel demand based DSM strategy resulted in a cost of thermal of 5.8 p/kWh. This value is weighted on the proportion of HP use to gas boiler use in a given day. With the given efficiency performance of the HP and gas boiler, as the proportion of heating supplied by the gas boiler increases in a given day, the cheaper the cost of thermal will be (it would be 4.9 p/kWh at 100% gas boiler use). If the HP were more efficient (greater than COP 2.45 in this example) the HP would be cheaper at producing thermal energy than the gas boiler. As a result greater use of the gas boiler in a given day would increase the combined cost of thermal. This is a significant point to make as seasonal COP of heat pumps in the UK would aim to be over a minimum of 2.5 and therefore at the given standard rate fuel tariffs it would not be cost efficient for a domestic consumer to participate in a DSM strategy such as this. Any cost benefit for the system operator or energy supplier would need to be filtered down to the consumer to encourage participation in such a scheme.

The daily CO_2e intensity of the thermal energy delivered to the house is shown in Figure 4-54 and is dependent on the HP and gas boiler COP. The combined intensity varies dependant on the proportion of heat provided from the HP and gas boiler and the respective operating COP. The average daily CO_2e intensity of heat delivered by the HP was 0.202 kg CO_2e/kWh thermal, the gas boiler was 0.226 kg CO_2e/kWh thermal, and combined was 0.210 kg CO_2e/kWh thermal. As the HP has a COP greater than 1 the HP CO_2e intensity producing thermal energy reduces as the COP increases. Therefore, even though UK GHG factor for domestic electricity is much greater than for domestic gas, 0.38443 kg CO_2e compared to 0.18416 kg CO_2e respectively in 2016, the HP is much less carbon intensive. Improved COP of the HP provides greater potential for carbon savings over the gas boiler which can only have

a maximum COP of 1 if it had no energy loss. In addition, decarbonisation of the electricity grid by increasing renewable penetration and improving grid efficiency further increases potential carbon savings for the HP.
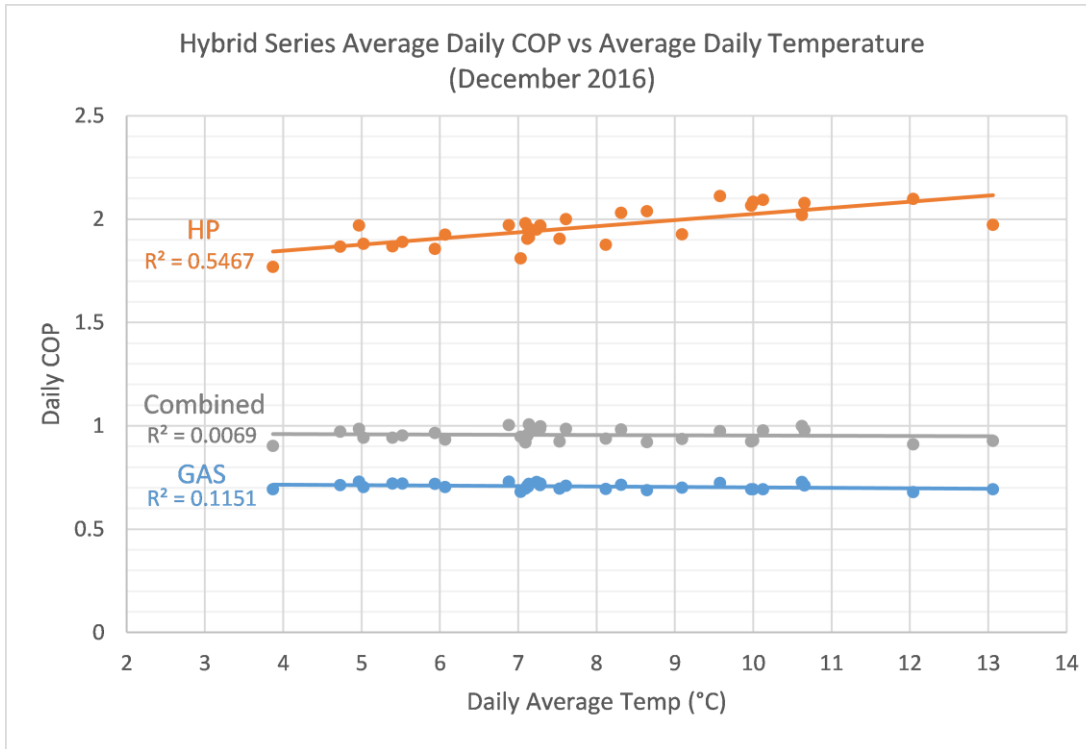
Figure 4-54 Cost of thermal energy delivered to the house based on domestic gas price of £0.04/kWh and domestic electricity price of £0.12/kWh based on cheapest domestic fuel prices (The Consumer Council NI, 2017b).
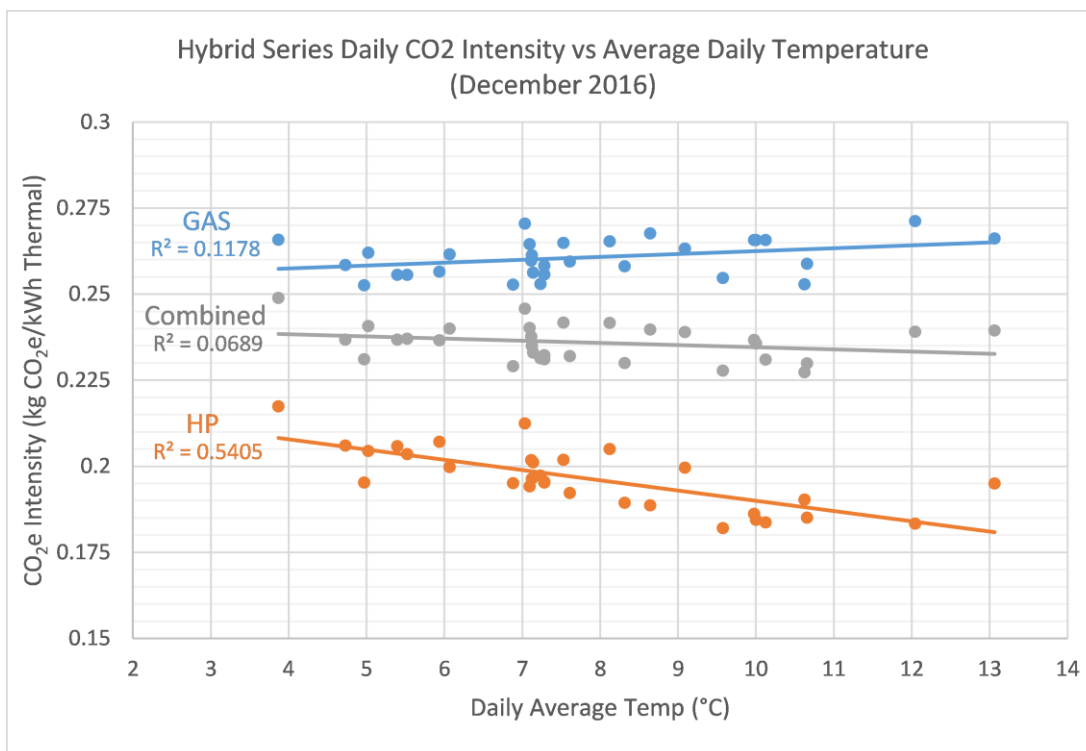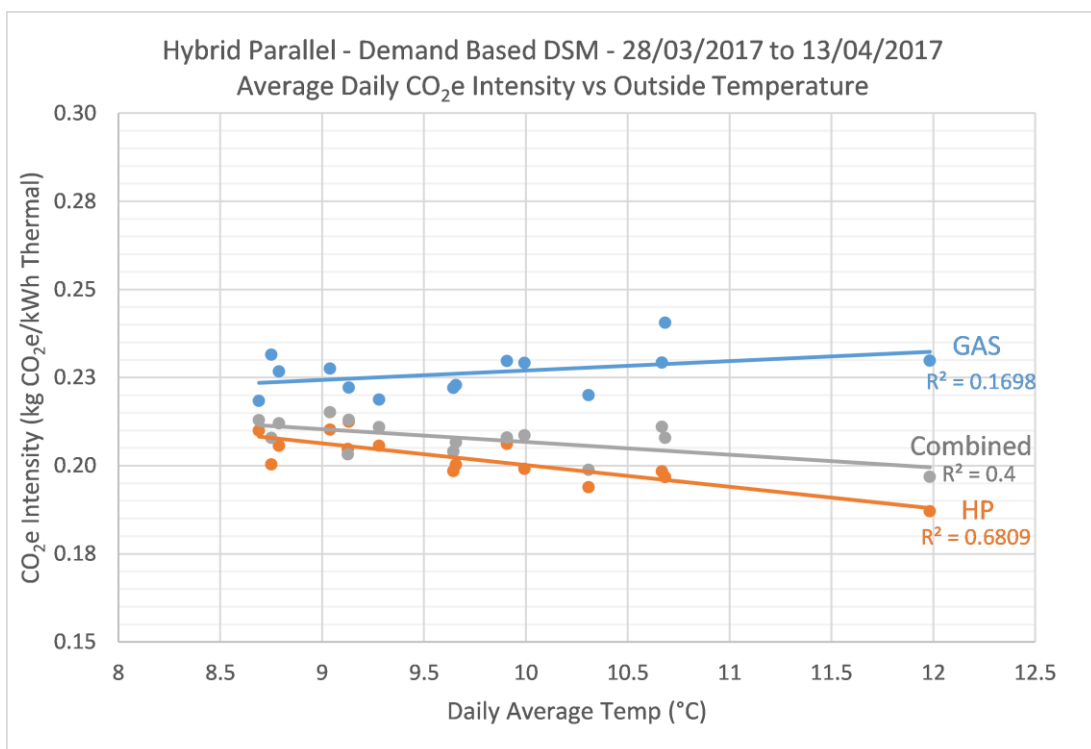

Figure 4-55 Daily CO_2e intensity of thermal delivered to the house by the gas boiler, HP, and combined. The calculation uses UK GHG factors for 2017 (BEIS, 2017b).

4.7.2   HP/Gas Boiler Hybrid Mode: Market Price Signal

The DSM strategy analysed in section 4.7.1 was modified to run either the HP or gas boiler based on market price signal as opposed to forecast system demand signal. Market price is an interesting signal to test because it is a combined representation of the grid interactions in terms of load balancing (demand vs generation), volumes of renewable and conventional generation on the grid, and hence to a degree the carbon intensity of the grid also. Price is also a clear signal as to how a customer should respond i.e. use the cheapest fuel to produce heat which in this case is either gas or electricity for the hybrid heating system. The makeup of the electricity SMP is described in section 1.5.3. In very simple terms increased volumes of renewable energy on the grid tends to push down the market price of electricity and hence the carbon intensity of that electricity. At a local household level, if a HP is being used at low market price and avoiding peaks, it follows that the electricity it will use will be of lower carbon intensity also. At peak electricity price the gas boiler is being used in place of the HP which means the customer (if they had access to a market tracking tariff) can avoid price spikes on the market. This means the customer can easily switch between the cheapest fuel to produce domestic heat whilst also having a positive knock on affect for the grid in terms of grid balancing and effective utilisation of renewable generation. However, it can be the case (at present) that high wind availability can push market prices up if that generation must be curtailed due to lack of demand or system operational constraint (SNSP levels). The above strategy would alleviate curtailment to an extent by increasing demand at times of low market electricity price and hence high volumes of renewable generation on the grid.

The strategy from section 4.7.1 remained the same in that the gas boiler would be activated above the 85th percentile. As outlined and justified in section 4.7.1, the calculation was changed to calculate the percentile within the current day (00:00 to 23:45). Figure 4-56 shows an example of the logged data from the Raspberry Pi controller. Indicated on the chart is the half-hourly all-island SMP price for Ireland retrieved from the EirGrid website. The blue line indicates the calculated 85th percentile of the SMP data. If the dataset was constant throughout the day it would be expected that the 85th percentile was a single and constant value also. However, it is evident that the calculated value varies at points throughout the day and this is a result of the SMP dataset being revised by the market operator as the day progresses. It is therefore advantageous for the Raspberry Pi to be retrieving the data on a continuous basis (set to 1-minute retrieval).
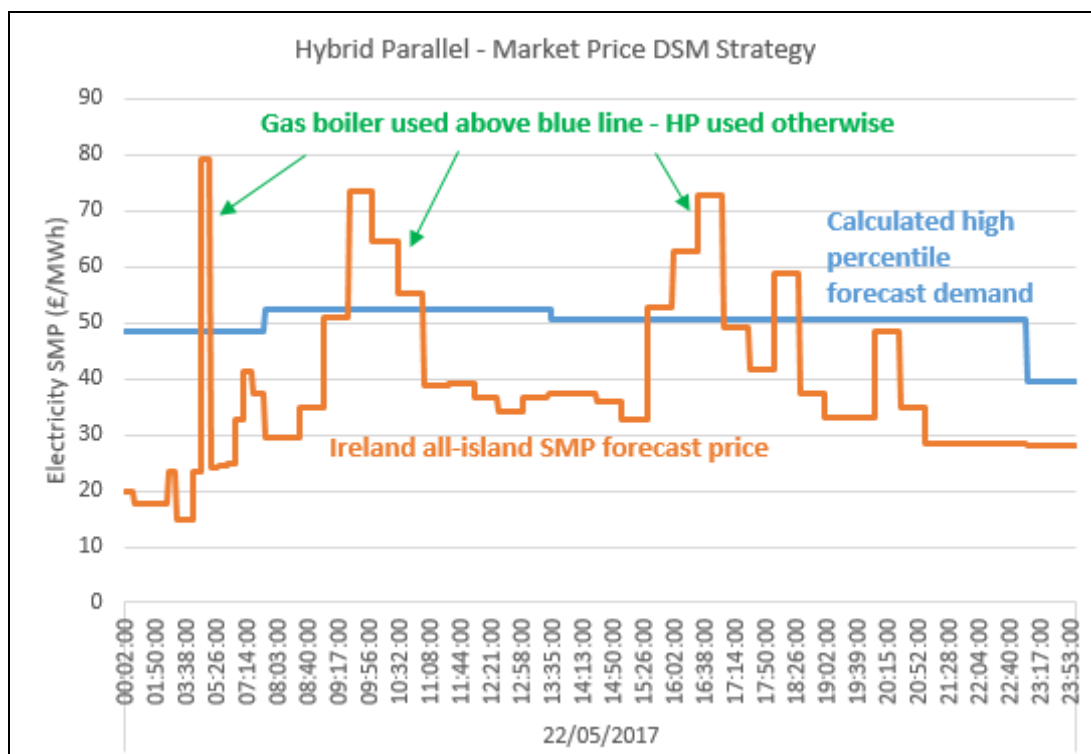
Figure 4-56 DSM strategy based on forecast SMP (system marginal price) for Ireland (all-island). The blue line is the calculated 85th percentile of the forecast electricity price in the current day (00:00 to 23:45). The forecast prices can change throughout the day and therefore the line is not a static number. The orange line is the SMP at the time the data is retrieved (data retrieved every minute, SMP price updated half hourly). The gas boiler will be activated above the 85th percentile and the heat pump will be active otherwise.

Above the blue line the gas boiler is activated, and the consumer avoids using electricity (via the HP) at high electricity prices throughout the day. Using the HP and gas boiler in this way provides an extremely flexible method of delivering autonomous DSM for the system operator and the seamless integration for the consumer means they are unaware the heating source has been changed. Using the market price signal has the advantage of improving integration of electric heating into the grid by avoiding impacting upon, and exacerbating, high electricity prices and price spikes.

The use of the 85th percentile is somewhat arbitrary in this situation as it is entirely dependent on what impact is required by the system operator to improve efficiency or avoid network issues. The value is dynamic however and could be altered dependent upon the level of DSM participation at any one time and the volume required to achieve the desired outcome. For a true consumer benefit a half hourly domestic tariff reflective of the SMP market price would allow a consumer to engage in the market and minimise their fuel costs by switching between electricity and gas to heat their home using this relatively simple

controller. This in turn could have a positive effect of a self-balancing market if enough customers are engaged in this type of DSM strategy. The controller function could be relatively simply extended to dynamically assess historical COP of the HP and gas boiler versus ambient temperature and take into account the half hourly tariff to calculate the cheapest fuel option.

The DSM strategy using market price was allowed to run longer than the demand based as demand based DSM had been previously trialled with the HP and thermal storage whereas DSM using market price was untested. The strategy ran from 13/04/2017 to 17/07/2017. Figure 4-57 shows a 1-week example of the controller data between 05 June and 11 June 2017.
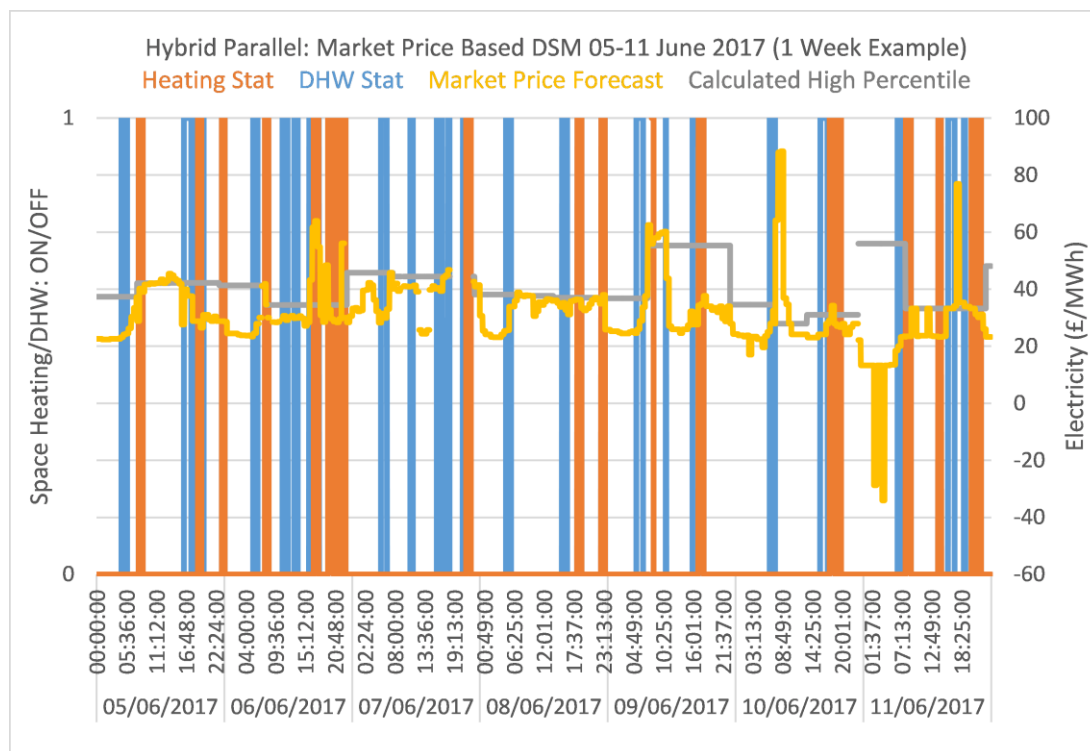
Figure 4-57 One-week example, 05 June to 11 June 2017, of hybrid parallel market price based DSM running data. Call for heat and hot water is also shown.

The forecast market price, calculated high percentile, call for heat and call for hot water data is included in the figure. The figure shows the high degree of variability in the market price, both within the day and from day to day. The market price can be seen to have a considerable spike on the 10th June reaching a high of £88.34/MWh and it can be seen to go negative on 11th June reaching a low of £-34.04/MWh. Negative prices tend to result from generators who are unable to reduce output generally at times of low system demand either due to prohibitive system or cost restraints. In this situation the generator bids in a negative price into the market pool to ensure their generation capacity is bought. In Figure 4-57 when the

calculated high percentile value is above the forecast market price the gas boiler is activated. The call for heat from the dining room thermostat and DHW tank thermostat are shown to illustrate the dynamic nature and variability of this element of the DSM strategy. The degree of variability means the gas boiler is more suited to the price based DSM strategy than a thermal store. The thermal store needs to be charged in order to be useful and even if charged it has a limited storage capacity. The gas boiler on the other hand has the benefit of unlimited capacity and availability, it therefore provides a much more flexible option for DSM. The disadvantage of the gas boiler over the thermal store is the inability to make use of low price (or even negative price) electricity and this is where an efficient thermal store has potential.

An energy comparison for the heat provided by the HP compared to the gas boiler is illustrated in Figure 4-58 (exclusive of the start and end dates as a full days data is unavailable). The data is also displayed proportionally (daily percentage split between HP and gas boiler) in Figure 4-59. The median daily temperature across the period was 13.4°C with an inter-quartile range of 3.4°C. 2885.8 kWh and 971.6 kWh of thermal energy was provided by the HP and gas boiler respectively equating to a 75.0% to 25.0% split. The proportion of heat provided by the gas boiler is promising considering the DSM activates the gas boiler for only 2.5 hours daily based on the 85th percentile (equating to 10.4% of the day), the market price is dynamic and the profile varies from day to day therefore the DSM occurs at different times each day, and the occupants of the house are unaware the DSM strategy is in place i.e. there is no bias towards using the heating at any particular time of the day. The relatively high heat demand throughout the day does increase the likelihood the gas boiler will be used in coincidence with a DSM event however i.e. there will be a call for heat from the house. From Figure 4-58 and Figure 4-59 it can be seen that the heating system is run almost every day and of the days it is run the HP provides all or the most of the thermal heat to the house.
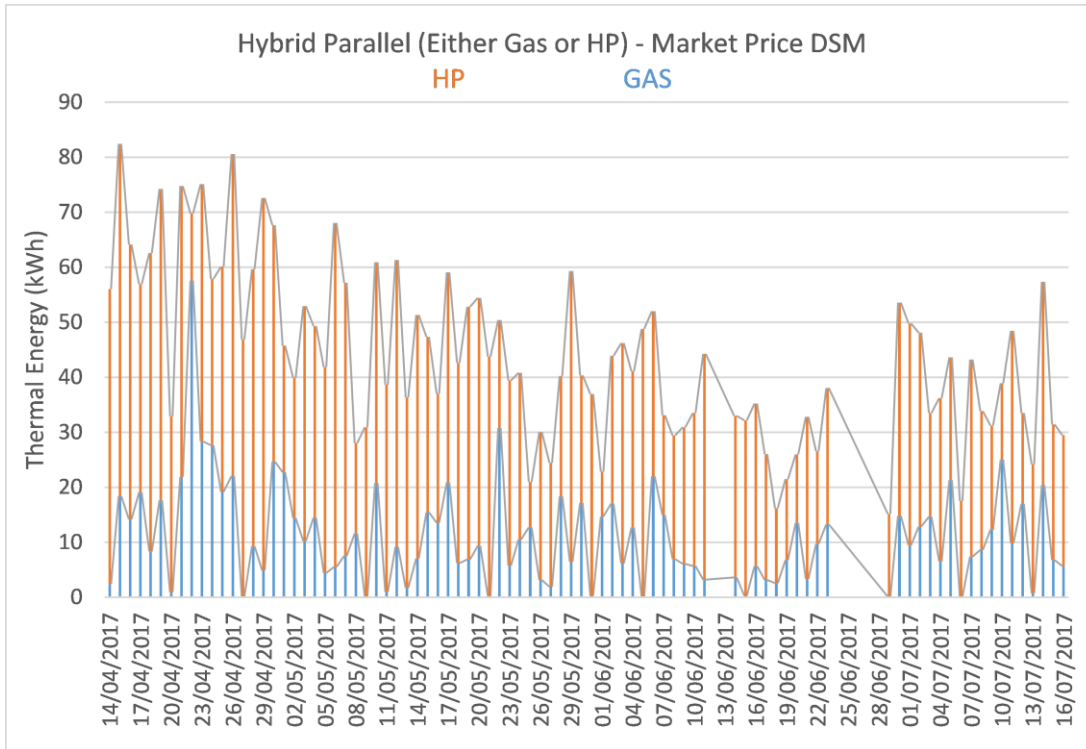
Figure 4-58 Total daily thermal energy delivered by the HP and gas boiler (stacked) to house 64 between 13/04/2017 and 17/07/2017 exclusive.
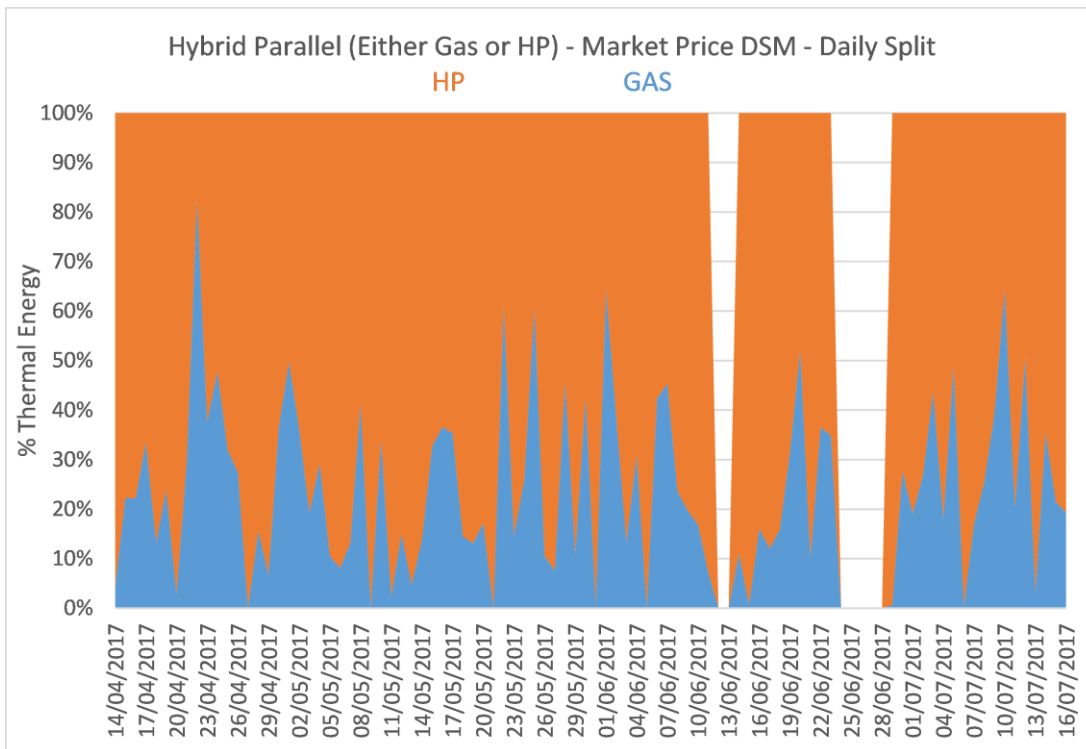
Figure 4-59 Percentage spilt of daily thermal energy delivered by the HP and gas boiler (stacked) to house 64 between 13/04/2017 and 17/07/2017 exclusive.

The daily average COP of the HP and gas boiler was calculated and plotted versus the average daily temperature. The results are illustrated in Figure 4-60.

An outlier analysis was performed on the COP values were values greater than the upper quartile plus 1.5 times the inter-quartile range or less than the lower quartile minus 1.5 times the inter-quartile range were deemed to be outliers. This was done for the HP and gas boiler COP. Four outliers were identified for the HP, highlighted in Figure 4-60 with solid red circles, corresponding to 25th May 2017, 1st June 2017, 29 June 2017 and 10 July 2017. In all cases the COP values are low outliers. When the days were analysed more closely it was observed that on the 25th May, 29th June and 10th July the HP was interrupted when running by a DSM event causing the heating system to switch over to the gas boiler. On these days the proportion of heating delivered by the HP to the house was much lower; 39.3%, 35.7% and 35.6% respectively. In order to ascertain if shorter running times may be a factor in lowering the daily HP COP Figure 4-61 was produced which shows the proportion of heat delivered to the house from the HP and gas boiler versus their respective daily calculated COP. The HP values for the 25th May, 1st June and 10th July are circled in solid red in a single group. There is a general trend showing decreasing HP COP with decreasing daily heat delivery proportion to the house. It would be expected that if the HP is providing a smaller proportion of heat to the house it is likely to be running for shorter periods also. In this case the daily COP would be reduced as a result of standby losses as both the indoor and outdoor HP units are fitted with 33W crankcase heaters which run during standby. As the daily COP is calculated from the total daily HP heat output to the house over the total daily HP electricity consumption, the COP will be affected by the duration of standby in a given day when the HP is not producing heat for the house but still consuming electricity. The fact that the HP was interrupted when running by a DSM event may also be a factor in reducing the overall daily COP of the HP.

The last HP outlier, 29th June 2017, showed a daily COP of 1.01 and is highlighted in Figure 4-61 on its own by a solid red circle. With closer analysis of the HP data for that day it became apparent that the flowmeter in the boiler room ('DT:20' on Figure 8-1) had malfunctioned and was not recording flow. This had occurred on the previous 5 days in which it appeared from the data that there was no active heating. However, after checking the pipe temperature sensors it was apparent that the heating was active and functioning normally.

For the gas boiler six low outliers were identified and these are highlighted on Figure 4-60 and Figure 4-61 by dashed red circles. The outliers were identified for the 20th and 29th April,

11th and 26th May, 14th June and 13th July 2017. When the data was looked at more closely for each of the days it could be seen that the gas boiler was on for very short periods and interrupted by a change in the DSM status or call for heat shortly after start up. This is consistent with Figure 4-61 were the outliers lie at the lower end of the proportion of heat delivered to the house.

The days in which no heat was delivered by the gas boiler were also looked at to establish if there was any particular reason for this. Of the 94 days analysed 15 of those showed no heat delivered by the gas boiler of which 6 (24th-29th June 2017) can be discounted due to the malfunctioning flowmeter in the boiler room (as previously detailed). Data for 2 others, 12th and 13th of June 2017, had to be discounted due to a data logging error. On the remaining 7 days; 27th April, 9th May, 21st May, 31st May, 5th June, 15th June, and 6th July 2017, there was no overlap between the call for heat from the house and a DSM event.

The DSM strategy could be seen to have an impact on reducing the daily COP of the HP and gas boiler relative to the normal inter-quartile range of the calculated respective values. Were the HP is interrupted shortly after start-up (within minutes) the COP is reduced because the initial high electricity consumption is not converted into useful heat delivered to the house. When the proportion of heat delivered to the house is low compared to the gas boiler i.e. the running time of the HP is shorter in a day, the HP daily COP is reduced as a result of standby electricity consumption. Similarly, the gas boiler COP drops when it starts up for short durations only to be interrupted by a change in the DSM or the call for heat is satisfied. In relative terms the lower COP values for both the HP and gas boiler tend to correlate with lower proportional consumption in a given day. It can be further summarised that the controller and design performed as intended across the period and the reliability of the controller was improved by software adjustments made to the network error handling detailed in section 4.7.1.
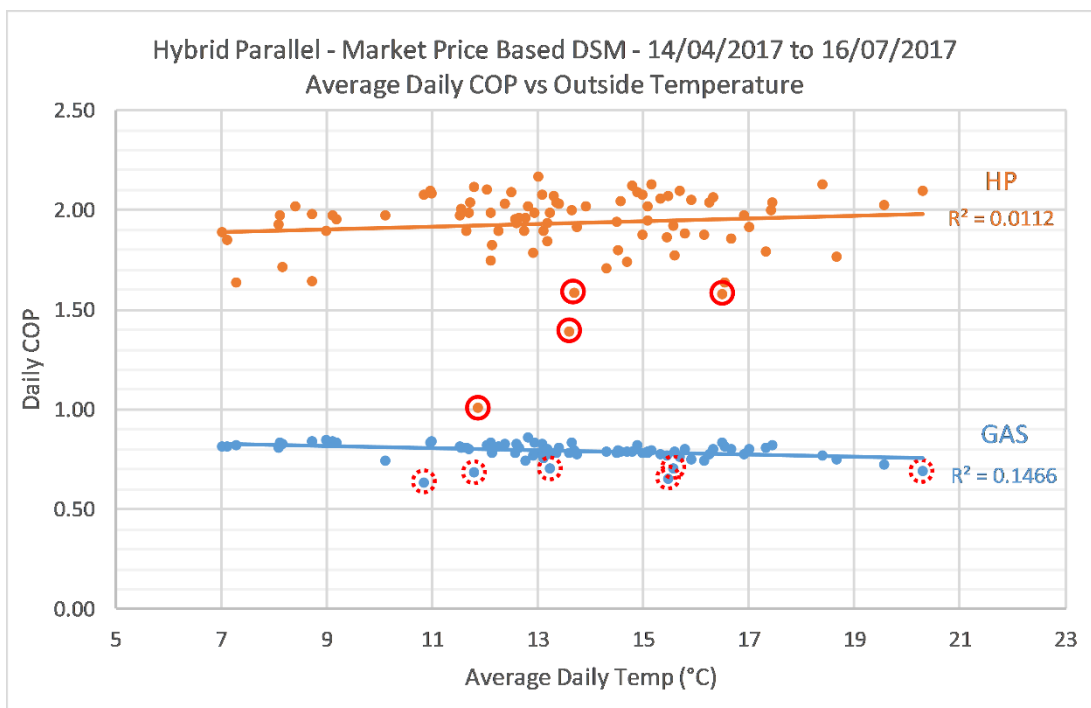
Figure 4-60 Daily average COP of the HP and gas boiler versus average daily temperature.
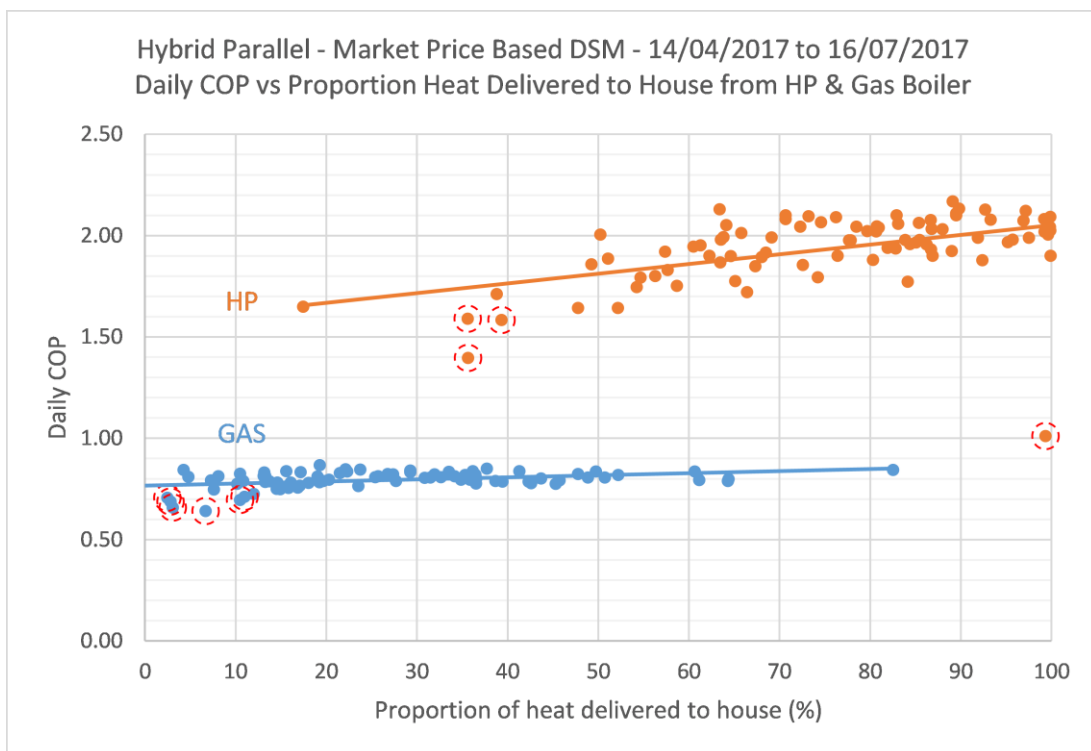
Figure 4-61 Daily COP of the HP and gas boiler versus their respective proportion of heat delivered to the house.

To gain an insight into the running costs of the hybrid system the daily COP data was used to calculate the average daily cost of thermal energy produced by the HP, gas boiler and the combined heating system. The results are shown in Figure 4-62. Across the period the average cost of thermal provided by the HP, gas boiler, and combined was 6.2, 5.1 and 5.8 p/kWh and COP averaged 1.93, 0.79 and 1.50 respectively with average daily temperatures ranging from 7.0 to 20.3 °C. The HP remains more expensive than the gas boiler throughout the trial period due to the low COP despite the relatively mild ambient temperatures. At the given domestic fuel prices and average gas boiler COP of 0.79 the HP would need to achieve a COP of 2.35 (electric cost divided by gas thermal cost) to reach parity with the cost of producing thermal energy with the gas boiler.

The daily CO_2e intensity of the thermal energy delivered to the house is shown in Figure 4-63 and is dependent on the HP and gas boiler COP. The combined intensity varies dependant on the proportion of heat provided from the HP and gas boiler and the respective operating COP. The average daily CO_2e intensity of heat delivered by the HP was 0.199 kg CO_2e/kWh thermal, the gas boiler was 0.233 kg CO_2e/kWh thermal, and combined was 0.204 kg CO_2e/kWh thermal. As the HP has a COP greater than 1 the HP CO_2e intensity producing thermal energy reduces as the COP increases. Therefore, even though UK GHG factor for domestic electricity is much greater than for domestic gas, 0.38443 kg CO_2e compared to 0.18416 kg CO_2e respectively in 2016, the HP is much less carbon intensive. Improved COP of the HP provides greater potential for carbon savings over the gas boiler which can only have a maximum COP of 1 if it had no energy loss. In addition, decarbonisation of the electricity grid by increasing renewable penetration and improving grid efficiency further increases potential carbon savings for the HP.

Figure 4-62 Cost of thermal energy delivered to the house based on domestic gas price of £0.04/kWh and domestic electricity price of £0.12/kWh based on cheapest domestic fuel prices (The Consumer Council NI, 2017b).
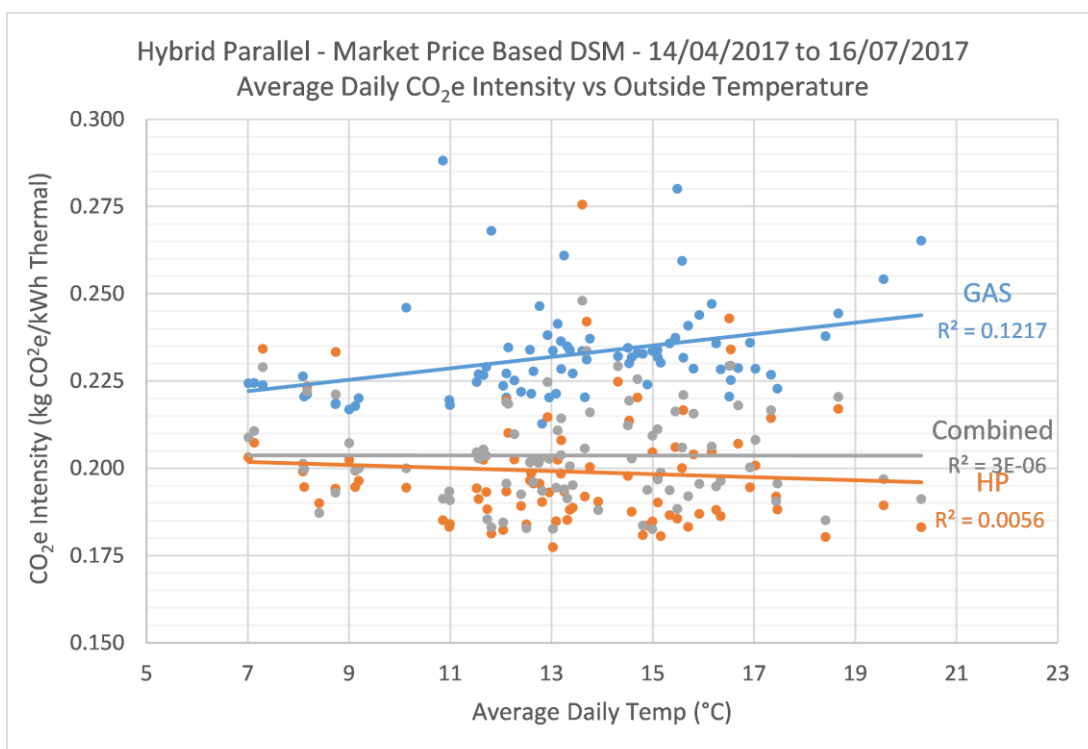
Figure 4-63 Daily CO_2e intensity of thermal delivered to the house by the gas boiler, HP, and combined. The calculation uses UK GHG factors for 2017 (BEIS, 2017b). Electricity GHG is inclusive of transmission and distribution GHG factor

5 SYNTHESIS OF EXPERIMENTS

5.1 Synthesis of Key Performance Indicators

In order to compare each of the experiments, that was run as summarised in Table 3-8 and analysed and discussed in detail in section 4, to each other, the key performance indicators COP, cost of thermal energy and carbon intensity have been plotted. As the experiments were run over different periods (and therefore different ambient temperature ranges) and for different durations a method of providing a summarised comparison was sought. The data for each of the respective KPIs was grouped by average daily temperature in groups of 2°C and the average of the respective KPI was calculated for each group. Each of the experiments was plotted on a graph, one for COP, one for cost of thermal and one for carbon intensity. The figures are illustrated as Figure 5-1, Figure 5-2 and Figure 5-3 respectively. Overall COP for the hybrid parallel modes are excluded as the figure is proportional to the operating ratio of the running time of the gas boiler and HP with respect to each other i.e. increasing or reducing the utilisation of the gas boiler will decrease or increase the overall system COP respectively. The COP of the HP and gas boiler when running in hybrid series are included however, as this mode of operation has a direct impact on the COP of each. In addition Table 5-1 provides a summary for each of the operating modes at an ambient air temperature grouping of 8-10°C (chosen because all modes operated at this condition), the DSM shift as a percentage of heat delivered from the thermal store or gas boiler with respect to the total heat delivered to the house, and for information the number of days each mode was operated for along with the total heat demand of the house.
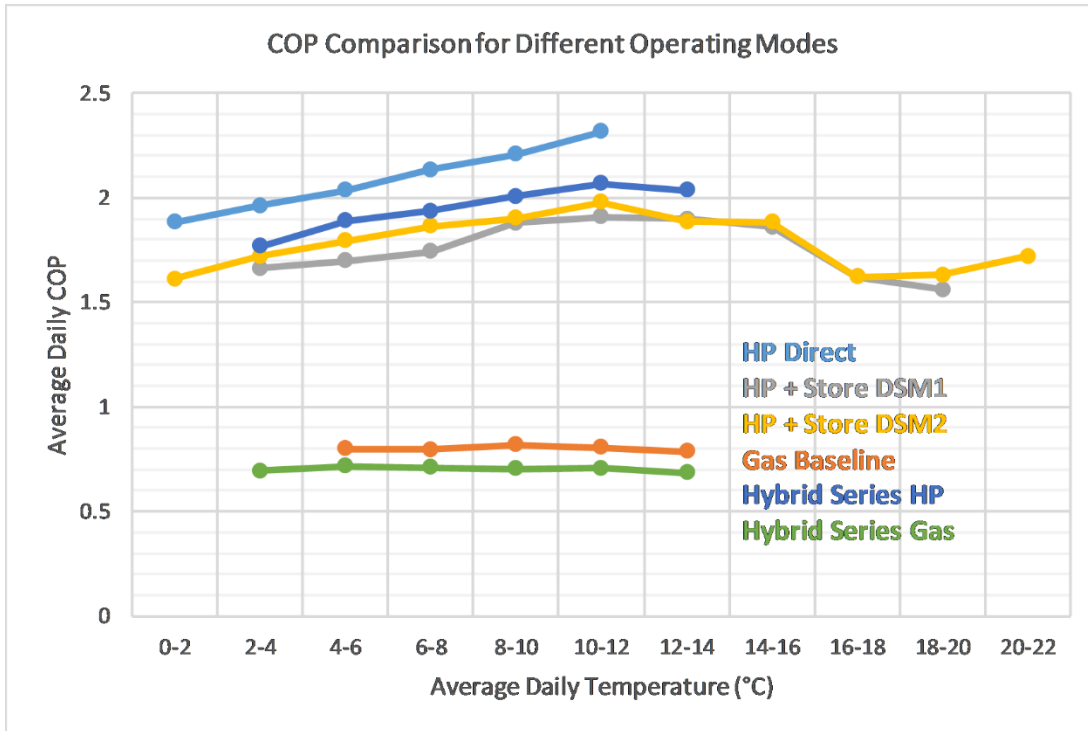
Figure 5-1 Summary of average daily COP versus average daily ambient air temperature for each of the operating modes (excluding hybrid parallel). COP for the operating modes has been grouped by average daily temperature in groups of 2°C and the average COP of each group is displayed. Hybrid not shown.
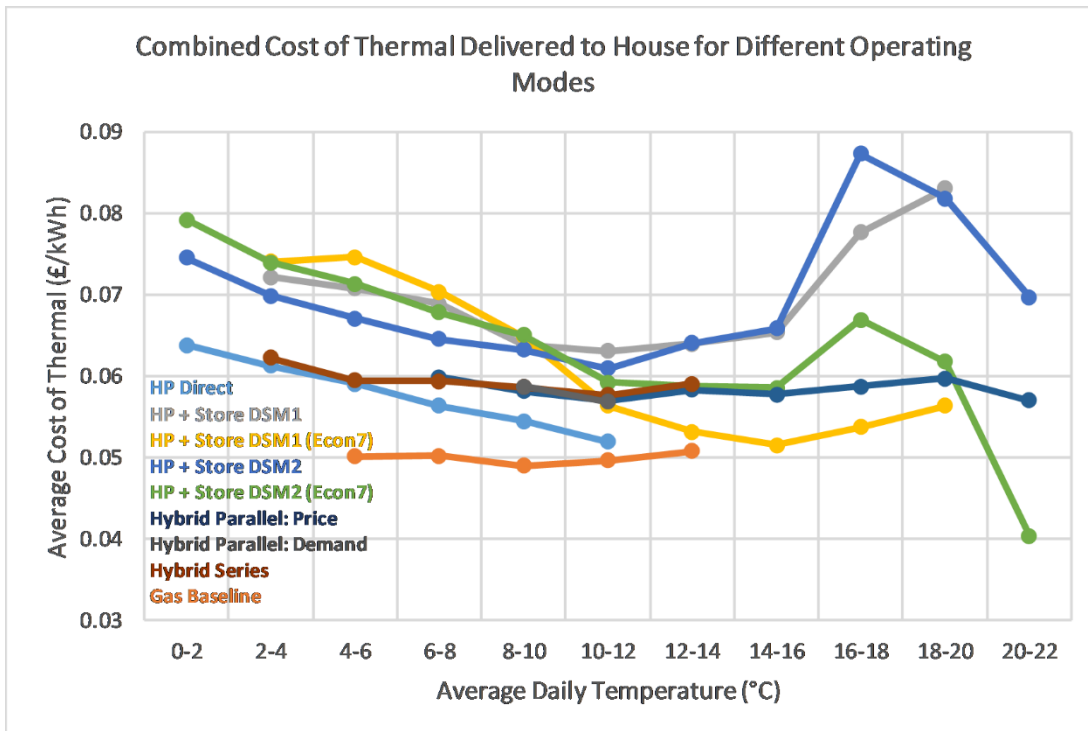
Figure 5-2 Summary of average daily cost of thermal versus average daily ambient air temperature for each of the operating modes. Cost of thermal for the operating modes has been grouped by average daily temperature in groups of 2°C and the average cost of thermal of each group is displayed.
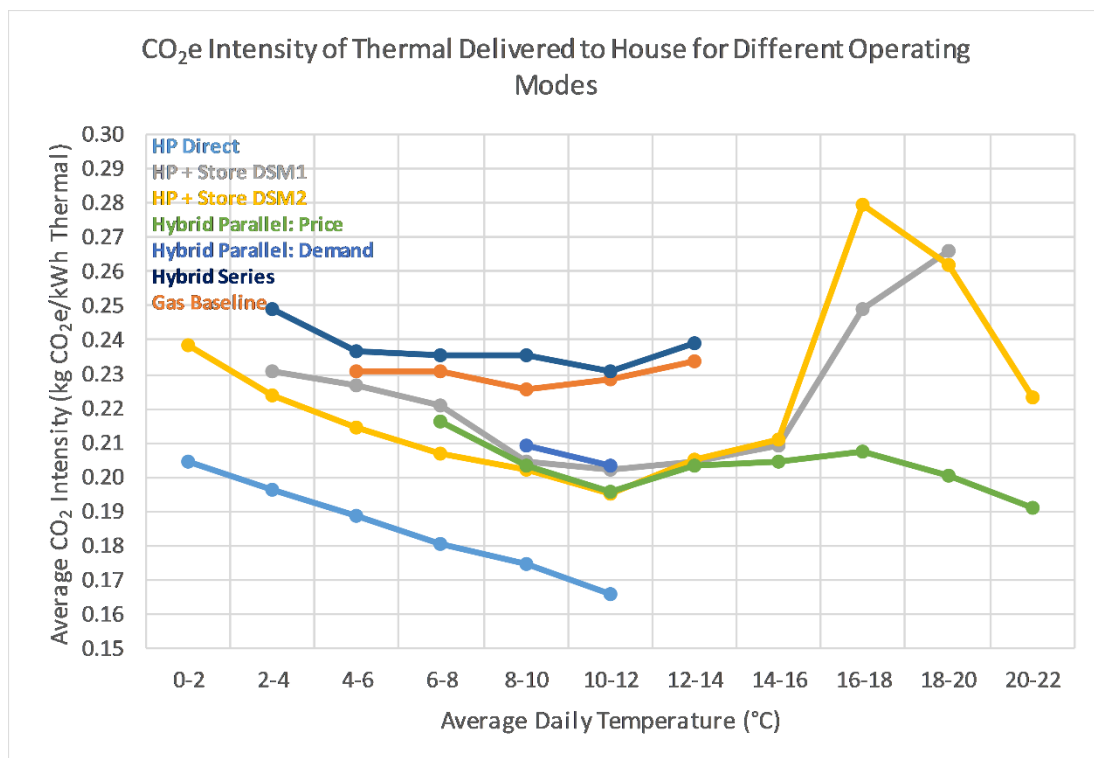
Figure 5-3 Summary of average daily CO_2e intensity versus average daily ambient air temperature for each of the operating modes. CO_2e intensity for the operating modes has been grouped by average daily temperature in groups of 2°C and the average CO_2e intensity of each group is displayed.

Table 5-1 Summary table for each of the operating modes with KPIs COP, cost of thermal and CO_2e intensity at 8-10°C. Combined COP of hybrid parallel excluded for reasons discussed in text. Also shown is the percentage DSM shift (heat delivered to house from store or gas divided by total thermal delivered to the house) across the respective operating periods for each mode, running days of each mode and total heat demand of house.

| System Mode | Ambient Air Temperature = 8-10°C group, average calculated below | | | DSM Shift (%) | Days | House Heat Demand (kWh) |
	Combined System COP	Cost (£/kWh)	CO_2e Intensity (kgCO2e / kWh)			
HP Direct	2.20	0.054	0.175	----	76	7398.21
Gas Direct	0.82	0.049	0.225	----	17	1268.46
HP & Storage DSM 1	1.88	0.064	0.205	8.68	173	6889.19
HP & Storage DSM 1 (Econ 7)		0.065				
HP & Storage DSM 2	1.90	0.063	0.202	5.32	301	18342.13
HP & Storage DSM 2 (Econ 7)		0.065				
HP & Gas Hybrid Demand DSM	----	0.059	0.209	35.90	30	1033.21
HP & Gas Hybrid Market Price DSM	----	0.058	0.203	25.10	95	3873.09
HP & Gas Boiler Series	0.95	0.059	0.236	----	37	2661.00

5.1.1 COP Comparison

The COP comparison for each of the modes versus daily average temperature is illustrated in Figure 5-1. The base line data for the HP in direct mode shows the highest COP which increases with average outdoor temperature. The lowest COP is achieved by the gas baseline and is not correlated with outdoor temperature. Firstly, considering the HP with thermal storage "DSM1" and "DSM2". In mode DSM1 the store was charged based on the lowest 0.1 percentile of forecast demand and discharged above the 0.85 percentile of forecast demand whereas in DSM2 the store was charged as before however the store was discharged until empty at the first call for heat (see Table 3-8). The change in discharge time does not appear to have had a significant effect on the combined system COP. However, from Table 5-1 it can be seen that the percentage demand shift for DSM1 and DSM2 is 8.68% and 5.32% respectively. It is illogical to think that using the thermal store at first call for heat would reduce the effective demand shift, as it would be expected that the standing heat loss would be reduced and therefore a greater percentage of heat would come from the store. The likely explanation is that DSM2 operated over a longer time period (301 days as opposed to 173 days for DSM1) and therefore operated at lower temperatures and thus the heat pump provided a greater proportion of heat directly to meet the larger heat demand. For both DSM1 and DSM2 the combined COP is reduced compared to the HP in direct mode as a direct result of using the thermal store. The thermal store introduces two efficiency losses. The first loss is seen when charging the thermal store which results from an undersized heat exchanger in the thermal store and charging at night time when air temperatures are lower. Above 10-12°C air temperature the combined COP of DSM1 and DSM2 begins to drop off and it is believed this is as a result of reduced household heat demand and therefore a greater proportion of heat is provided from the thermal store (which has a lower efficiency) compared to directly from the HP.

The individual COP of the HP and gas boiler when running "Hybrid Series" were the HP was run in series with the gas boiler (HP feeding return of gas boiler) is also included on Figure 5-1. The series test was run without any DSM for 1 month to test how the system would perform without any particular optimisation in terms of a common control system. As analysed and discussed in section 4.6 the COP of both the HP and gas boiler are negatively impacted by the lack of a common control which resulted in cycling of the gas boiler and the HP trying to modulate its capacity. From Figure 5-1 it can be seen how the COP of the series mode HP and gas boiler compares unfavourably to the baseline HP and gas boiler COP respectively. It should be reiterated that little optimisation was done and with some tweaking

of the flow temperatures from the HP and gas boiler the impact on the HP and gas boiler COP could be removed. In that regard it would be unfair to discount the operation mode as unfeasible because running the HP at a lower temperature should achieve a higher COP and with optimum control the gas boiler should run close to the measured baseline COP. The difficulty in optimising the flow temperature is the delta T that can achieved over the house, for example a delta T of 20°C over the house and a gas boiler flow temperature of 80°C may have a temperature at the boiler return of 70°C and therefore a flow temperature of 70°C from the HP and a temperature of 60°C at the HP return. When the delta T over the house is not large enough the gas boiler will likely cycle as seen in this experiment resulting in a negative impact on the COP. Sizing of the HP and gas boiler is also important as both have limits within which they can efficiently modulate their heat output capacities.

When using Figure 5-1 to compare the COP of the HP with storage it must be considered that the differences in COP are relative to the proportion of total house heat provided from storage as well as the thermal storage efficiency. To illustrate this point a summary of the thermal store efficiency, and the baseline gas boiler COP from section 4.5, is provided in Table 5-2. In addition Figure 5-4 illustrates the effective COP of the thermal store (useful heat provided to the house divided by the electrical energy used by the HP when charging) and the thermal efficiency of the store (useful heat provided to the house divided by the heat input to the store) both with respect to the daily average temperature. The gas baseline COP is also included for reference. As with Figure 5-1 to Figure 5-3 the data in Figure 5-4 is grouped by average daily temperature for each of the operating modes in 2°C groups and averaged within the group.

The effective COP for the thermal store for each of the operating modes from Table 5-2 show that with increasing thermal efficiency the effective COP of the HP increases. Thermal efficiency increased for two reasons: (1) DSM1 discharged the stored thermal energy at peak grid demand (in the evening) whereas DSM2 discharged at first call for heat (generally in the morning) therefore the longer period between charge and discharge for DSM1 resulted in greater standing heat loss; (2) for DSM2 insulation was added to the tank approximately half way through the experiment and therefore standing heat loss was reduced as a result. When we compare the effective COP of DSM1 and DSM2 to the gas baseline COP it can be seen that the effective COP of DSM2 is higher than the gas baseline of 0.80 however DSM1 is lower. In other words, if in a DSM situation the gas boiler provided the same amount of energy as that of a thermal store the combined system COP of HP and gas or HP and Store would be lowered dependant on the COP of the gas boiler or effective COP of the thermal store. It is clear the

thermal efficiency of the thermal store is poor with the literature review indicating it should lie within 50-90% for water based storage (Table 2-2). Therefore, a thermal store with improved thermal efficiency would have less impact on the overall system COP (Figure 5-1) than using the gas boiler for DSM. In addition, analysis in section 4 showed that the HP had a reduced COP when charging the tank which if improved would also improve the effective COP of the thermal store. In terms of energy use it would be preferred to use an efficient thermal store in combination with a high COP HP than using the gas boiler for DSM, especially if the store is charged at times of high renewable capacity which would otherwise be curtailed. The caveat being that the gas boiler is unlimited in the capacity of DSM that can be provided whereas the thermal store is limited by size and capacity. Nonetheless the DSM window size needs to be optimised as oversizing will mean more energy than may be necessary is supplied to the house from the thermal store or gas boiler than from the most efficient method, direct from the HP.

Table 5-2 Thermal storage performance summary. The table shows the thermal efficiency of the storage (calculated as the useful heat provided to the house from the store divided by the thermal energy input into the store), the effective COP of the thermal store (calculated as the useful heat provided to the house from the store divided by the electrical energy used by the HP when storing) and the COP of gas boiler for reference.

Operating Mode	Thermal Efficiency (Heat Out/Heat In)	Effective COP (Heat Out/Energy to Produce)	From
DSM1	0.35	0.71	Table 4-1
DSM2 (No Insulation)	0.45	0.85	Table 4-4
DSM2 (Insulation added)	0.49	0.96	Table 4-5
Gas Baseline	N/A	0.80	Section 4.5
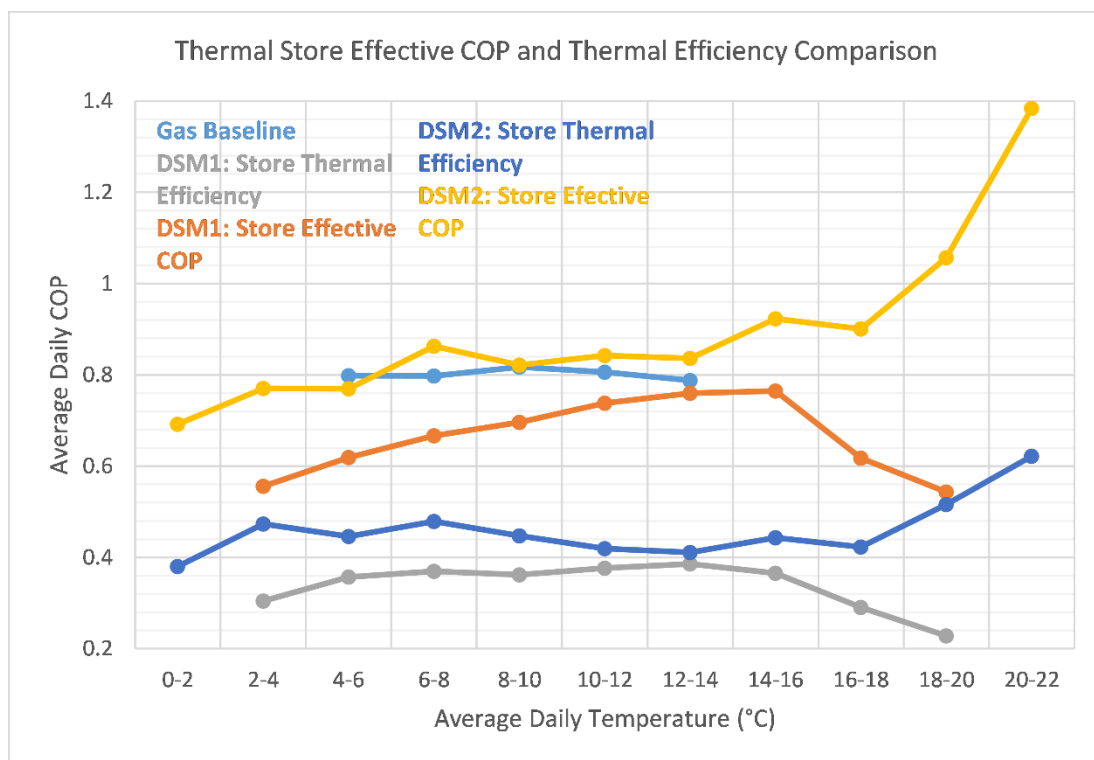
Figure 5-4 Thermal store effective COP and thermal efficiency comparison for DSM1 and DSM2 versus daily average ambient temperature. Also included is the gas baseline COP for reference.

5.1.2 Combined Cost of Thermal Comparison

The combined system cost for each of the operating modes is illustrated in Figure 5-2 and summarised for the ambient air temperature grouping 8-10°C in Table 5-1. The cost of each of the individual operating modes was analysed in detail in section 4 so only a comparison between the operating modes will be discussed in this section. As per the previous section the tariffs compared are cheapest domestic electricity tariffs for Northern Ireland as of August 2017: (1) standard fixed rate 12p/kWh (The Consumer Council NI, 2017b); (2) economy 7 rate of 6.95p/kWh (night rate between 01:00 – 08:00 GMT) and 14.25p/kWh (day rate 00:00 – 01:00 and 08:00 - 00:00) (The Consumer Council NI, 2017a). The calculated cost of thermal energy delivered to the house is based on the combined system COP i.e. the COP determines the cost which was discussed in detail in the previous section.

From Table 5-1 we can see that the gas boiler baseline provides the lowest running costs, £0.049/kWh thermal, even though it has the lowest COP. This is due to the relatively low price of gas compared to electricity. The HP in direct mode has the next lowest running cost of £0.054/kWh thermal at 8-10°C average air temperature, as it has the best COP. For DSM1 and DSM2 which used the HP combined with thermal storage, the cost of thermal was calculated using the standard electricity price and the Economy 7 tariff (used to incentivise use of electricity at low demand). Interestingly the cost of thermal when using the Economy 7 tariff was marginally higher for both DSM1 and DSM2 when examining Table 5-1. The reason for this is that the Economy 7 tariff charges a higher day rate compared to the standard domestic rate. The HP runs in direct mode during the day outside of a DSM window in order to fulfil the household heat demand and therefore if the heat demand of the house is high the Economy 7 tariff will be more expensive than the standard domestic rate. This is illustrated in Figure 5-2 which shows how the variation in air temperature effects the cost of thermal energy. Looking at DSM1 and DSM2 with and without the Economy 7 tariff it can be seen that the Economy 7 tariff is more expensive below 8-10°C air temperature and less expensive above 8-10°C compared to the standard tariff. The two rates are approximately equal around 8-10°C average air temperature. This is an important point to make because the Economy 7 tariff is supposed to incentivise night time demand and has been historically used with electrical storage heaters however houses with high heat demand may not be able to benefit from the low night time prices when using a HP unless enough energy can be stored at night to avoid running the HP for long durations during the day. This would require a thermal store with greater capacity which in turn would require greater space. Sizing of the

thermal store based on accurate house heat demand is therefore critical for calculating the economics of the system.

The hybrid operating modes are slightly cheaper than the HP and thermal storage modes, as seen in Table 5-1 for the 8-10°C air temperature group. Again, this is despite the fact the COP of the hybrid modes are lower than the combined COP of the HP with storage modes and is related to the lower price of gas compared to electricity. The hybrid modes both parallel and series appear to be less effected by variation in ambient temperature when examining Figure 5-2. This is because the gas boiler COP is not correlated to varying air temperature unlike the HP. With the hybrid a greater level of DSM is possible in terms of avoiding peak grid demand or avoiding peak market prices however the benefit of being able to store energy at low demand or low market price is not possible. The benefits of storing energy from the HP at low demand for the consumer using the Economy 7 tariff do not appear to stack up in this situation. It is believed that some sort of newly designed tariff which considers HPs coupled with thermal storage should be considered. This would be designed as a mutual benefit for both the grid and for the consumer i.e. the grid could increase wind penetration or avoid peak demand for example and the consumer would get very cheap or free electric for participation without being over penalised at times of peak demand. Again, it should be noted that the Economy 7 tariff was designed around storage heaters which are relatively much cheaper than a HP and thermal store combination however they are not necessarily more energy efficient.

5.1.3   Carbon Intensity Comparison

The combined CO_2e intensity for each of the operating modes is illustrated in Figure 5-3 and summarised for the ambient air temperature grouping 8-10°C in Table 5-1. The calculation of CO_2e intensity uses UK GHG factors for 2017 (BEIS, 2017b). The electricity GHG factor is inclusive of transmission and distribution GHG factor. The CO_2e intensity of each of the individual operating modes was analysed in detail in section 4 so only a comparison between the operating modes will be discussed in this section.

The carbon intensity of the thermal energy delivered to the house for combined modes is dependent on the proportion of heat supplied by the HP and the gas boiler to the total house heat demand, the respective COP of the HP and gas boiler and therefore quantity of fuel used by each, and also the respective CO_2e intensity of the fuels used to produce the heat namely electricity with transmission and distribution losses and natural gas. The UK 2017 GHG factors were used which for electricity was 0.38443 $kgCO_2e/kWh$ and 0.18416 $kgCO_2e/kWh$ for gas.

The HP in direct mode has the lowest carbon intensity and the highest carbon intensity is from the gas baseline and the hybrid series modes. From Figure 5-3 it can be seen for DSM1 and DSM2 that as the average daily temperature drops the carbon intensity increases reaching parity with the gas boiler in the 2-6°C temperature range. This is reflective of reducing COP of the HP as the air temperature decreases. For DSM1 and DSM2 above 14°C air temperature the carbon intensity appears to increase dramatically however the small number of data points and very small heat demand in this temperature range mean that the quantity of carbon released at these operating conditions is minor.

The most important point to make is that even with the HP operating at a mediocre COP it is still less carbon intensive than the gas boiler. This still holds true even with the DSM operation using a thermal store which is not as efficient as it should be. Also, the GHG factors used will continue to reduce as the grid continues to decarbonise and therefore so too will the heat produced by the HP. It would be expected that a HP operating at a higher seasonal COP with a highly efficient thermal store will further the cause even more strongly for the deployment of HPs for domestic heating over the use of conventional fossil fuel heating such as gas and even more so with oil. Also, what is not taken into account when using the grid GHG factors, which are an average across the year, is the potential to operate the HP based on a real time grid carbon intensity signal. As an example, the HP could be used at times of low grid carbon intensity to charge the store or heat the house whilst discharging the store at times of high grid carbon intensity. If the HP creates a load by charging a store at a time when wind, for example, would otherwise be curtailed, the efficiency of the grid would actually be increased resulting in a reduction of grid carbon intensity. The research has shown that it is actually relatively simple to set up a system that can respond to a signal however specifying the components of the system in terms of capacity (HP, thermal storage) is critical to ensure that the optimum efficiency can be achieved.

5.2   DSM Controller Performance

A major part of the research project was the development of a controller which could facilitate the automated DSM control of the various components that would provide heat to the house. The control had to be designed so that it would not affect the supply of heat to the house as the house was occupied by a family. In addition, the design should not adversely affect the thermal comfort of the occupants. Therefore, a robust design was required so that in the event of a hardware or software failure the heat could still be activated by the internal household controller. Also, a manual backup facility in the worst case situation was also needed so that the occupants could switch the system over to the gas boiler. For this side of the controls various wiring configurations were designed to interface the hardware (valves, pumps, HP, gas boiler) via a series of relays with a low cost Raspberry Pi (RPi) computer which would default to a 'dumb' mode (i.e. no input from the RPi defaulted to direct control by the household heating controller). The wiring designs which are detailed in the methodology evolved as the research project progressed to a point where the HP, thermal store, gas boiler modes could be activated by the RPi computer as desired by the DSM strategy. The occupant remained in control of the call for heat however the controller decided were the heat would come from dependant on the DSM strategy being employed. The occupant therefore did not have to concern themselves with implementing the DSM as the controller provided a fully autonomous DSM solution. At no point over the course of the project did the occupants complain about a lack of thermal comfort as a result of the control strategies employed. In addition, when software issues arose on the RPi the system defaulted to a 'dumb' mode and the occupants heating continued to work as per the hardware design.

The other part of the controller design was the production of software to facilitate the DSM operation of the HP in combination with the thermal store or in hybrid combination with the gas boiler. For this the controller needed to know two basic things: (1) the temperature of the thermal store and therefore the state of charge; (2) the state of the grid i.e. a dynamic grid signal which would allow a DSM strategy to operate in real-time in response to the actual grid conditions was required. A temperature sensor was placed in the thermal store and connected with the controller which provided an indication of thermal store charge. The upper charge limit was set at 75°C (based on 80°C maximum flow temperature of the HP) and the lower discharge limit was set at 55°C (based on the high temperature radiators in the house and factoring in thermal store energy losses). Some analysis of the upper charge limit was provided in the Results & Discussion section and it was concluded an upper set-point of 69°C may have been better due to the reduced heat transfer to the store above this.

However, this also would have reduced the useful heat that could have been stored and therefore the demand shift possible. Ideally a system model could have been used to interrogate the optimum thermal store temperature setting however it was not possible (given the time that would have been required to learn a modelling program). It could be possible in future work to apply a learning programme so that the historical heating demand of the house is known with respect to the outdoor temperature. This would allow the controller to predict the expected heat demand based on forecast weather data. This could be particularly beneficial at higher air temperatures when the house has lower demand i.e. the heat stored to the tank could be reduced based on the predicted heat demand. This may also be beneficial in homes that have a lower heat demand (i.e. better insulated).

In order for the controller to establish the state of the grid, the RPi connected to the internet and retrieved the actual forecast grid data from the system operator EirGrid. As one of the main goals of the project was to facilitate integration of HPs onto the grid by reducing impacts on peak grid demand, a DSM strategy based on the forecast day ahead demand was designed. The controller downloaded the data for the day ahead and calculated the 10th and 85th percentiles from the data which were used as threshold values for charging and discharging the store respectively. The rationale for using a percentile calculation was that the valley and peak of the system demand would be effectively captured i.e. either side of both. The calculation was repeated on every loop of the program also, therefore the controller was able to dynamically react to changes in the state of the grid or changes in the forecast demand data. The 10th and 85th percentiles were chosen related to the window of time they produced. The 10th percentile was matched to the time that would be required to charge the thermal store (around 2 hours). The 85th percentile (equating to around a 3.5 hour window), was more difficult to select and was chosen on balance that there would be a call for heat within that window (i.e. the stored heat would not be wasted) and the impact of the HP coinciding with peak grid demand would be avoided. From analysis it could be seen that the store sometimes discharged before peak demand on the grid was reached and this is as a result of the window being slightly too large. A suggestion to improve this could be to reduce the window size so that if a call for heat did coincide with peak grid demand the HP would not activate within this narrower window and if a call for heat did not coincide with the peak grid demand the heat in the store wold be made available for use at any time after the window had passed until the next charging cycle the following day. The percentile values used for this project were static and the rationale for choosing them has been described. However, if the controller was deployed in combination with storage of different capacity,

charging, discharging characteristics etc. it would be ideal if the controller could self-optimise the charging and discharging windows i.e. the percentile values. This could be done using a historical record of the thermal store temperature and a piece of code that could learn the heat up rate, heat loss rate, and discharge rate from those records and in turn optimise the percentile values used for calculating the charging and discharging windows for maximum DSM value to the grid. Effectively the controller could calculate the capacity for charge and discharge of the thermal store.

In reality HPs with thermal storage are likely to be controlled by an aggregator who can provide a meaningful DSM capacity to the grid. If the controller, as mentioned, could calculate the charge and discharge capacity of the on-site storage and report back to an aggregator it may allow for greater DSM impact for the grid. In this instance the aggregator would be able to see the capacity for charge and discharge across an array of HPs and in turn provide the DSM signal most appropriate based on positive impact for the grid (be that for example based on system demand, electricity price, or grid carbon intensity). The controller for this project only retrieved data however implementation of code that could report back to an aggregator or the grid (i.e. 2 way communication) would be trivial.

The wiring setup of the controller means that effectively any signal imaginable can be used to trigger the mode of operation all that is required is a logical strategy. The setup used on/off signals to control the DSM but future work could look at using the controller for reducing capacity i.e. turning down the output capacity of the HP to reduce grid load. This could be done indirectly by reducing the flow temperature of the heat pump and therefore taking advantage of the modulation provided by the variable speed compressor. In addition the HP could be used as a local frequency regulator by modulating up or down in response to the real time grid frequency. The Raspberry Pi does have the ability to output a varying signal e.g. pulse wave modulation (PWM) however a method of interfacing with a particular heat pump is likely to require a bespoke solution. It is likely newer HPs coming onto the market will eventually have an interface of some sort to provide this facility. Further testing however would be required to establish how such modulation would affect performance or lifespan of the HP, particularly concerning the compressor, and how the COP of the HP would also be affected.

The method of DSM control in the designed software is also applicable across other types of energy storage for example electric battery storage or electric car charging. The algorithms designed could be easily applied in these situations to provide similar DSM for the grid.

Problems surrounding heat loss and reduction in HP performance when charging would not arise if the DSM strategies were applied to electric charging and discharging. Similar benefits for the grid could be realised as described for the HP and thermal storage in terms of negating impacts on peak demand, providing grid capacity etc.

5.3   Thermal Store Performance

The thermal store as previously discussed underperformed in the research project compared to expected performance detailed in the literature review. The performance in terms of thermal efficiency and effective COP is summarised in Table 5-2 and Figure 5-4. In addition, the large size of the thermal store mean that it would be impractical for most types of retrofit installation were floor space is at a premium. However, it is believed a well-designed thermal store using materials with higher storage density has the opportunity to improve the overall system COP and make the system more practical.

The theoretical and measured heat loss of the thermal store was assessed in section 4.3. A number of areas were identified which may results in a higher heat loss than would be theoretically expected. These include the possibility of evaporation from the tank overflow pipe, lower than expected internal air temperature in the shed housing the store, and the tank insulation not providing the expected thermal resistance. A heat loss model which considers the possible loss of heat via evaporation would prove useful in quantifying this to assess if it is the likely design flaw. Simple improvements to the store could be carried out and a measured heat loss experiment could be repeated to assess any improvement in the thermal store efficiency.

5.4   DSM Impact

The impact provided by the DSM is limited by the size of thermal store that can be deployed per household, the heat loss of the thermal store and then the number of households that can be aggregated together to provide a meaningful controllable load for the grid. The previous sections have discussed how this could be improved. By using a demand based DSM strategy the aim was to first and foremost to limit the impact of the HP on peak grid demand by shifting the load to the lowest system demand. This was achieved but at the detriment of the combined system COP and therefore cost of thermal increased and carbon intensity increased compared to the HP in direct mode. The electrical energy used by the HP when charging the thermal store and the heat stored is summarised in Table 5-3. The table shows that on average across the DSM strategies the average daily electric used for charging the store was 5.23 kWh.

Table 5-3 Summary of average daily electric energy used by HP when charging the thermal store and heat stored across each the operating mode.

Operating Mode	Average Electric Storing (kWh/day)	Average Heat Stored (kWh/day)
DSM1	5.88	11.76
DSM2 (No Insulation)	5.60	10.57
DSM2 (Insulation Added)	4.21	8.28
Average	5.23	10.20

If we take for example the curtailed wind in Ireland in 2017, shown in Figure 1-9, 386 GWh was dispatched down across the year, with the highest dispatch down occurring between the hours 23:00 and 09:00 with peak dispatch down occurring at 04:00. It is beyond the expertise of the author to calculate the direct impact for the grid of creating a night time load that corresponds with the curtailed wind but as way of a crude example a simple calculation was performed which is detailed in Table 5-4.

Table 5-4 Estimation of number of thermal stores that could utilise curtailed wind in Ireland for 2017 using average daily electric energy consumed charging the store across the examined operating modes.

Description	Value	Unit
Wind dispatch down 2017 in Ireland	386	GWh/year
Average daily electric used for charging thermal store across operating modes	5.23	kWh/day
Conversion of electric used for charging to GWh	0.00000523	GWh/day
Assume store is charged every day (multiply above by 365)	0.00190895	GWh/year
Number of thermal stores that dispatched wind could charge assuming it can all be utilised	202205	Number of thermal stores/households

The calculation in Table 5-4 assumes all curtailed wind could be utilised and the thermal stores would be charged every day. In reality not all the curtailed wind could be utilised, and the thermal stores would not be charged every day either (i.e. in summer when no heat demand). The calculation estimated 202205 stores could be charged given the same operating conditions and performance experienced across the DSM experiments. This is a significant number of homes given that in Northern Ireland 703275 homes responded to the 2011 census with regard to central heating type (Table 1-1). For this crude example, the impact for the grid is evident. Effectively the built environment can act as an energy store transferring this unutilised energy to the peak system demand. In turn a HP is able to achieve a factor increase in thermal energy compared to other types of thermal storage such as storage heaters. As the heat produced is from a renewable source the carbon intensity of the electric used by the HP is effectively zero and so too is the thermal energy produced. Therefore, the carbon intensity of household heating can be improved.

Benefits for the consumer are also difficult to quantify. It has been shown that the intervention in terms of providing DSM with a thermal store and heat pump will increase running costs compared to direct heating with a HP. It was also shown that the tariff designed to encourage use of night time energy, Economy 7, can actually be more expensive at times of high house heat demand (low air temperature) due to the penalty applied by the day rate in the tariff. Other incentives that pay for the quantity of thermal energy produced from a renewable heat source (of which a HP is one), have not been considered as it is the authors opinion it may incentivise the unnecessary use of energy. However, considering the example calculation in Table 5-4 which utilises energy which would otherwise be curtailed, an appropriate incentive might be to offer this energy at a very low rate or even for free. The intricacies of the electricity market are beyond the scope of the research and the knowledge of the author, however the fact that wind energy could be used that may otherwise have to be curtailed may in effect offer a saving for the market even if the electricity is offered for free. For an appropriately designed system it would be hoped that the consumer would benefit in terms of cheaper fuel costs which would have high impact on consumers in fuel poverty.

As pointed out previously the sizing of HPs and thermal storage is critical so as to ensure the system operates in the most efficient manner and the energy demand is as small as possible. It is always the case that the most efficient method of decarbonisation is reduction in energy consumption and thus a 'fabric first' approach should always be adopted. Other grid services such as grid frequency response will be the subject of future work.

6   CONCLUSIONS & FUTURE WORK

The synthesis section 5 provides a concise and detailed summary of the overall project with discussion for improvements and ideas for future work. However, a list summary of the work completed and the key outcomes will be provided in this section as a quick reference.

6.1   Conclusions

- A high temperature air source cascade heat pump (Daikin Altherma HT 11kW, maximum 80°C flow temperature) was selected for retrofit into one of two occupied test houses on the Ulster University Jordanstown campus as a replacement for a condensing gas system boiler. The single brick test house was built to 1900 standards with minimum insulation specification (loft insulation, double glazing windows).

- The HP was coupled with a 600 litre thermal store containing water as a heat storage medium. The store had the capacity to store approximately 12kWh of useful heat based on a maximum charge temperature of 75°C and minimum discharge temperature of 55°C.

- A number of wiring configurations were designed to allow independent control of the HP, thermal store, gas boiler, 3-way valves, and circulation pumps through a series of relays.

- A low cost Raspberry Pi (RPi) computer was used to control the switching of the relays which based on a programmed DSM strategy chose the appropriate heat source for the house.

- The controller was designed to be completely independent of the house heat demand which was controlled as normal by the existing heating controls in the house (dual space and hot water controller with room thermostat). The controller therefore could provide fully automated DSM control of the heating system independent of the occupants' behaviour.

- The retrofitted heating system and wiring was designed so that in the event of the RPi crashing the heating system would continue to operate in 'dumb' mode ensuring the occupants' thermal comfort was not affected. The controller also provided an email notification in such an instance so that the problem could be speedily resolved.

- The DSM strategies were implemented in Python code running on the RPi controller with the primary aim of limiting the HP impact on peak system demand by shifting a portion of the heating demand from the lowest grid demand to the peak grid demand by charging and discharging the thermal store.

- The software was able to use the actual system operator forecast grid demand data in real-time which was accessible over the internet. By doing this the controller could react dynamically to the changing conditions of the grid both within day and over the course of the week/season. As the software was fully automated the DSM strategy was not compromised by lack of compliance of the house occupants.

- The hardware side of the system and backup worked as designed with no major issues arising. No complaints were received from the occupants regarding lack of heating over the testing period.

- The software side of the controller suffered from initial bugs and glitches which were alleviated as the research evolved. The most notable glitch concerned the reliability of the EirGrid website from which the grid data was acquired. As the experiments progressed the website became less reliable and as a result the controller would switch the HP on/off sometimes from minute to minute. This was solved by modifying the code to count glitches and act only after a certain number was reached. This removed the reliability issue for the most part.

- The HP was also coupled with the gas boiler to produce a hybrid system. The hybrid HP and gas boiler was operated in two modes: (1) Parallel were the thermal store was effectively replaced by the gas boiler to provide the DSM function based on firstly a forecast system demand signal (the same as that used with the thermal store) and secondly a forecast system marginal price (SMP) signal; (2) Series mode were the HP fed the gas boiler return in series without any DSM functionality.

- For the gas boiler in parallel the rational was to use the gas boiler in place of the thermal store to avoid the HP impacting on peak grid demand. The advantage being that the gas boiler would not suffer standing heat losses like the thermal store and the gas boiler could provide guaranteed firm DSM capacity. With this in mind, the use of a forecast price signal (SMP) which is variable across the day could also be used to signal when the gas boiler should be activated (i.e. had high SMP price). The disadvantage of using the gas boiler in this manner was that the lack of storage meant the benefit of storing heat at low system demand, low system price, or high renewable generation (wind) could not be realised.

- The hybrid series mode was run for curiosity to see how the system would perform without a common optimised controller between the HP and gas boiler. The conclusion was that poor performance was achieved for exactly this reason. Cycling of the gas boiler at higher flow temperatures resulted in an average COP of 0.71 across the testing period

compared to 0.80 for the gas baseline. The HP COP also was negatively impacted resulting in a drop from an average COP of 2.10 at average daily temperature of 5.4°C for the HP baseline to a COP of 1.96 at average daily temperature of 7.8°C. The overall combined system COP for the hybrid series across the operating period was 0.96. It is thought that more work in optimising the flow temperature settings of the HP and gas boiler may improve the overall COP or perhaps designing the controller to switch of the gas boiler (to avoid it cycling) when the house is up to temperature might improve the modulation capacity of the overall system. Ultimately sizing of the two components and their respective modulation capacities is critical to achieving a good COP.

- The DSM possibilities for the hybrid series, although not investigated, could be along the lines of reducing the HP heat output (rather than switching the HP of completely) and making up the extra proportion of the household heat demand from the gas boiler. If the system was optimised correctly the combined system COP could be higher than just operating the gas boiler alone without compromising the thermal power of the heating system and therefore the thermal comfort of the occupants.

- The DSM strategies employed are summarised in Table 3-8. The impact of the DSM interventions was assessed relative to using the HP to directly heat the house without storage (HP baseline) and the gas boiler baseline. Three key performance indicators were used in order to do this, namely: COP; cost of thermal delivered to the house and; CO_2e intensity of the thermal delivered to the house. A detailed synthesis of how the three KPIs varied as a result of the DSM strategies can be found in section 5.1 Synthesis of Key Performance Indicators.

- For COP the baseline HP (direct mode) performed the best with a COP of 2.20 in the ambient air temperature range of 8-10°C. For the same temperature range the DSM2 strategy which charged the store at night and used at first call for heat was next with a combined system COP of 1.90 followed by the DSM1 strategy, which charged at night and discharged at peak grid demand, with a combined system COP of 1.88. The thermal store charging reduced the COP of the HP when storing to 1.92 for DSM1 and also 1.92 for DSM2 for the 8-10°C temperature range. The thermal storage effective COP (heat to house via store divided by electric used by HP storing) for DSM1 and DSM2 was 0.70 and 0.82 respectively for the 8-10°C temperature range. The thermal efficiency (useful heat out divided by total heat in) of the store for DSM1 and DSM2 was 0.36 and 0.45 respectively. The effective demand shift for each of the operating modes was 8.68% and 5.32% of total household heat demand respectively. The poor thermal efficiency of the store and reduction in HP COP when charging the tank were the causes of the reduction

in combined system COP. It is believed that if the thermal store performed to current standards and the heat exchange between the HP and tank was optimised the impact on combined system COP could be greatly reduced (compared to running without thermal storage) and the effective DSM shift would thus be greater.

- For running the hybrid parallel system, were the gas boiler was used in place of the thermal store, two DSM strategies were run. The first used the forecast grid demand signal (as was used for the thermal store) and the second used the forecast SMP price of electric on the market. The gas boiler was activated above the 0.85 percentile of demand or price respectively. The COP for the operating modes was 1.37 for the demand signal and 1.53 for the price signal for the 8-10°C range with effective demand shifts of 35.90% and 25.10% of the total heat demand respectively. The higher DSM shift is partly due to a change in the computer code and how the data was retrieved from the EirGrid website between the demand and price based DSM strategies. The higher proportion of heat provided by the gas boiler in the demand based DSM compared to the price based DSM results in the comparatively lower combined system COP.

- Comparing the hybrid mode with the HP and thermal store mode, it can be seen that even with the poor performance of the thermal store the combined system COP is higher for the HP and thermal store. However, a greater proportion of heat is provided directly by the HP i.e. the DSM shift is lower for the HP and thermal store mode.

- When comparing the cost of thermal delivered to the house from the different operating modes it was found that the gas boiler baseline was the cheapest with running cost of £0.049/kWh thermal followed by the HP baseline costing £0.054/kWh at 8-10°C air temperature range. For DSM1 and DSM2 operating modes the cost of thermal using a standard domestic tariff and Economy 7 tariff was calculated (Figure 5-3, Table 5-1). It was found that it was more expensive to use the Economy 7 tariff at times of higher heat demand (low ambient air temperature) due to the higher day rate i.e. the HP had to run in direct mode for long periods during the day as the night time storage was insufficient to meet the day time heat demand. This highlighted the importance of correctly sizing the thermal store considering the house heat demand, thermal store loses and system COP.

- Comparing the hybrid modes to the HP and thermal storage modes it was seen that the hybrid modes were slightly cheaper despite the lower COP of the hybrid modes. The hybrid modes were also less sensitive in terms of cost of thermal to air temperature

variation. However, the hybrid mode could not store energy which may be cheaper in the future (compared to Economy 7) if DSM tariffs evolve.

- The carbon intensity (CO_2e) of thermal energy delivered to the house of each of the operating modes was also calculated using UK GHG factors for 2017. The HP in direct mode realised the lowest carbon intensity of 0.175 kg CO_2e/kWh thermal in the 8-10°C air temperature range with the hybrid series and gas boiler baseline realising carbon intensities of 0.236 and 0.225 kg CO_2e/kWh thermal respectively. The critical point is that even at the relatively poor operating COPs of the HP the carbon intensity was still lower than the gas boiler including with the DSM interventions. In addition, the GHG factors will continue to reduce as the grid decarbonises further in the future and therefore so too will the carbon intensity of heat provided using a HP.

- Overall the research showed that autonomous DSM can be provided relatively cheap and easily using low cost components. Sizing of HPs to match the heat load along with thermal storage sizing is critical to ensure energy consumption is minimised. Aggregators need to be able to extract value from systems such as this if it is to become economically viable i.e. all parties gain including the aggregator, consumer, and grid operator.

Upfront capital costs of HP systems are currently large and adding components such as thermal storage further increases cost. The field trial running costs using a high-temperature HP are currently similar when compared to a gas boiler due to the relatively low price of gas and high price of electricity. This means the system does not make financial sense currently. However international and scientific consensus is that we must move rapidly towards a low carbon society in order to prevent global temperature rises moving beyond the control of mankind. The longer the problem remains unaddressed the greater the environmental, societal and economic impact will be. Methods of decarbonisation in all sectors need urgent attention and policies by governments should make the switch to a low carbon society economically attractive in the short term at least. As action is taken and momentum grows the benefits of taking control sooner, rather than later, for the planet and future generations will be irrefutable.

6.2   Future Work

Ideas for future work have been discussed throughout. A summary list is provided here.

- Investigate use of real-time grid carbon intensity as a DSM signal and how it may work in practise with a HP coupled with a thermal store. Such a signal would provide an indicator of greater renewable energy generation availability and would produce heat via a HP with a much lower carbon intensity.

- Improve the thermal storage (create compact low loss stores) including optimisation of the heat exchange between the HP and store in order to alleviate the impact of reduced COP experienced when storing. Investigate alternative materials such as PCM with higher storage densities that could replace the existing thermal store thus increasing the practicality of such a system by reducing size.

- Investigate how the heating systems examined here (HP coupled with thermal storage) could be simplified in order to reduce capital costs including installation and maintenance costs thus reducing the cost barrier of deployment.

- Further development of DSM techniques and controls. In this research basic on/off control was used however further investigation into capacity modulation as an alternative should be investigated e.g. reducing/increasing HP heat output in response to a DSM signal. Work is needed in order to establish how this might affect HP COP performance as well as possible increased component stress and consequences in terms of reduced product lifespans.

- Investigate methods of implementing up and down dynamic frequency regulation for the grid by using HPs with variable speed compressors. Which could lead to reducing demand via aggregated HP frequency reduction which may mean less need for storage by using house thermal inertia.

- Improve DSM controls to allow 2-way communication with aggregators e.g. current capacity status, load reduction capability, storage capability etc.

- More work should be done to develop a business case for HP coupled with thermal storage with particular attention on how the consumer can benefit.

- More work should be done with regard to the benefits of DSM for the grid relating to HPs combined with thermal storage. Including grid stability, electric cost, and effects of local grid constraints (e.g. possible need to stagger HP activations) and the role aggregators can have in realising the benefits for the grid.

- Investigate application of the DSM algorithms developed in this research for domestic electric storage. It is believed the algorithms would be largely cross-compatible but

would benefit from the lack of energy loss seen with thermal storage. Areas of domestic electric storage could include: Vehicle to grid storage, PV to battery to heat pump, PV to vehicle battery to heat pump.

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8 APPENDICES

Appendix A   Detailed Sensor Lists

Table 8-1 Detailed list of sensors installed in test house 63 and 64 using the Eltek GenII wireless telemetry data logging system. Refer to Figure 3-2 for indication of relevant location within the buildings. For central heating specific sensors refer to Figure 8-1 for indication of relevant sensor location using the figure reference number.

Location (house number)	Measured Parameter	Input	Range	Unit	Transmitter ID	Transmitter Channel	Figure Ref. No.
Kitchen (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16525	A	NA
Kitchen (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16525	B	NA
Dining room (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	11670	A	NA
Dining room (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	11670	B	NA
Living room (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	14173	A	NA
Living room (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	14173	B	NA
Box bedroom (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16526	A	NA
Box bedroom (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16526	B	NA
2nd bedroom (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16527	A	NA
2rd bedroom (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16527	B	NA
Master bedroom (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	14175	A	NA
Master bedroom (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	14175	B	NA
Bathroom (63)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	14830	A	NA
Bathroom (63)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	14830	B	NA
Kitchen (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16533	A	NA
Kitchen (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16533	B	NA
Dining room (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16668	A	NA
Dining room (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16668	B	NA
Living room (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	14174	A	NA
Living room (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	14174	B	NA
Box bedroom (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16534	A	NA
Box bedroom (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16534	B	NA
2nd bedroom (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16532	A	NA
2rd bedroom (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16532	B	NA
Master bedroom (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16669	A	NA
Master bedroom (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16669	B	NA
Bathroom (64)	Room temperature	Sensirion Temperature	-30.0 to 65.0	°C	16531	A	NA
Bathroom (64)	Room relative humidity	Sensirion Humidity	0.0 to 100.0	% RH	16531	B	NA
Boiler room (63)	Ground floor radiator flow	Pulse Count	0 to 65000	1 pulse/ltr	11479	A	E:9
Boiler room (63)	1st floor radiator flow	Pulse Count	0 to 65000	1 pulse/ltr	16641	A	E:10
Boiler room (63)	DHW tank flow	Pulse Count	0 to 65000	1 pulse/10 ltr	16640	A	E:12
Living room (63)	Electricity consumption	Pulse Count	0 to 65000	1 pulse/Wh	16639	A	NA
Boiler room (64)	Ground floor radiator flow	Pulse Count	0 to 65000	1 pulse/ltr	12923	A	E:9
Boiler room (64)	1st floor radiator flow	Pulse Count	0 to 65000	1 pulse/ltr	15410	A	E:10
Boiler room (64)	DHW tank flow	Pulse Count	0 to 65000	1 pulse/10 ltr	15411	A	E:12
Boiler room (63)	Gas consumption	Pulse Count	0 to 65000	1 pulse/0.01 m^3	15421	A	NA
Boiler room (63)	Ground floor radiator flow temp	T type Thermocouple	-200.0 to 200.0	°C	13196	A	E:1
Boiler room (63)	1st floor radiator flow temp	T type Thermocouple	-200.0 to 200.0	°C	13196	B	E:2
Boiler room (63)	DHW tank flow temp	T type Thermocouple	-200.0 to 200.0	°C	13196	C	E:3
Boiler room (63)	Boiler return flow temp	T type Thermocouple	-200.0 to 200.0	°C	13196	D	E:4
Boiler room (64)	Ground floor radiator flow temp	T type Thermocouple	-200.0 to 200.0	°C	15308	A	E:1
Boiler room (64)	1st floor radiator flow temp	T type Thermocouple	-200.0 to 200.0	°C	15308	B	E:2
Boiler room (64)	DHW tank flow temp	T type Thermocouple	-200.0 to 200.0	°C	15308	C	E:3
Boiler room (64)	Boiler return flow temp	T type Thermocouple	-200.0 to 200.0	°C	15308	D	E:4
Hot press (63)	DHW consumption	Pulse Count	0 to 65000	1000 pulse/m^3	15414	A	E:11
Hot press (64)	DHW consumption	Pulse Count	0 to 65000	1000 pulse/m^3	15419	A	E:11
Hot press (63)	DHW hot outlet temp	T type Thermocouple	-200.0 to 200.0	°C	15306	A	E:6
Hot press (63)	DHW cold inlet temp	T type Thermocouple	-200.0 to 200.0	°C	15306	B	E:5
Hot press (63)	DHW boiler flow temp	T type Thermocouple	-200.0 to 200.0	°C	15306	C	E:7
Hot press (63)	DHW boiler return temp	T type Thermocouple	-200.0 to 200.0	°C	15306	D	E:8
Hot press (64)	DHW hot outlet temp	T type Thermocouple	-200.0 to 200.0	°C	15307	A	E:6
Hot press (64)	DHW cold inlet temp	T type Thermocouple	-200.0 to 200.0	°C	15307	B	E:5
Hot press (64)	DHW boiler flow temp	T type Thermocouple	-200.0 to 200.0	°C	15307	C	E:7
Hot press (64)	DHW boiler return temp	T type Thermocouple	-200.0 to 200.0	°C	15307	D	E:8
Living room (64)	Electricity consumption	Pulse Count	0 to 65000	1 pulse/Wh	10977	A	NA

Table 8-2 Detailed list of sensors installed on the HP, thermal store, and central heating system using the Datataker DT85 smart datalogger. For central heating specific sensors refer to Figure 8-1 for indication of relevant sensor location using the figure reference number. The column 'Sensor Ref. No.' can be used to cross-reference the measuring device used with Table 3-10.

| Location	Measured Parameter	Channel Name	Input	Unit	Schedule	Figure Ref. No.	Sensor Ref. No.
Shed 64	Current Draw: HP Outdoor Unit	Current1_R410A	4-20mA	Amps	A	NA	5c
Shed 64	Mains Voltage	Voltage_R410A	Volts	Volts	A	NA	5b
Shed 64	Current Draw: HP Indoor Unit	Current2_R134a	4-20mA	Amps	A	NA	5c
Shed 64	HP Flow: Heating circulation	Flow meter	4-20mA	ltr/s	A	DT:22	3
Shed 64	Discharge Pressure: HP Outdoor Unit	Pdis_R410A	4-20mA	bar	A	NA	6
Shed 64	Suction Pressure: HP Outdoor Unit	Psuc_R410A	4-20mA	bar	A	NA	6
Shed 64	Discharge Temperature: HP Outdoor Unit	Tdis_R410A	Resistance	°C	A	NA	1
Shed 64	Condenser Temperature In: HP Outdoor Unit	TCin_R410A	Resistance	°C	A	NA	1
Shed 64	Condenser Temperature Out: HP Outdoor Unit	TCout_R410A	Resistance	°C	A	NA	1
Shed 64	Heat Exchanger Temperature In: HP Outdoor Unit	TExin_R410A	Resistance	°C	A	NA	1
Shed 64	Heat Exchanger Temperature Out: HP Outdoor Unit	TExout_R410A	Resistance	°C	A	NA	1
Shed 64	Evaporator Temperature Out: HP Outdoor Unit	TEout_R410A	Resistance	°C	A	NA	1
Shed 64	Suction Temperature: HP Outdoor Unit	Tsuc_R410A	Resistance	°C	A	NA	1
Shed 64	Discharge Pressure: HP Indoor Unit	Pdis_R134a	4-20mA	bar	A	NA	6
Shed 64	Suction Pressure: HP Indoor Unit	Psuc_R134a	4-20mA	bar	A	NA	6
Shed 64	Suction Temperature: HP Indoor Unit	Tsuc_R134a	Resistance	°C	A	NA	1
Shed 64	Discharge Temperature: HP Indoor Unit	Tdis_R134a	Resistance	°C	A	NA	1
Shed 64	Condenser Temperature In: HP Indoor Unit	TCin_R134a	Resistance	°C	A	NA	1
Shed 64	Condenser Temperature Out: HP Indoor Unit	TCout_R134a	Resistance	°C	A	NA	1
Shed 64	Evaporator Temperature In: HP Indoor Unit	TEin_R134a	Resistance	°C	A	NA	1
Shed 64	Evaporator Temperature Out: HP Indoor Unit	TEout_R134a	Resistance	°C	A	NA	1
Shed 64	Flow from Thermal Store	Flow2 Tank	Pulse Count	1 pulse/20 ltr	A	DT:21	4
Shed 64	Temperature Thermal Store Inlet HP Heating Coil	Tcoil1_inlet	Resistance	°C	A	DT:10	1
Shed 64	Temperature Thermal Store Outlet HP Heating Coil	Tcoil1_outlet	Resistance	°C	A	DT:9	1
Shed 64	Temperature Thermal Store Inlet Discharge Coil	Tcoil2_inlet	Resistance	°C	A	DT:12	1
Shed 64	Temperature Thermal Store Outlet Discharge Coil	Tcoil2_outlet	Resistance	°C	A	DT:11	1
Boiler Room 64	Temperature Flow from House Heating Circulation	T boiler Flow	Resistance	°C	B	DT:7	1
Boiler Room 64	Temperature Return from House Heating Circulation	T boiler return	Resistance	°C	B	DT:8	1
Boiler Room 64	Flow to House Heating Circulation	Flow1 boiler	Pulse Count	1 pulse/20 ltr	B	DT:20	4
Shed 64	Temperature in Shed 64	Shed temp1	Resistance	°C	B	NA	1
Shed 64	Temperature in Shed 64	Shed temp2	Resistance	°C	B	NA	1
Shed 64	Outdoor Relative Humidity	Humidity Ext	Voltage	%	B	NA	NA
Shed 64	Outdoor Ambient Temperature	Amb Temp	Voltage	°C	B	NA	NA
Shed 64	Energy Consumption: HP Indoor Unit	EnergyM1_R134a	Pulse Count	1 pulse/Wh	B	NA	5a
Shed 64	Energy Consumption: HP Outdoor Unit	EnergyM2_R410A	Pulse Count	1 pulse/Wh	B	NA	5a
Shed 64	Thermal Store Temperature	Tank7	Resistance	°C	B	DT:19	1
Shed 64	Thermal Store Temperature	Tank1	Resistance	°C	B	DT:13	1
Shed 64	Thermal Store Temperature	Tank2	Resistance	°C	B	DT:14	1
Shed 64	Thermal Store Temperature	Tank3	Resistance	°C	B	DT:15	1
Shed 64	Thermal Store Temperature	Tank4	Resistance	°C	B	DT:16	1
Shed 64	Thermal Store Temperature	Tank5	Resistance	°C	B	DT:17	1
Shed 64	Thermal Store Temperature	Tank6	Resistance	°C	B	DT:18	1
Shed 64	Outdoor Ambient Temperature	Evp fin temp	Resistance	°C	B	NA	1
Boiler Room 64	Gas Consumption of Gas Boiler: House 64	Gas_meter_(0.01m3)	Pulse Count	1 pulse/0.01 m3	B	NA	7
Boiler Room 64	DHW Thermostat: Call for Heat/Satisfied	DHW_STAT_R1_BR	Switch Position	1=ON, 0=OFF	B	NA	8
Boiler Room 64	User Controls: Hot Water On	HW_ON_R2_BR	Switch Position	1=ON, 0=OFF	B	NA	8
Boiler Room 64	Dining Room Thermostat: Call for Heat/Satisfied	ROOM_STAT_R3_BR	Switch Position	1=ON, 0=OFF	B	NA	8
Boiler Room 64	User Controls: Space Heating On	CH_ON_R4_BR	Switch Position	1=ON, 0=OFF	B	NA	8
Boiler Room 64	Temperature DHW Flow Pipe	T_DHW_FLOW_BR	Resistance	°C	B	DT:6	2
Boiler Room 64	Temperature DHW Return Pipe	T_DHW_RETURN_BR	Resistance	°C	B	DT:5	2
Boiler Room 64	Temperature 1st Floor Radiators Flow Pipe	T_MIDPIPE_FLOW_BR	Resistance	°C	B	DT:4	2
Boiler Room 64	Temperature 1st Floor Radiators Return Pipe	T_MIDPIPE_RETURN_BR	Resistance	°C	B	DT:1	2
Boiler Room 64	Temperature Ground Floor Radiators Flow Pipe	T_LEFTPIPE_FLOW_BR	Resistance	°C	B	DT:3	2
Boiler Room 64	Temperature Ground Floor Radiators Return Pipe	T_LEFTPIPE_RETURN_BR	Resistance	°C	B	DT:2	2
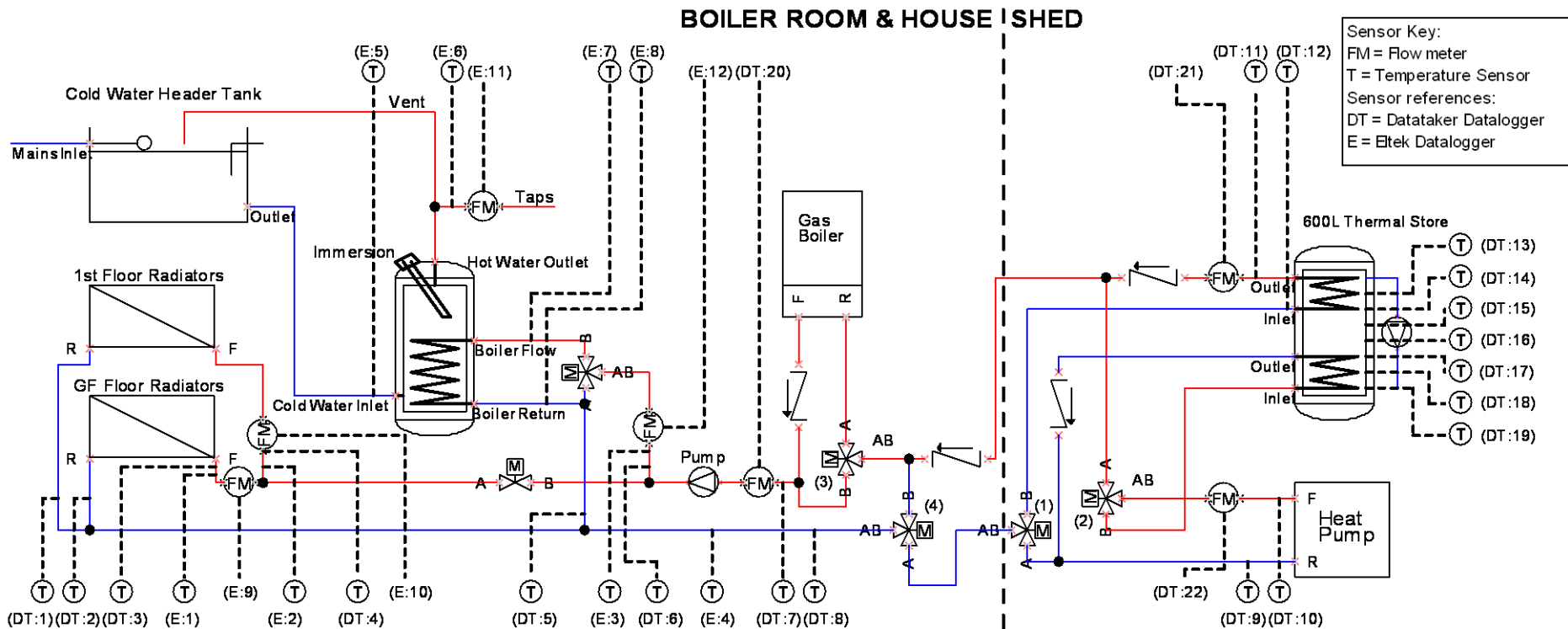
Figure 8-1 Complete house 64 central heating system schematic indicating position of temperature and flow sensors used on the Eltek and Datataker data logger systems. Sensor reference 'E' indicates the sensor is logged by the Eltek data logging system whereas sensor reference 'DT' indicates sensor is logged by the Datataker data logging system. Sensors not shown are gas consumption, HP electricity consumption, and HP mounted sensors. The sensor reference numbers can be looked up in Table 8-1 (Eltek) and Table 8-2 (Datataker) for specific information.