Department of Mechanical and Aerospace Engineering

Investigation into Decarbonising the District Heating Network at West Whitlawburn Housing Co-operative

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Signed: Calum McKeown Date: 25/08/2020

Abstract

District heating networks offer a potential solution for decarbonising the heating systems for entire communities. This thesis analyses an existing 3rd generation district heating network in Cambuslang, Scotland. Having undergone thermal efficiency upgrades, the next stage of reducing emissions from heat in this district heating network is to decarbonise the supply.

The modelling in this thesis was undertaken using EnergyPRO exclusively. In total four different models were made that assessed the potential of varying sources of renewable heat or electricity. The common component was an air source heat pump and thermal store. Initially, the DHN was modelled to run solely using grid electricity. Photovoltaic panels, flat plate solar collectors and a wind turbine were then added to the model and individually assessed. The system operational strategy, environmental impact and operational finances of each system were assessed.

Results of the thesis indicate that reducing the carbon produced through heating the network is viable using resources local to the network. A system composed of an ASHP and thermal storage can provide substantial CO_2 reductions of 82% whilst offering a realistic daily operation strategy. The addition of PV or solar collectors would add to these reductions whilst reducing the annual operation costs. Additionally, a private wire to a nearby wind turbine would further benefit both the financial viability of the DHN and the reduction in CO_2 volume.

This report finishes by summarising the limitations and potential future areas of study. Finally, it concludes that whilst a private wire to a wind turbine used to primarily power the ASHP would be the optimal source of energy for operational costs and system CO_2 reduction, the more realistic approach would be use the grid in conjunction with on-site PV panels and both thermal and electrical storage.

Acknowledgments

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Acronyms

4GDH	4th Generation District Heating
5GDH	5th Generation District Heating
ASHP	Air Source Heat Pump
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
DHN	District Heating Network
FPSC	Flat Plate Solar Collector
GSHP	Ground Source Heat Pump
HP	Heat Pump
NOCT	Nominal Operating Cell Temperature
PV	Photovoltaic
RHI	Renewable Heat Incentive
WSHP	Water Source Heat Pump
WWHC	West Whitelawburn Housing Co-operative

1 Introduction

Net zero carbon by 2045. This is the ambitious goal set by the governments in both Holyrood and Westminster in response to the current climate crisis facing society. In Scotland there has been a tremendous amount of effort put into decarbonising our electricity supply over the last decade, with installed capacity rocketing from 3,799MW to 11,839MW. However, these results have not translated from electricity generation to energy for heating requirements; the majority of homes in Scotland are heated by natural gas. Transitioning from fossil fuel produced heat to a more sustainably sourced system will require a massive shift in the way we supply, distribute and apply heat (RSE, 2019).

District heating networks (DHNs) supply thermal energy, generated at nearby sites, to a number of different buildings over a variably sized area. These systems offer a way of phasing out our current dependency on individual natural gas fuelled boilers. An integral part of the Scottish Government's current route map to net zero is that new house builds will have to utilise renewable or low carbon heat from 2024 onwards. They envisage a diverse heating landscape across the country in which DHNs will play a vital role. In conjunction with district heating's low carbon potential they offer lower costs of heating for customers, often having a positive impact on fuel poverty rates. Overall, these networks (if run with renewable energy sources) offer a way to balance the energy trilemma of future environmental sustainability, equity and security (Scottish Government, 2019a).

Currently, the designs of district heating schemes are changing to better reflect the way in which heat is being used in society. Building stocks have become more energy efficient, reducing the country's heating demand, whilst there is also a greater emphasis on decarbonising our heat supply (Scottish Government, 2019a). This has resulted in a switch from 3rd generation district heating networks - often centralised, fossil fuelled heat sources with high distribution temperatures - to newer 4th generation configurations. These are generally run using more sustainable, locally available heat sources and have far lower distribution temperatures, which increases their efficiency.

This thesis uses West Whitelawburn Housing Co-operative (WWHC) as a case study of a district heating system that can be powered by renewable energy and that existing district heating networks can be upgraded to, in order to better meet future requirements. Currently, the WWHC utilises a heating system that is fuelled by a combination of natural gas and biomass pellets, making it an example of a 3rd generation district heating system. Through demonstrating that this system can be upgraded to run effectively using renewable, more sustainable sources of heat, this thesis analyses the viability of decarbonising this specific heating network as well as a potential wider decarbonisation of the heating sector in Scotland.

1.1 Aim and Objectives

The aim of this report is to evaluate potential renewable energy sources local to the WWHC, which can be used to operate a fully decarbonised system. The focus will be to determine a system that can meet demand whilst simultaneously taking into account the mission statement of the co-operative, mainly that the proposed system should be sustainable and affordable for the community. The three specific objectives of the project are as follows:

1. Evaluate the performance of different potential renewable energy sources for supplying heat to the West Whitelawburn Heating Co-operative.

2. Analyse how these differing sources of energy affect the optimum operational strategy of the District Heating Network.

3. Assess the CO_2 output of each new system and compare the reduction against the current system.

1.2 Thesis Structure

The thesis is split into 5 distinct chapters, each covering a different aspect in order to achieve the aims previously outlined. The chapter titles are listed below alongside a brief overview:

- **Chapter 1:** This section of the thesis introduces the topic of study and highlights the importance of this area of study. Additionally the aims and methodology are summarised concisely.

- **Chapter 2:** Comprised entirely of the literature review, this chapter discusses the need to decarbonise the heating sector, the development of district heating networks and varying components that can be used to operate them.

- **Chapter 3:** This area starts with an assessment of the operation and history of the WWHC and a review of the current DHN. The inputs for the modelling phase are then listed. This includes external environment data, DHN thermal demand data and the characteristics of the various heat and electric production components used in the models. The chapter concludes with a summary of the simplifications used for the thesis.

- **Chapter 4:** Contains the results from the modelling and analysis stage of the thesis. This section includes the operation of each model as well as some environmental and financial analyses. The modelling strategy is outlined in more detail in the overview below.

- **Chapter 5:** This chapter concludes the thesis, briefly summarising the findings. It goes on to outline the studies limitations and possible areas of future study.

1.3 Methodology Overview

EnergyPRO software was used for all the modelling undertaken in this thesis. The modelling strategy was to utilise different sources of local, renewable heat or electricity to operate the DHN. Every model incorporated an air source heat pump (ASHP) as the primary source of heat. A base model was made in order to understand how the current DHN operates using the EnergyPRO software. This then moves onto 4 differing scenarios that consist of different components to fuel the DHN that are less carbon intensive. An outline of the components that make up each scenario can be found in Figure 1 below. The figure also contains the assessed areas for each of the scenarios in bullet points.

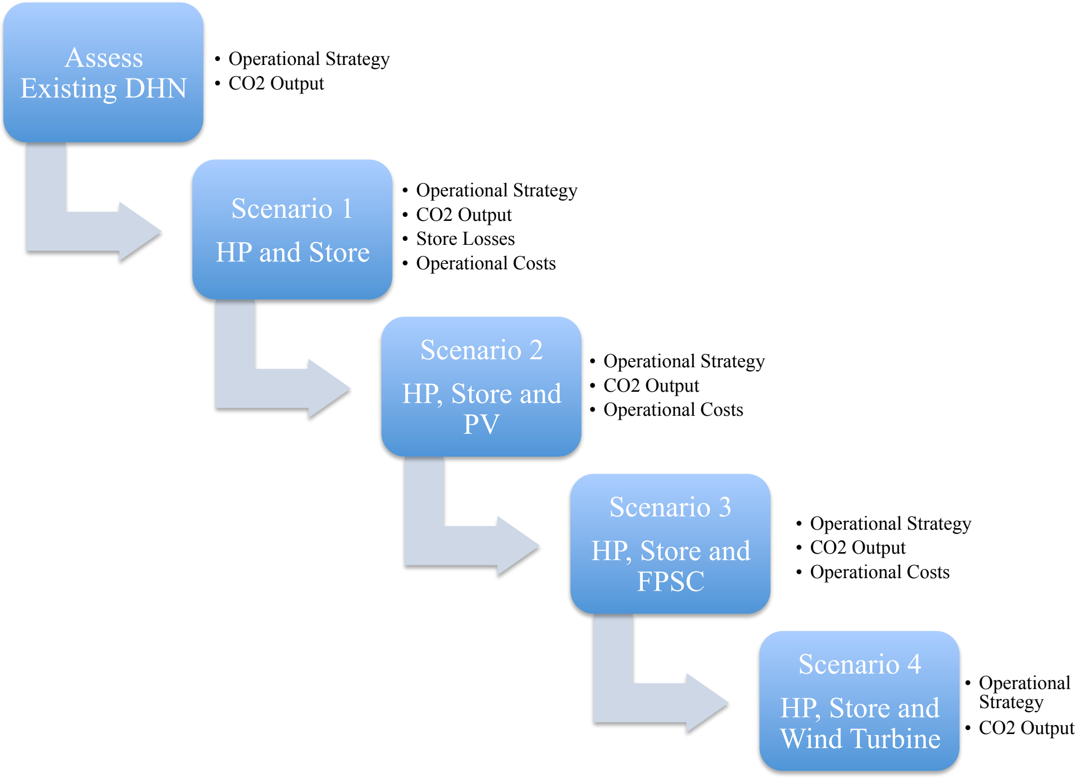


Figure 1: Modelling methodology flow diagram

2 Literature Review

2.1 Heating in Scotland

The Scottish Government has set ambitious targets for tackling the climate crisis currently facing the world. Changing climates threaten everything from the natural environment to resource security. The Government's overall aim is to produce net zero carbon emissions by the year 2045. With this in mind, great strides have been made in decarbonising the country's electricity supply, with 83.1% of the total being derived from low carbon sources in 2018. However, whilst the political will to tackle climate change has resulted in the near total decarbonisation of the electricity grid, the same cannot be said for the country's heating systems (Scottish Government, 2019a).

Presently, the majority of heating systems in Scotland are natural gas boilers, individually fitted into buildings and connected to the national gas grid. Around 78% of Scottish homes currently use this system (Morrison and Moyes, 2018). This single fuel dominance has resulted in natural gas being the cheapest and easiest method to heat buildings, which translates into producing the largest share of Scotland's CO_2 emissions (Figure 2). With this in mind, the Government has pledged to derive 50% of the country's energy demand from renewable sources by the year 2030 (Scottish Government, 2019a).

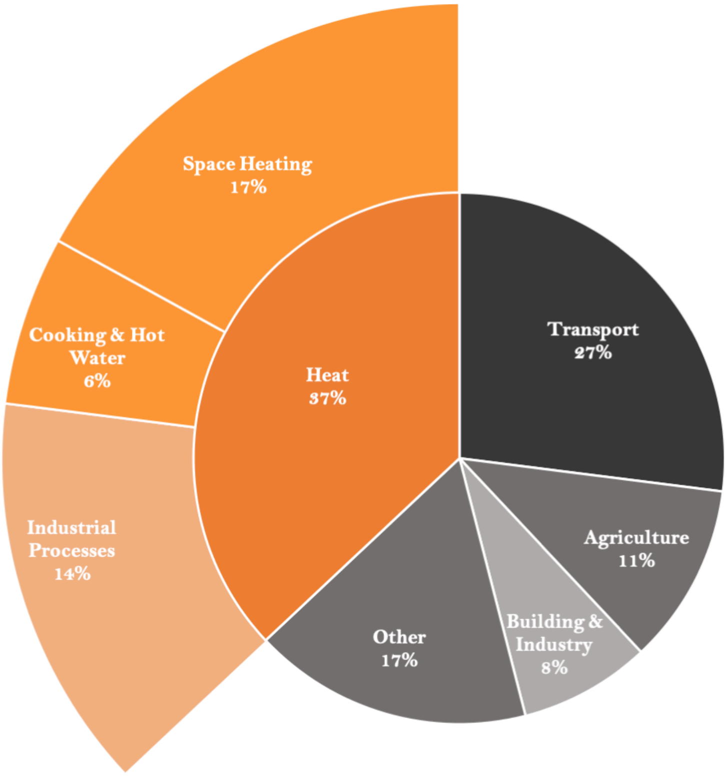


Figure 2: UK CO2 emissions by sector (BEIS, 2019)

The climate crisis highlights the need to transition to a low carbon economy. However, legislatures must take into account a variety of factors when promoting low carbon heating alternatives. Prime amongst these is cost – can customers afford to use new systems, or will they adversely affect living standards? As of 2017, fuel poverty rates in Scotland stood at 24.9%, with 11.9% in extreme fuel poverty. Breaking down these statistics further, 52% of households that use electricity as the primary heating fuel are considered fuel poor compared to just 19% of gas households (Scottish Government, 2019b). With the majority of Scotland's electricity coming from low carbon sources, electricity would be an environmentally sustainable way of providing thermal energy. However, it would be unacceptable for the Government to potentially put more people into fuel poverty as a result.

2.1.1 Government Strategy

The Scottish Government has taken a planned approach in addressing the decarbonisation of heat as outlined in Figure 3. The short to medium term approach has been to reduce demand by improving the efficiency of the current housing stock. This has been the main priority, with a billion pounds invested in improving housing efficiency since 2009. Reducing the energy required for space heating results in less greenhouse gases being emitted, and financial savings being made. Longer-term, the Government's plan is to alter the way heat is distributed and stored; this could take the shape of a DHN (Scottish Government, 2019a).

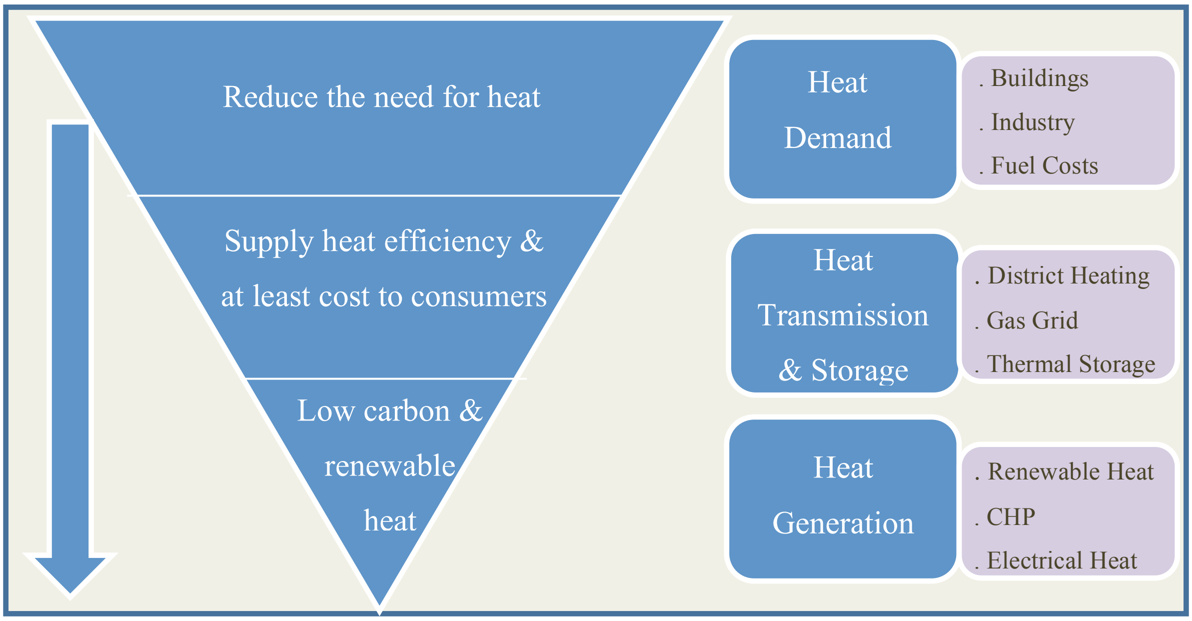


Figure 3: Scottish Government route map to decarbonising heat

In order to achieve each step in the above plan, the Holyrood, Westminster and EU legislatures have implemented various policies and initiatives. An example of these support programs is the Renewable Heat Incentive (RHI), which is implemented by the UK government. This incentive scheme gives homeowners financial help to offset the cost of installing low carbon heating systems. It rewards user's renewable heat sources with a fixed tariff for seven years. Technologies eligible for RHI include biomass boilers, solar water heating, and air source and ground source heat pumps. The majority of non-domestic systems installed using RHI have been biomass boilers at 76% of the total heat delivered (Lowes, Woodman and Fitch-Roy, 2019). Whereas the majority of domestic RHI installations have been air source heat pumps with 52% of accredited installations. The scheme is split into two streams – domestic and non-domestic RHI, although DHN falls into the non-domestic category. Overall, the RHI is mainly utilised for buildings that are not on the gas grid, with 87% of the total RHI uptake coming from off-grid properties in Scotland, leaving a lot of work to do in decarbonising the majority of household heating (Scottish Government, 2019a).

2.1.2 Existing Low Carbon Heating

The current most common way to decarbonise heat in Scotland has been to replace natural gas with biofuels in a boiler system. The Westminster government sees biofuels as increasingly important to achieve emissions targets that the UK is legally bound to achieve (Welfle et al., 2017). Biofuels can take many forms, including; domestic waste, landfill methane and ethanol fuels. The most commonly used is wood in the form of pellets. Grafius et al. (2020) argue that Scotland is perfectly placed to uptake biofuels to replace our dependence on natural gas. They contend that if urban green spaces are utilized with the correct biomass crop to grow there could be a continuous source of net zero carbon fuel if it is constantly replanted. Although the combustion of biofuels creates CO_2 as a by-product, in theory, this is mitigated by the carbon uptake during the photosynthesis processes during growth. A study on maximising the greenhouse gas reductions for biomass was undertaken in 2015 by Thornley et al. They examined the life cycle assessment and concluded that biomass offers a significant reduction in green house gases when compared with the fossil fuels currently used (Thornley et al., 2015).

There are a myriad of issues with burning biomass, prime among them being the questionable reality of its eco-credentials. Although CO_2 is absorbed during the photosynthesis processes, burning biomass still releases carbon monoxide (CO), nitrogen oxides (NOx) and particulates. In addition, biofuels are often transported large distances from where they are grown to where they are used, increasing the volume of CO_2 produced and pushing the overall system into the carbon positive column rather than neutral (Thornley et al., 2015; Hastings et al., 2014).

Further to pollution issues, growing biomass for fuel would require reconfiguring the country's agricultural sector to grow more biomass for fuel and less for food. This is a critical issue with the growth of the biofuel industry around the globe, as total population increases require more space to live and more food crops to be harvested (Hastings et al., 2014). A 2020 study by Grafius et al. determined that this land use conflict could be resolved in the UK through utilising green spaces within cities and underused surrounding land to grow biomass. They modelled ten different cities around the UK for their potential arable land and for crops that offer the greatest yield in each region. They determined that urban areas have a large untapped potential for growing biomass. However, this would all be under unrealistic optimal conditions. Ultimately, this would shift rather than solve the land use conflict from the countryside to cities, as local ecosystems would be altered and recreational space reduced in densely populated areas (Grafius et al., 2020).

Direct electric heat offers a thermal resource that is increasingly carbon free, courtesy of an increasingly renewable electric grid. In Scotland electricity is the primary heating fuel in 12% of homes. The benefit of direct electric heating is that most buildings are on the electric grid in some way even if they are not connected to the gas grid. These are predominantly electric storage heaters and have the drawback of being generally more expensive to run than their gas counterparts (Scottish Government, 2019a). Heat pumps are another option for utilising Scotland's green electricity. They transform low-grade heat into heat of a higher grade, which can then be deployed as central heating. Finally, solar thermal technology can be utilised in Scotland, although this is limited by the resource that is available. Though not suitable as a stand-alone option, there is however scope for solar thermal heat sources to play a supplementary role in a future diverse heating sector in Scotland (Renaldi and Friedrich, 2019).

2.2 District Heating

District heating and cooling networks are a way of supplying energy for space heating and cooling as well as for hot water. Figure 4 shows a schematic of a DHN in which the heat comes from a CHP. The fundamental concept is to utilise local sources of heat to meet the demands of consumers in a fixed area. Although the overall operation characteristics of DHN have evolved since they were first used in the 19th century, this concept remains unchanged (Li and Nord, 2018).

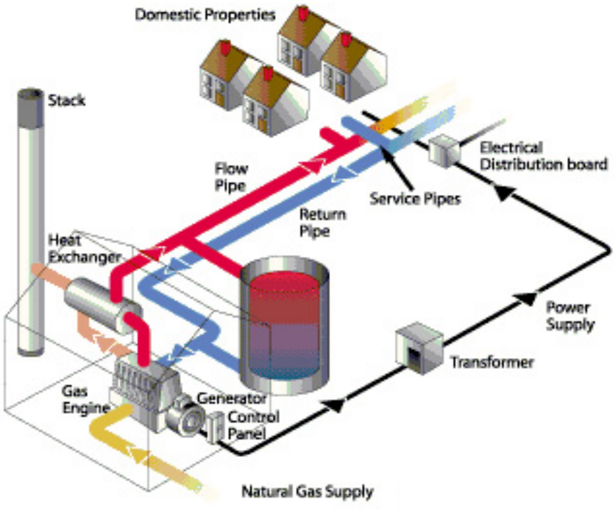


Figure 4: Schematic overview of a CHP DHN (Eneteq, 2017)

DHNs supply multiple buildings over a variably sized area of land and can have diverse sources of heat. Ultimately, the resources available locally determine the source of heat energy. Energy sources that can be used in district heating systems include: biomass, fossil fuels, waste heat, solar thermal energy, cogenerated heat, nuclear power and ground source heat pumps (Lake, Rezaie and Beyerlein, 2017). Purely renewable sources of energy have been successfully used in district heating schemes in Europe, such as the Monterusciello system in Southern Italy, which utilises geothermal energy as a heat source (Carotenuto, Figaj and Vanoli, 2017). The heat is then distributed throughout the system via a network of buried pipes that carry heated water to buildings and bring the cooler water back. These pipes are well insulated to reduce heat losses during distribution.

In their 2017 article, Lake et al. break down how best to categorise different DHNs as follows:

1. **Heat Transport Fluid**: this refers to the state that thermal energy is distributed within the pipes. In most systems the heat transport fluid is hot water, however it can also be hot air or low-pressure steam.

2. **Thermal Energy Transported**: this describes the function of the network. Some areas require heating or cooling, and others require both. The thermal energy transported is ultimately determined by the needs of the end user.

3. **Heat Resource Used**: this describes the origin of the heat source. DHNs can operate using a single, centralised heat source, or have multiple heat resources feeding into the system.

DHNs can be designed to suit the end use and accommodate heat resources that are available locally. Ideally they can take advantage of heat that would otherwise be wasted; an example of this would be a combined heat and power (CHP) plant. Whilst providing electricity directly into the grid, the waste heat from the industrial process in a CHP plant can be used in a DHN locally. These systems tend to be cost effective and have been found to increase energy efficiency to over 80% (Lake, Rezaie and Beyerlein, 2017). However these systems are geographically limited to areas where industrial activity is present. Depending on the fuel used by the CHP plant, this system can be less environmentally friendly despite recycling heat that would otherwise be wasted, for example coal or oil fuelled CHP (Persson and Werner, 2011).

Further to their increased efficiency, DHNs can offer greater energy and financial security by having a few centralised energy supply centres, especially when compared with individual gas boilers in every home. The downside to this is that efficiency can be lost in the distribution pipe network, especially if the DHN operates at high temperatures (Werner, 2017).

2.2.1 History of District Heating Networks

DHNs are not new systems; having been first introduced in the 1880s, they can be split into 5 distinct periods or generations. Each generation of DHNs was designed to use the fuel that was abundant or cheap at the time of operation. They can also be defined by prevailing government policy of the period; for example later generations are designed with carbon reduction legislation in mind, so they therefore utilise sustainable sources of heat.

The first generation of DHNs were largely designed to transport steam produced through the burning of coal or supplied with waste heat from industrial processes. These systems were introduced mainly in areas that saw a lot of activity during the Industrial Revolution (northern Europe and north-eastern USA). First generation systems were initially used to heat larger buildings and then were phased into use at nearby domestic accommodation. The reason they were introduced was to bring secure heating to many homes and to utilise waste heat that would otherwise be rejected into the environment. However, the high steam distribution temperature of over 100˚C resulted in low efficiency through thermal losses (Woods and Overgaard, 2015).

The need for improvement was evident as first generation systems could suffer failures resulting in deadly steam explosions. This would be addressed by the second generation of DHNs through changing the heat transport fluid from steam to hot water. Although the transport fluid would remain at temperatures close to 100˚C. Introduced in the 1930s, they coincided with the widespread electrification of the industrialised world. This meant that utilising the heat that would otherwise be wasted in CHP plants could make further efficiencies. Using CHP plants as a heat source also lowered the cost of using the systems. However, depending on the security of fuel, running costs could fluctuate - oil prices were prone to fluctuating in response to global events and political decisions (Woods and Overgaard, 2015; Lake, Rezaie and Beyerlein, 2017).

The third generation of DHNs were first used in the 1980s and their development and implementation occurred mainly in Nordic countries, which resulted in these systems being named the "Scandinavian District Heating" (Woods and Overgaard, 2015). There are three changes that define third from second generation, with the first being lower distribution temperatures. Although temperatures differ between each system, the average supply and return temperatures in Sweden is 86-47˚C (Averfalk and Werner, 2017). Secondly, the distribution network is composed of prefabricated highly insulated buried pipes to avoid heat loss. Lastly, more diverse heat supplies are used; third generation is the first time heat pumps and biomass are used in conjunction with traditional fossil fuels and heat from industrial processes (Averfalk and Werner, 2017).

2.2.2 Future of District Heating

The three generations of systems described in the previous section have led to the DHNs that are beginning to be used today. The fourth generation, like every new stage before it, seeks to build on previous developments and is shaped towards the needs of society today. A core principle of these systems is to incorporate more renewable sources of heat in order to decarbonise the heating sector. Newer systems are trending towards multiple sources of heat, with each system tailored to the needs of the community they serve and the local energy options. In their 2014 article, Lund et al. set out five main challenges that 4th generation district heating (4GDH) must meet in order to comply with future sustainability policy. They act as a general guide as to what defines future DHN:

1. The ability to distribute thermal energy for space heating and hot water at lower temperatures than previous systems to existing buildings, energy-renovated existing buildings and new low-energy buildings.

2. The ability to distribute heat in the DHN with lower thermal grid losses.

3. The ability to integrate more renewable sources of heat, including recycled heat, from low-temperature sources.

4. The ability to be incorporated into a smart energy system, for example a smart electric grid.

5. The ability to ensure suitable planning, cost and motivation structures are in place in relation to implementing the systems and operating them long-term, ensuring they remain compliant with sustainability policy.

It is vitally important that as the sources of energy for DHNs are modernised, the thermal efficiencies of the dwellings they supply are also upgraded. Incidentally, this is in line with the Scottish Government's own plan to decarbonise the country's heat supply as outlined previously – to first lower demand then decarbonise the supply. Through doing this it allows for greater flexibility in future DHNs, the main benefit being that thermal energy can be distributed at a lower temperature than older networks that supply less efficient buildings (Lund et al., 2018).

A common theme within the Lund et al. guide is the expectation that future district heating systems will operate at low distribution temperatures. Lowering the temperature has been the goal for successive generations of engineers throughout the history of DHN technology. Within low temperature district heating systems the fluid is distributed at temperatures between 50˚C and 70˚C (Pellegrini and Bianchini, 2018). In general, lower temperatures would increase the overall efficiency of a DHN, through reducing heat losses (Schmidt et al., 2017). Table 1 is a summary of the positives that derive from a lower distribution temperature.

Table 1: Summary of the advantages in having a lower thermal distribution temperature in a DHN (Lund et al., 2014; Li and Nord, 2018)

Area	**Advantages**
Heat Storage	• Reduced heat losses from thermal storage units increases system efficiency • An increased storage volume required with lower thermal temperatures makes responding to spikes in demand easier
Distribution Network	• Higher efficiency from less heat loss within the network • Lower thermal stress causing less pipe leakages and subsequent maintenance savings • Cheaper, less insulated distribution pipes made from plastic can be used for low pressure areas • Decreased risk of water boiling in the pipes lowers the risk of a two-phase-flow in pumps
Building	• Low thermal distribution will better equip the building for future changes in heat demand and changing external environmental conditions
Occupant	• Drastically reduced chance of scalding in the event of leakages • System efficiency savings potentially passed on as cheaper heat for customers
Heat Sources	• Generally, a higher capacity output

Lowering the temperature of a DHN comes with certain issues that must be addressed. Firstly, lower temperatures allow for the potential growth of legionella, a bacteria that can cause serious illness. The danger is depending on how the system operates and legionella multiplies in water under 50˚C. Remedies to this danger include sterilization of the water through various means: chlorine, thermal treatment and ionization.

The final generation of DHN is the 5th (5GDH). These systems seek to build on the low temperature and efficiency goals of 4GDH, whilst keeping heat supplies local and renewable. The uniqueness of 5GDH is that they use individual HP for each building that draw energy from a shared distribution network which is kept at a constant ambient temperature, ranging between 0˚C and 30˚C (Buffa et al., 2019). Additionally, they incorporate cooling supply into the network and any excess low-temperature heat can be recovered and utilised. Excess energy from one building can be utilised by another; particularly useful when buildings have different thermal requirements (Buffa et al., 2019). There are instances of these systems being deployed, for example in the Netherlands there is a 5GDH that utilises geothermal energy in abandoned mines that have flooded. One cold and one hot temperature mines are used to satisfy both the heating and cooling demands of nearby buildings, future proofing the network against any changes in climate (Boesten et al., 2019).

2.3 Low Carbon Alternatives

This section of the literature review discusses potential renewable alternatives to gas and biomass boilers for supplying a DHN. The alternative DHN components discussed here can all be applied to the case study used in this thesis.

2.3.1 Heat Pumps

Heat pumps (HPs) are used to take heat from an environment (known as the heat source) and redistribute it to another location (the heat sink). This is used for space and water heating in buildings but can also be used to cool areas by transporting thermal energy away from the source. In order for this to happen HPs are driven by an external source of energy - for example, from the electric grid. This means that any emissions produced by a HP system derive solely from the carbon intensity of the electricity used to operate it. Overall, HPs take advantage of ambient heat that otherwise would not be utilized by conventional heat production technologies (The Danish Energy Agency and Energinet, 2016).

Generally speaking, there are three sources that a HP can draw thermal energy from: ground (GSHP), air (ASHP) and water (WSHP). GSHPs are buried in the earth and use heat exchangers to transfer the inherent ground heat into the DHN. ASHPs have their heat exchangers exposed to the external environment, drawing heat from the air. Finally, WSHPs are submerged in water to a depth that allows for the most uniform temperatures to extract a consistent level of thermal energy. Different sources have different positives and negatives when compared against each other; outlines available in Table 2. To make things more straightforward, the WSHP and GSHP share attributes in the table, as these systems operate in similar ways (Carvalho, Mendrinos and De Almeida, 2015).

Table 1: Positives and negatives of varying heat pump sources (Carvalho, Mendrinos and De Almeida, 2015)

ASHP		**GSHP/WSHP**	
Positives	**Negatives**	**Positives**	**Negatives**
Simple to add into an existing DHN, no groundwork required	Potential that the system can freeze during winter	Conditions can be more stable underground	Higher capital costs due to need to construct underground or underwater
Lower capital costs courtesy of fewer construction requirements	More visual and noise pollution as system is connected to the external environment	Less visual pollution as system is buried	Require a lot of unused land nearby to point of use
	Efficiency can vary due to seasonal temperature differences	System is protected from damage from external environment	Initial disruption to the site during installation – particularly when retrofitting

2.3.2 Solar

Energy derived from the sun has the potential to supply carbon free electricity or hot water. DHNs that rely solely on solar energy are rare and usually depend on inter-seasonal storage to compensate for less daylight hours in winter, particularly in northern Europe. Further to this, in order to be a viable heat source for an entire DHN a lot of space is required to install enough capacity; this can be particularly difficult to achieve in urban areas. Photovoltaic (PV) panels can be used to generate carbon free electricity to power some form of heat generator like a HP or solar collectors can be used to directly feed into the DHN (Pauschinger, 2015).

2.3.2.1 Photovoltaic Panels

PV panels can generate the electricity required to operate low carbon heating systems like HPs. They are composed of modules of solar cells, which generate electrical power in a direct current. This can be used to power components of a DHN or stored in a battery to be used when a system requires the energy. Any surplus power can be exported to the grid, reducing operating costs of the system. These attributes can make a DHN more energy efficient and cheaper to run (Dupeyrat et al., 2011).

DHNs that have available space can use PV panels to great effect; an example of this is Marstal in Denmark. This DHN used oil to heat the network before transitioning to a PV fuelled electrical system with a biomass boiler. There was unused land that now houses a 10 hectares solar PV field that generates enough energy to cover more than half of the town's annual heating demand. Denmark, like Scotland, is situated in northern Europe; meaning less PV energy is generated during the darker winter periods. This necessitates large inter-seasonal thermal storage for a DHN that uses PV panels as a primary source of energy. The example in Marstal has enough space for a 75,000m^3 thermal store, which it uses to somewhat address the imbalance of solar energy between seasons (Dannemand Andersen, Bødker and Jensen, 2013).

2.3.2.2 Solar Thermal Collectors

Solar thermal energy is a well-developed and mature technology being used widely around the world. Currently, the majority of installed capacity is at a domestic level for heating and hot water, however the technology can be applied to DHNs. Studies have shown that thermal collectors can be successfully retrofitted into DHNs, reducing the CO_2 output of the system as well as operational costs. Solar thermal collectors can be separated into two categories; flat plate and evacuated tube collectors (Winterscheid, Holler and Dalenbäck, 2017).

Flat plate solar collectors (FPSCs) are the most common type currently in use in Europe. The solar absorber is a metallic plate with spaces to allow for fluid to circulate all within an enclosed space with a transparent facing, allowing solar energy to be absorbed. The heat transfer fluid often contains anti-freeze, particularly in colder climates. This can then be either stored or transmitted straight to the point of use - which for this report would be a DHN distribution system (Pauschinger, 2015).

Evacuated tube collectors are more common throughout the rest of the World than in Europe. Consisting of a solar absorber surrounded by a glass tube, they effectively create a vacuum, which reduces heat losses through both convection and conduction. The absorber in this system consists of either a second glass tube or, like the flat plate collectors, a metallic tube (Sokhansefat et al., 2018). Like the flat plate, the thermal energy can be used within a DHN.

2.3.3 Storage

Whilst not being a direct source of energy, stores play an important role in allowing the deployment of more environmentally friendly sources of heat like a HP. If DHNs (powered by renewable energy sources) are to play a key role in the future heating industry, the ability to store thermal energy will become vitally important (Guelpa and Verda, 2019). Benefits that come with thermal storage are summarized below:

- Increasing the flexibility of the system to operate at optimal times - for example when electricity is cheaper or when external conditions are favourable - can cut down the operational cost of the DHN.
- Increase system efficiency through time-varying management.
- Alternative method of smoothing the peak thermal demand that typically occurs during the day.

- Increased security of heat supply – if the heat source breaks down, for example a HP, the stored heat, depending on volume, can meet demand for a period of time.

Battery storage can also be used to good effect in the right DHN. They can be used to store electricity that is produced on site, particularly if the intended end use for the electricity produced is in the DHN rather than exported to the grid. Like the stored thermal energy, the stored electricity can be used at an optimum time; for example when demand on the grid is high. Overall, battery storage can account for the intermittent nature of renewable energy resources. However, whilst battery storage capacity and efficiency are constantly improving, the technology suffers from being inherently expensive (Li, Rezgui and Zhu, 2017).

2.4 Renewable District Heating Case Studies

This section looks at various examples of DHNs that presently utilise some form of renewable heat. The following case studies were selected as they operate in areas with a similar climate and economy as the area analysed in this thesis (WWHC).

2.4.1 Drammen, Norway

Drammen, pictured in Figure 5, is a town 40km southwest of Norway's capital Oslo and has a population of approximately 60,000. It was an industrial town with a reputation for being run-down, triggering the local government to redevelop the town centre; at the heart of this was a DHN. The project had the ambition to lower energy bills and reduce emissions. Initially the heat source was biomass boilers; however, as the DHN was expanded the source of heat was changed to a WSHP in 2011(David et al., 2017).

The DHN now supplies over 85% of the town with heating and hot water. The heat pumps were built by Glasgow based company Star Refrigeration and the three of them combine to produce 15MW of thermal heat. Additionally, there are two 30MW natural gas fuelled boilers that provide back up. The source of the water for the heat pumps is seawater from the Oslo Fjord, which the town sits on. The water temperature at approximately 40m below the surface is reasonably consistent - meaning the heat pump can operate reliably away from the fluctuating air temperature. The glacial processes that carved out the fjord mean that the seafloor drops drastically close to the shoreline, making it easier to reach stable temperature depths. The DHN supplies water at temperatures that vary depending on demand, which coincides, generally, with seasonal temperature differences. This results in summer supply temperatures of 75˚C and this increases up to a maximum of 120˚C in winter when demand is highest (Ayub, 2016; David et al., 2017).

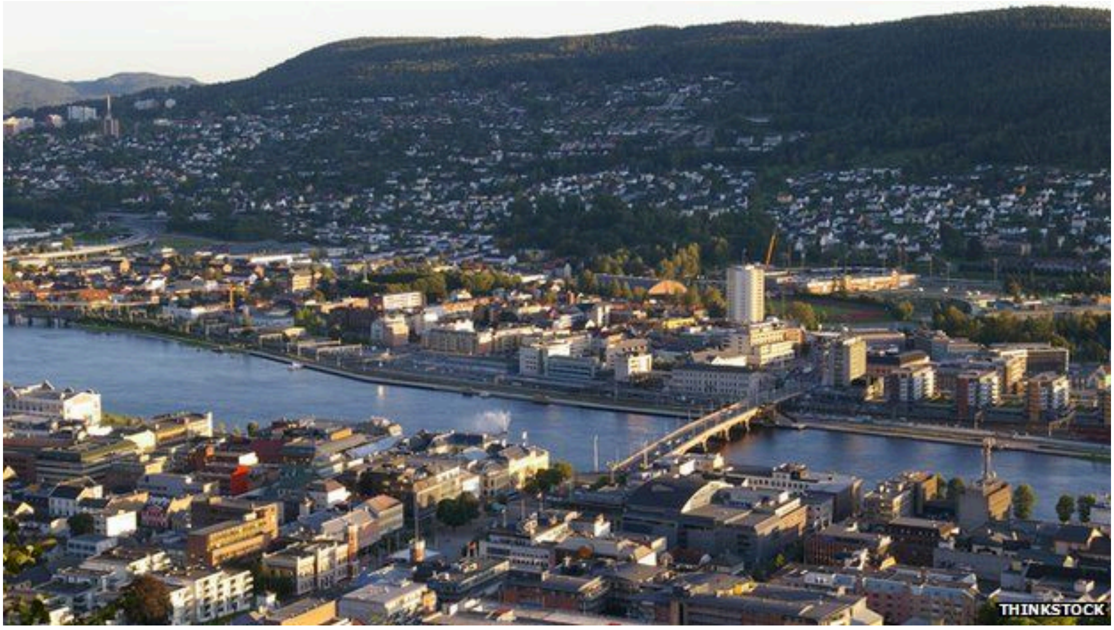


Figure 5: Drammen, Norway (Anderson, 2015)

This case study is an example of a DHN that can use a renewable source of thermal energy (WSHP) to meet a significant proportion of heat demand for a large town. Additionally, as this case study is situated in a colder winter climate than the UK, this system has potential to be replicated in the UK within areas that allow for deployment.

2.4.2 Hillpark Drive, Glasgow

The majority of ASHPs are single units, used to heat individual properties, but larger and more sophisticated models have been developed for use on a district scale. Hillpark Drive is a housing estate built in the 1970s and, on average, residents have always suffered from fuel poverty. The estate was heated using costly electric storage heaters. The Glasgow Housing Association, seeking to alleviate this poverty and cut carbon emissions, has retrofitted a DHN to the area. This DHN derives thermal energy from an ASHP; other thermal sources were considered but ruled out based on the characteristics of the community. Biomass was rejected as an option due to air quality concerns; GHSPs were not considered suitable due the lack of available space in the area; and a WSHP was ruled out as there was not a suitable body of water (Jures, 2016).

Figure 6: Example of the ASHP deployed at Hillpark Drive DHN (Pearson, 2015)

The system deployed is a 700kW ASHP that delivers output temperatures at 60˚C. It provides heating and hot water for 350 households and as a result is physically large, measuring at 8 metres in length and weighing 10000 kilograms. The ASHP unit is pictured in Figure 6. It was designed to be installed at a centralised energy centre to feed a DHN that supplies numerous buildings. This plug and play characteristic makes ASHPs of this nature ideal for a 4GDHN. The layout of the estate is shown in Figure 7; the green lines indicate thermal distribution pipes and the red circle highlights the location energy centre where the ASHP has been installed (the DHN is controlled at this location too). The project aims to save 19,000 tonnes of carbon; this is achievable through the decarbonisation of Scotland electricity grid. Installation of PV panels used to power the ASHP further enhances the schemes green credentials (Jures, 2016; Reid 2017). This case study demonstrates that local renewable heat resources can be utilised to decarbonise a DHN. It also shows that these technologies can be retrofitted into older building stock successfully.

Figure 7: Birds eye plan of the Hillpark Drive DHN (Jures, 2016)

2.5 Conclusion

This literature review has outlined the need to tackle the carbon intensive nature of Scotland’s current heating sector. It discussed the current ways in which we heat spaces and water, as well as outlining the Government's plan to decarbonise in order to meet ambitious net zero goals.

This chapter also covered DHNs: how they operate and why they are a potential solution for decarbonising the heating sector. The history of these networks was briefly outlined before discussing how they operate today. This gave an indication as to the future trends of district heating; to operate at a lower temperature with varied sources of renewable heat, tailored to the area that they are designed for.

This review also examined low carbon alternatives to supplying heat to a DHN. Reviewing different sources for heat pumps was the main focus on decarbonising the heat production process. In addition, the potential of energy derived from solar sources was looked at to offer different ways of heating water for the DHN or for powering the systems that do so.

This literature review has provided a base of knowledge in relevant areas for the subsequent investigation in this report and describes options for decarbonising a DHN in order to cut emissions. Additionally, it analyses the operation of existing low carbon DHNs, providing insight into how such systems can operate in a climate that shares characteristics with the case study. The next section of this report will outline the methodology used, beginning with a summary of the case study featured in this report – the West Whitlawburn Heating Co-operative.

3 Materials & Methodology

This chapter outlines the details of the case study, giving an overview of WWHC's history, aims and current DHN. It then goes on to discuss the software used for modelling in this project, as well as the strategy deployed for devising a zero carbon alternative DHN. Finally, the input values required to produce the models are discussed in this chapter.

3.1 West Whitlawburn Overview

This section provides the details of the case study used in this report. It includes a brief history of the housing co-operative as well as a summary of the current system.

The West Whitlawburn Housing Co-operative (WWHC) was built in Cambuslang, a town to the south of Glasgow, in the 1960s. The locations in relation to Glasgow is outlines in Figure 8. This area is one of the poorest in the country and suffered from high crime rates and social issues. In conjunction with this, the housing stock within the estate was poorly planned and not fit for purpose. For the first 20 years the area was council-run social housing; in 1989 the residents purchased the estate. This has been resounding success, lowering energy prices for home residents and reducing social problems in the estate (WWHC Ltd, 2014).

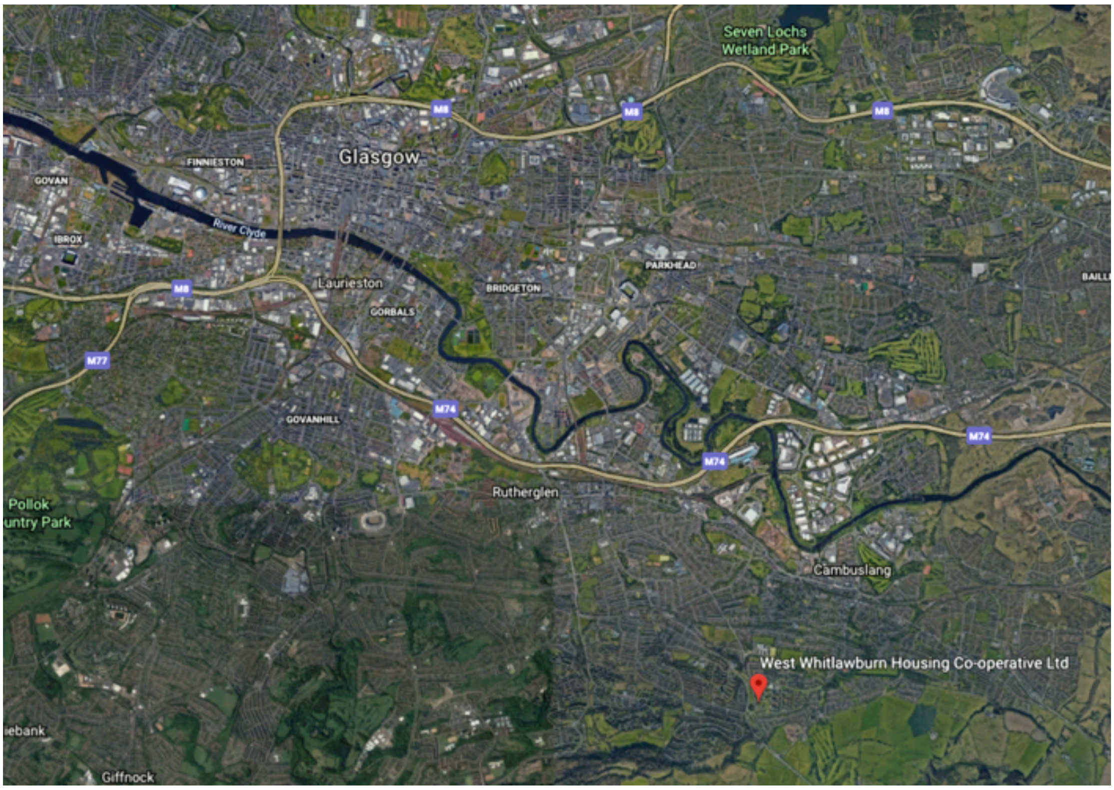


Figure 8: Location of WWHC in relation to Glasgow (Google Earth)

3.1.1 Structure of the Co-operative

The 1989 community buyout allowed the estate to transition into a tenant-run co-operative. Their mission statement is to:

"Provide high quality housing and services at affordable rent, and will promote community and environmental sustainability."

In order for this to be achieved, approximately £50 million has been invested in a number of energy, housing and social schemes since1989. The current strategic objectives for 2018 - 2021 revolve around helping tenants to mitigate any negative impacts that changes to state welfare may be having, alongside a focus on improving the local community (WWHC Ltd, 2014).

All tenants are co-operative members and there are a total of 664 properties that vary in type. There are 6 high-rise tower blocks and 5 low-rise terraces, as well as 100 newer properties built since the co-operative was formed. In 1996 a community centre was built using lottery funding. This further contributed towards the goal of community sustainability. Initially, the co-operative was heated exclusively by electric storage heaters situated within each property. This contributed to the fuel poverty of residents due to its high operational cost, and has since been replaced with a DHN that uses both biomass and natural gas as fuel (WWHC Ltd, 2014).

3.1.2 Upgrades

The buildings in the WWHC have been extensively upgraded since 1989. These upgrades are partly to improve the community socially; for example the deployment of CCTV controlled entry systems. The other upgrades have been to make these buildings more energy efficient. This is an ongoing endeavour and is in line with the Scottish Government's route map to net zero, the first step of which is to decrease demands through building stock improvements (WWHC Ltd, 2014).

The housing stock has seen numerous retrofit upgrades to improve both thermal efficiency and living conditions for residents. These works included: enclosing the balconies within the high-rise flats, addition of an aluminium rain screen, replacement of windows and the addition of exterior wall and roof cladding. The cladding contains mineral wool insulation and has built in firebreaks making them safer in the event of combustion. In addition to improving efficiency and safety, the cladding works to improve the aesthetics of the housing estate. Figure 9 is the exterior of the high-rise towers before the upgrades and Figure 10 shows the exterior post-upgrades (d+b facades, 2011).

Figure 2: Higher-rise tower block at WWHC before efficiency upgrades

(d+b facades, 2011)

Figure 10: High-rise tower block at WWHC post efficiency upgrades

(d+b facades, 2011)

3.1.3 Current District Heating Network

The WWHC replaced the expensive and inefficient electrical storage heaters with a district heating system. This DHN has the dual aim of reducing both the energy bills for residents and the overall carbon footprint of the estate. The network currently derives its thermal energy from a centralised energy centre, location shown in Figure 11. The energy centre contains one 740kW biomass boiler and three 1300kW backup gas boilers. The heat is then stored in a 50m^3 thermal storage tank (WWHC Ltd, 2014).

Figure 11: Aerial view of WWHC, community buildings and the energy centre are highlighted beside the residential buildings

The thermal energy is transported from the thermal store to each building in the estate and then to each individual flat. The thermal fluid is distributed by an underground pipe network, at supply temperatures of 85°C. This then heats each residential unit's heating system; this is made up of a heat exchanger, radiators and a hot water tank. Each unit now has more control over energy usage through the installation of thermostats and improved radiators (WWHC Ltd, 2014). The heating system currently deployed has reduced both the energy bills for residents and the carbon footprint of the estate. However, as Scotland aims to achieve net zero carbon, the current system is still inadequate.

3.2 Software Selection

There are multiple options in software for modelling a DHN and some have more desirable attributes than others. A report by Lyden et al. in 2018 was used to help narrow down the potential software options. The report categorises the capabilities of different modelling software, as well as developing a selection process for selecting a tool to suit the needs of a project.

The characteristics necessary for this project were as follows:

- Capable of modelling for a DHN
- Allow multiple sources of renewable energy
- Allow for thermal and electric storage
- Operate using thermal demand with time steps in minutes
- Ease of access and downloading due to restrictions in the COVID-19 lockdown

Although several modelling tools were considered, EnergyPRO was ultimately selected for this project. It is made by Danish software company EMD, and was chosen for a number of reasons. Firstly, it meets each criterion that is set out above as being vital for the requirements of this report. Secondly, the researcher's previous experience of the capabilities and operation of the software were beneficial, having used the tool for a previous project. In addition, any type of technology and energy system can theoretically be modelled using this software (EMD International, 2017). Lastly, the analytical optimisation method, summarised below, that the tool deploys was advantageous for this report.

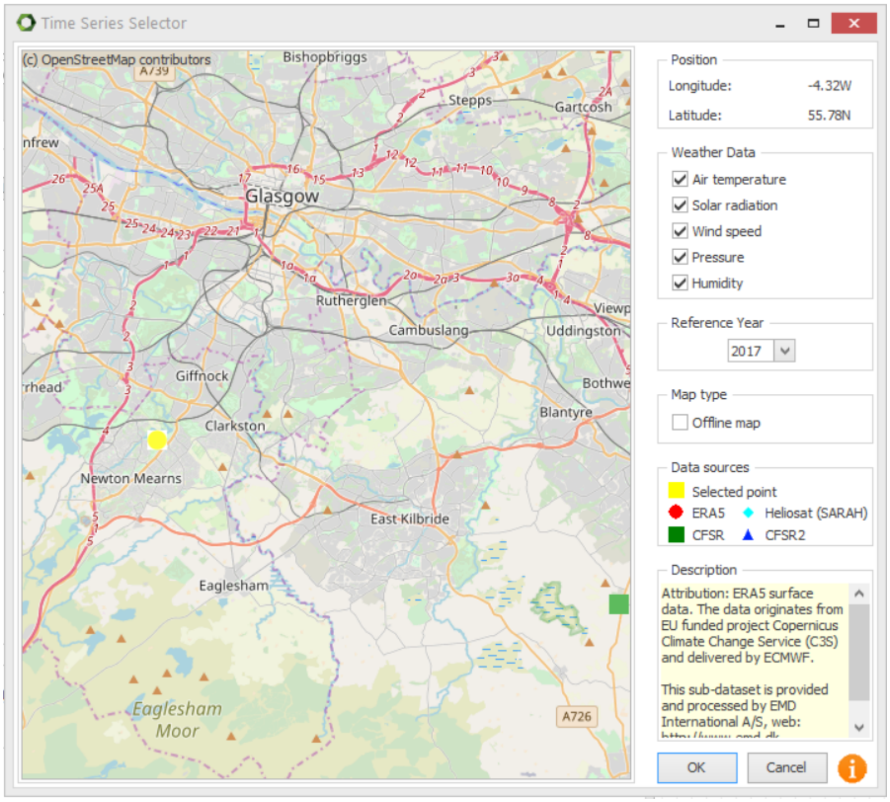
EnergyPRO calculates the analytical optimisation method after a model has been constructed and it involves calculating the optimal operation strategy. The strategy calculated is dependent on the operation goals that are defined by the user. When calculating the optimal operation strategy, EnergyPRO follows an analytical approach. To this end, in every time-step, a priority number for each production unit is calculated. Then, based on these priorities, units are put in operation, starting with the unit with the best priority. This is then succeeded by the unit with the second best and so on. This will continue until the demands on the system have been met or the energy sources have been exhausted (EMD International, 2017).

3.3 Modelling Input Data

This section outlines the data that was used for the modelling in this report. Beginning with the external conditions data and the thermal demand data specific to WWHC DHN.

3.3.1 Climate Data

External weather data was gathered using EnergyPRO's integrated database of climate data. It provides annual figures for air temperature, solar radiation, wind speed, precipitation and humidity. Although there are no monitoring stations at the studied site in Cambuslang, a site in Newton Mearns was selected in its place, being only 12km apart (Figure 12). The datasets came from ERA 5, which provides data in hourly time step intervals. They are produced through combining historical observations into global estimates and all data is quality assured and published within three months of real time. 2017 data was chosen over more recent data so as to coincide with the same year that the thermal demand data is gathered from.



Position
Longitude: -4.32W
Latitude: 55.78N

Weather Data
☑ Air temperature
☑ Solar radiation
☑ Wind speed
☑ Pressure
☑ Humidity

Reference Year
2017

Map type
☐ Offline map

Data sources
🟨 Selected point
● ERA5 ◆ Heliosat (SARAH)
🟩 CFSR ▲ CFSR2

Description
Attribution: ERA5 surface data. The data originates from EU funded project Copernicus Climate Change Service (C3S) and delivered by ECMWF.

This sub-dataset is provided and processed by EMD International A/S, web:

Figure 12: EnergyPRO external conditions selector map

3.3.2 Thermal Demand

The thermal demand data is derived from a meter, which measures the flow and return temperatures alongside the mass flow in order to calculate the energy demand. This meter is located in the energy centre at WWHC, where the entire DHN is constantly monitored. Previous work carried out by the University of Strathclyde gathered this data during an in person site tour in 2017. It was impossible to gather more up to date demand figures for this study due to the current lockdown imposed by the COVID-19 pandemic.

Although gathered three years ago, the 2017 data is assumed to be representative of the system today. This is because there has been no further thermal efficiency upgrades to the dwellings within the community. In addition, external climate has not changed significantly.

The raw data first had to be processed to remove anomalies that prevented it from being inputted into EnergyPRO. Times with negative thermal demands had to be replaced with figures that were representative of the time of year data fell in. The resulting figures were used to produce the below graph showing a typical annual thermal demand profile for a DHN in temperate, northern Europe (Figure 13).

The peak demand on the system is 1.4MW. Although the overall demand may seem low for a DHN that supplies 664 homes, this is assumed to be down to three different factors. Firstly, the majority of the 664 dwellings are in large blocks of flats, resulting in lower thermal demand. Secondly, as previously outlined, the community has undergone extensive thermal efficiency upgrades, which further reduces demand on the DHN. Lastly, the area has a history of fuel poverty; residents may be less inclined to use as much energy as an average household.

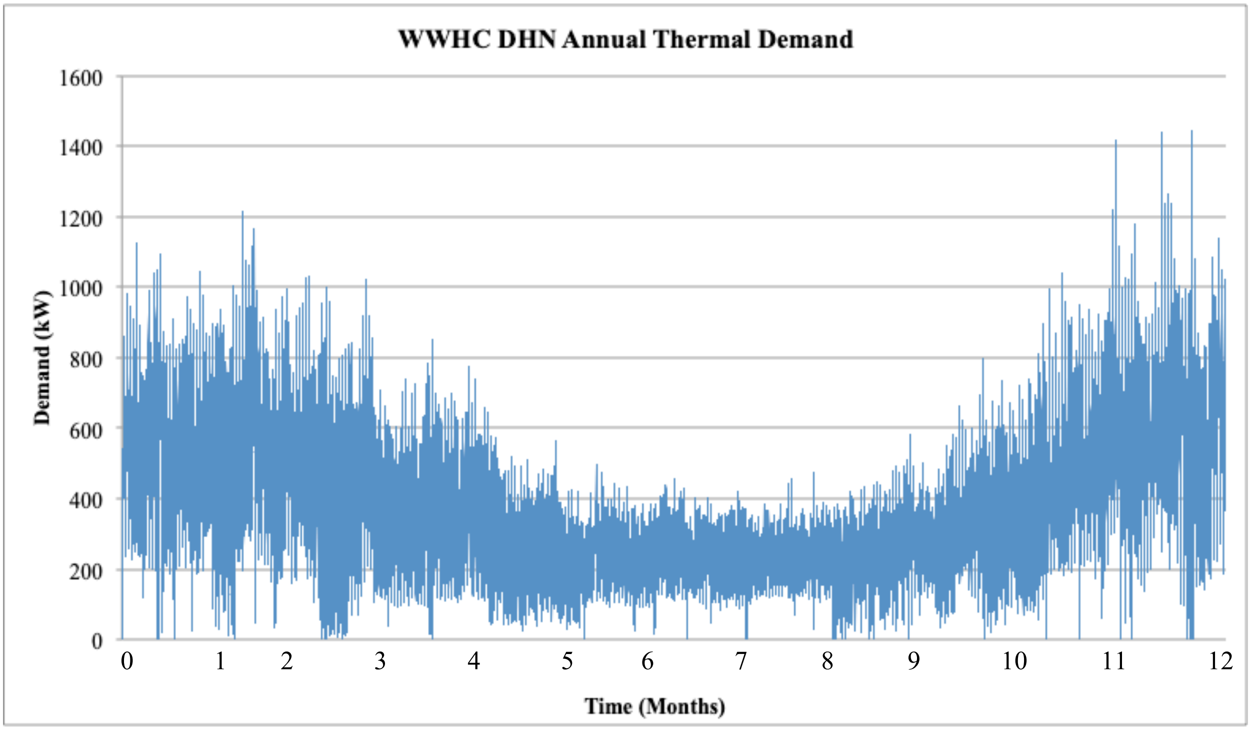


Figure 13: Annual thermal demand for the WWHC DHN

3.3.3 Emissions

The indicator used to determine changing levels of emissions was CO_2. The sources of CO_2 in the modelling are the combustion of natural gas and biomass pellets as well as carbon produced during production of grid electricity. The figures for the CO_2 released through burning these fuels were taken from the UK Governments Forest Research Group:

- Natural Gas – 227kg/MWh
- Biomass Pellets – 15kg/MWh

To derive a figure for the grid carbon intensity the GridCarbon app was used. This app offers summary data for the source of generated electricity within the UK grid. It uses two sources for the data: ELEXON and Sheffield Solar. The app collates this data and produces a grid carbon intensity value through comparing each generation's method by its share of the electricity in the grid and its unique carbon intensity (Rogers and Parson, 2017). Using the app, multiple values were taken over a week and the average of these was used to determine an average grid carbon intensity to be used in the report, the value of which is 224gCO_2/kWh.

3.3.4 Finances

The financial realities of each system modelled were analysed solely using the annual operational expenditures of each system. The expenditures covered the cost of importing electricity and of annual maintenance. However, the models that produced electricity could sell this back to the grid, lowering the overall operational costs.

The tariff used for each model was a Fixed Economy 7, using figures from the UK Government's Department for Business, Energy and Industrial Strategy. The figures used are for Southern Scotland in 2019. The set time period ranges from 06:00 to 23:00 for the day tariff, with the rest of the day being the night tariff. The electricity prices for the period are as follows:

- Day Tariff – 210 £/MWh
- Night Tariff – 100 £/MWh

Using this information, EnergyPRO can calculate the approximate annual operating costs during each simulation. If electricity generation is built into the model then this can be sold back to the grid. These figures are also taken into account by the software when calculating the system's operational costs. The export tariff is derived from adding the standard feed in tariff rate with the generation tariff attributed to the particular technology in use. The standard rate used is 5.5 p/kWh and the export tariff prices used are shown below in Table 3.

Table 3: Export tariff rates for PV and wind (Ofgem, 2020)

Generation Method	**Capacity (kW)**	**Generation Tariff (p/kWh)**
Large Solar PV	250-1000	1.36
Wind Turbine	1500-5000	0.48

3.4 Model Components

The following are the specifications for the different components used when modelling the current WWHC DHN, as well as potential renewable alternatives.

3.4.1 Base Model Boilers

These components are only used to understand how the current system at WWHC operates in the base model. Their specifications are taken from the specifications outlined by WWHC, which have been outlined in detail earlier in the methodology. In summary, the biomass boiler has a 750kW continuous output and there are 3 back-up gas boilers each with a capacity of 1300kW.

3.4.2 Air Source Heat Pump

Reviewing the success of ASHP in the DHN at Hillpark Drive in Glasgow suggested that deploying a similar system at WWHC would have similar success. The first stages of modelling involved simulating the ASHP at varying electrical capacity: Table 4 contains the specifications that remained constant during each simulation. The temperature values that the ASHP is designed for are a combination of the temperature used currently by the DHN at WWHC as well as specifications taken from Star Refrigeration, a heat pump manufacturer.

Table 4: Technical Specifications of the ASHP

ASHP Specifications	
Electrical Capacity (kW)	Variable
Min. Electrical Load (kW)	100
Heat Pump COP	Calculated
Heated From (C˚)	45
Heated to (C˚)	65
Cooled From (C˚)	External Climate Data
Cooled to (C˚)	External Climate Data - 2
Efficiency	Calculated

The cooled from and cool to figures depend on the source temperature, which for this system is the outside air temperature. As such, it is linked to the external temperature climate data that can be inputted via EnergyPRO and fluctuates throughout the year. Using the actual temperature data, from the same EnergyPRO source, a theoretical COP is calculated. This value is then multiplied by the efficiency calculated in order to find the system's actual COP. The software repeats this process during every new simulation.

3.4.3 Electric Boiler

The electric boiler component was introduced so that thermal demand was met during each simulation. Moreover, the boiler was sized to meet the peak demand of 1.4MW and had a 99% efficiency rating (The Danish Energy Agency and Energinet, 2016). To test this, seven random days were selected for the DHN to operate solely using the boiler. This had the added benefit of simulating periods in which the ASHP is undergoing maintenance. The operational strategy for the boiler was to only work in the event that all other sources of thermal energy for the DHN were exhausted.

3.4.4 Thermal Storage

The thermal store component was added to achieve an operation strategy that was more cost effective. The values for the thermal store are shown in Table 5. The volume was varied in simulations to test optimal size in conjunction with electrical capacity of the ASHP. The other values in the Table are reasonable assumptions based on the default values that EnergyPRO suggests.

Table 5: Thermal storage tank specification

Thermal Storage Specifications	
Volume (m3)	Variable
Temperature in the top (C˚)	90
Temperature in the bottom (C˚)	50

Further to this, the storage losses can be determined using EnergyPRO, varying with every simulation depending on storage volume and operation strategy. Table 6 contains the raw data required for EnergyPRO to carry out the loss calculations. The ambient temperature of the area the tank is situated is assumed to be constant for most simulations. However, during Scenario 1 varying ambient temperature conditions are tested as it the insulation thickness to determine the subsequent effect on losses.

Table 6: Thermal tank losses specification

Storage Loss Specifications	
Storage Height (m)	5.2
Insulation thickness (mm)	300
Thermal Conductivity (W/m2K)	0.037
Ambient Temperature (C°)	20

3.4.5 Photovoltaic Panels

The PV panels used in the model had specifications based on the NF-250QCS model from Sharp. Table 7 contains the specifications required by EnergyPRO to run a PV system. The installed capacity is varied in the simulations. However, the maximum flat roof space provides a ceiling of 1MW of capacity.

Table 7: PV panel specifications

PV Panel Specifications	
Installed Capacity	Variable
Inclination of PV	35°
Orientation of PV	South
Maximum Power	250W
Temperature Coefficient	-0.36
NOCT	47.5°C
Aggregated Losses	10%

3.4.6 Flat Plate Solar Collectors

The FPSC used for modelling was based on the Vitosol 200-F device from Viessmann. The input specifications are outlined in Table 8. EnergyPRO uses the solar diffuse and direct radiation as well as the external temperature to determine the heat output of the FPSC. Using the size specifications for this particular panel there is an assumed maximum workable space of $2000m^2$.

Table 8: Flat plate solar collector specifications

FPTC Specifications	
Total Area	Variable
Inclination of panel	35°
Orientations of panel	South
Start Efficiency	0.815
Heat Loss Coefficient U1	3.79
Heat Loss Coefficient U2	0.0021

3.4.7 Electrical Storage

EnergyPRO does not differentiate between different types of battery; instead it relies solely on the inputted specifications that can be found in Table 9. The battery was sized to store 4MWh of capacity; the remaining values in the table are standard and pre-set from EnergyPRO. The battery capacity of 4MWh is sized to hold the average daily production electrical output of the PV panels.

Table 9: Electrical storage specifications

Electrical Storage Specifications	
Max Capacity (MWh)	Variable
Charging Power	
Capacity (MW)	1
Efficiency (%)	95
Discharging Power	
Capacity (MW)	1
Efficiency (%)	95

3.4.8 Wind Turbine

The wind turbine used in this case study is the 3MW machine on Cathkin Braes, situated 2.3km from the WWHC. Built by Glasgow City Council, in conjunction with Scottish and Southern Energy, part of the turbine's mission statement is to support a community trust to support local projects (Nicoll, 2013). This model component works off of the assumption that a private line could be established in order to supply WWHC with purely renewable electricity to heat the network.

Table 10: Wind turbine specifications

Wind Turbine Specifications	
Measure Height (m)	10
Hub Height (m)	100
Hellmann Exponent	0.16

EnergyPRO calculates turbine output using the inputs outlines in Table 10 in conjunction with a wind speed time series. The measurement height refers to the height that the wind speed data was measured at and is taken from the ESRA 5 set, outlined previously. The hub height of the turbine is taken from published data on the turbine (Vestas, 2008). The Hellmann exponent varies on the location of the turbine and is dependent on the coastal location, shape of the terrain and the stability of the air. In this case the area was assumed to have neutral air and situated on open land, giving it an exponent of 0.16. The power curve of the turbine was specified in a table, which EnergyPRO uses to construct the graph shown in Figure 14 (Vestas, 2008). Using both the external wind speed and power curve of the turbine, EnergyPRO calculates the annual production of the turbine.

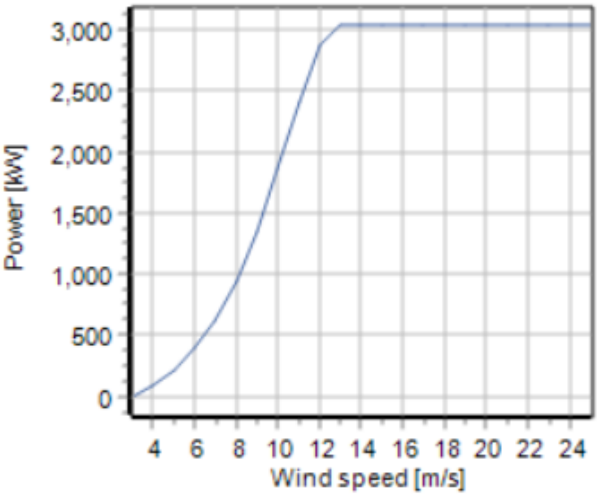


Figure 14: Power curve of wind turbine produced by EnergyPRO

3.4.9 Modelling Strategy

The strategy for modelling in this thesis starts with analysing the current DHN setup at WWHC. This moves onto the new systems that are grouped into 4 distinct scenarios. The composition of these 4 new scenarios is outlined below in Table 11.

Table 11:Modelling scenario components

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
ASHP	✓	✓	✓	✓
Electric Boiler	✓	✓	✓	✓
Thermal Store	✓	✓	✓	✓
PV	×	✓	×	×
FPSC	×	×	✓	×
Battery	×	✓	×	×
Wind Turbine	×	×	×	✓

EnergyPRO produces an optimum operational strategy for each simulation, this is analysed to determine how the DHN would run with that specific configuration. Additionally it analyses both financial and environmental factors that would be key in implementing an affordable system that cut the carbon emissions in line with national targets. Financial analysis focused solely on the annual operational costs associated with each new model, to gauge the impact of the new components. The environmental analysis involved plotting the amount of CO_2 produced annually alongside the percentage reduction in CO_2 this represents from the base model. Below is a break down of performance indicators that are specific to the scenario:

- **Base Scenario:** This model is composed of the components that make up the existing DHN at WWHC. It was modelled to get an understanding of how the DHN currently operates as well as having an EnergyPRO model of it to better compare the other models using different components. This allowed for the determination of the CO_2 reduction rates that each new scenario offered.

- **Scenario 1:** Primarily determined the optimum size of ASHP and thermal store for the DHN. This was done through analysing the operational strategy produced by the software. Specifically, the share of the heat supply provided by the ASHP over the boiler and the percentage of low cost electricity that the

ASHP could use through filling the thermal store. Simulations were run to test the effect of varying the location and insulation thickness on the efficiency of the thermal storage tank.

- **Scenario 2:** Operation involved using PV panels to generate carbon free electricity for use in the DHN with the surplus being sold to the grid. Installed capacity of PV was varied in each simulation to create different options for the DHN. Each simulation was analysed for percentage of electricity that was used by the DHN or exported to the grid. Alongside this the share of total electricity requirements of the DHN that was met by PV, day tariff imports and night tariff imports was plotted. Further to this, the effect of adding electrical storage was simulated to determine their effect on these key indicators.

- **Scenario 3:** Involves the addition of flat plate solar collectors, the area they occupy varying with each simulation. As this offered an alternative source of completely carbon free heat the assessed indicator was the percentage of heat demand that was met by each of the heat production components.

- **Scenario 4:** This scenario involves the addition of a private wire from a wind turbine to the model. The analyses in this involved discussing how the operational strategy works over periods with high wind speeds and periods of no electrical output from the turbine. The final environmental graph is produced that shows the effects of wind turbine addition to each of the 3 previous scenarios.

3.5 List of Assumptions

Assumptions made regarding specific model component input specifications are outlined previously in this chapter. Discussed below are the broader assumptions made regarding the modelling.

The thermal demand of the DHN is assumed not to change in the future. The demand could increase or decrease as the external climate changes or further improvements are made to the building stock. The demand data used for all modelling was taken directly from WWHC and is for the year 2017.

Another assumption made is that EnergyPRO accurately modelled the current operating system at WWHC based on parameters available online. It was considered useful to have a base model that was designed on the same modelling software as the proposed new models. This would allow for more accurate comparisons between the different systems.

Modelling Scenario 3 involves installing a private wire between the part-council owned 3MW wind turbine on Cathkin Braes and WWHC. Built by Glasgow City Council, in conjunction with Scottish and Southern Energy, part of the turbine's mission statement is to support a community trust to support local projects. This model component works off of the assumption that a private line could be established in order to supply WWHC with purely renewable electricity to heat the network.

4 Results

The following chapter addresses the results of the work carried out in this report. It contains analysis on each model developed; these are split up into sections and labelled as different scenarios.

4.1 Base Scenario

The first results obtained were for the base model, designed using the specification of the current system in operation at WWHC. The schematic for this model is in Figure 15. One biomass boiler is the primary source of heat with three back up gas boilers to help meet demand at all times. The system also uses a 50m^3 thermal store.

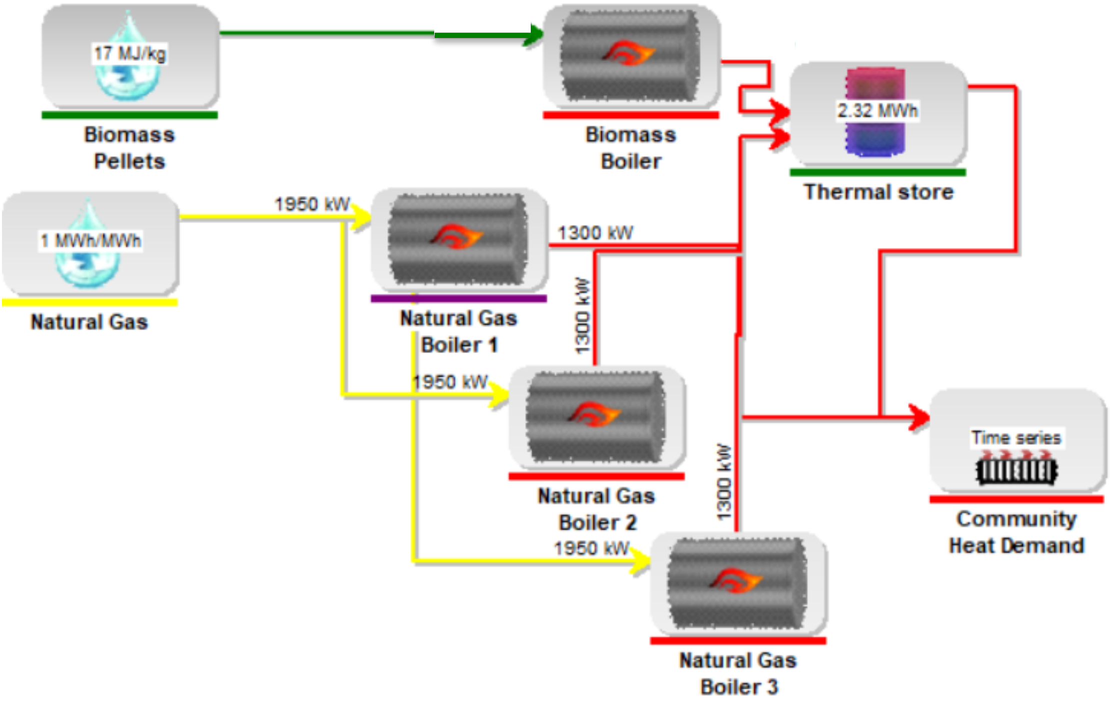


Figure 15: Base scenario model schematic

4.1.1 Base Scenario Characteristics

The operating strategy of the base scenario has the biomass boiler operating continuously throughout the year. It satisfies the majority of demand and stores surplus energy at times of low demand to then use during the day. The gas boiler provides extra heat to cover spikes in the demand. This strategy is shown in Figure 16. It shows that only one boiler is typically needed annually to ensure demand is met. This is expected, as the three back-up boilers are each sized to cover the maximum thermal demand of 1.4MW. This suggests that the extra gas boilers are incorporated into the system mainly for thermal supply security in the event the biomass boiler fails.

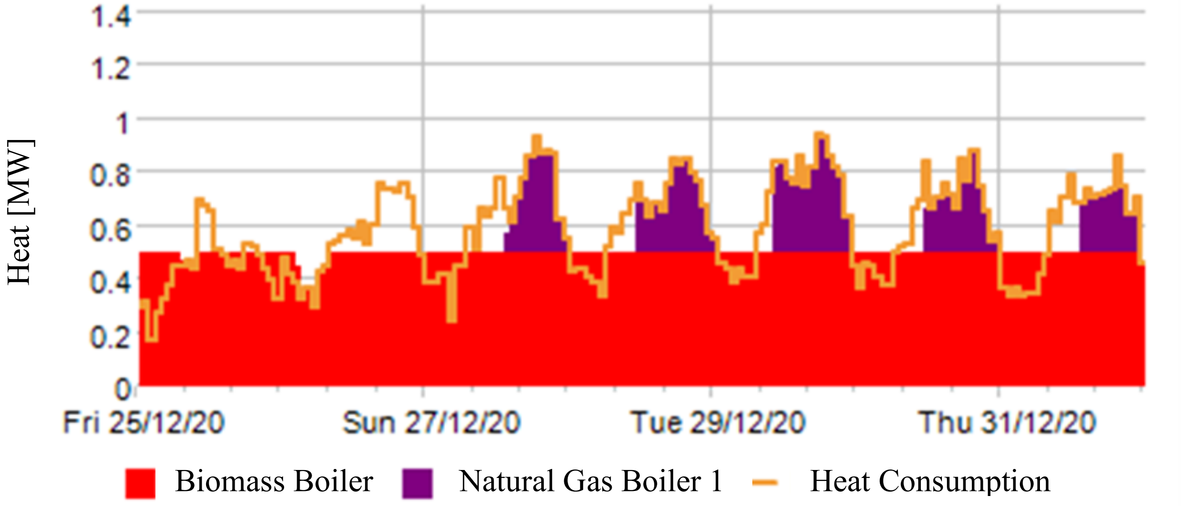


Figure 16: Base Scenario thermal operation graph for a week in winter

Environmentally, the characteristic assessed was the annual CO_2 produced by the system. The main sources of CO_2 in the base model derive from the burning of the two fuels –natural gas and biomass pellets. Biomass pellets produce CO_2, NOx and particulate matter; however it is only the first of these that is modelled for in this report, as CO_2 is the main contributor to climate change. The CO_2 produced annually through the burning of natural gas and biofuel was calculated by EnergyPRO to be 1525 tonnes. This works out at 2.3 tonnes per dwelling, which is lower than the UK average of 2.7 tonnes (Citu, 2020). This is most likely because WWHC has already undergone energy saving measures as outlined previously. However, this figure does not include the emissions produced during transit of the biomass pellets.

4.2 Scenario 1: Heat Pump & Thermal Store

This scenario assesses the different sizing options and combinations for decarbonising the DHN at the WWHC. The general schematic for these simulations is shown in Figure 17. It consists of an ASHP and electric boiler, both of which draw power from the grid. Additionally, a thermal storage tank is utilized to meet the community heat demand. The results of running these initial simulations provided indicators as to how different sized systems would operate for the WWHC.

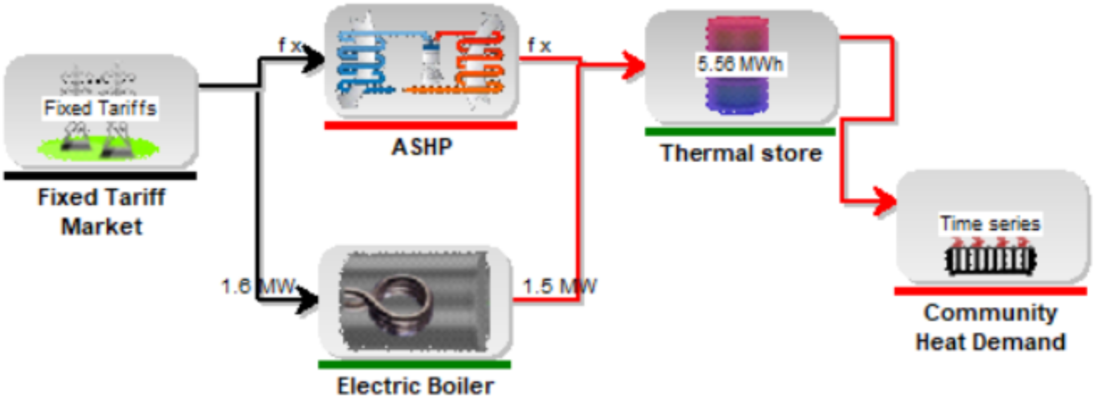


Figure 17: Scenario 1 model schematic

4.2.1 Heat Pump and Thermal Store Sizing

The results of the Scenario 1 simulations gave an indication into the size of ASHP and thermal store that would not just meet the thermal demand but also do so in an economically friendly way by maximising the amount of cheaper electricity used. Selected raw results used in the Scenario 1 analysis are found in Appendix A. With this in mind, the results for this section are presented with two key performance indicators. The first is the percentage of heat demand met by the ASHP over the electric boiler. The second is the percentage of low cost electricity used by the ASHP annually. Figure 18 shows each of the simulated systems plotted for the first of these criteria.

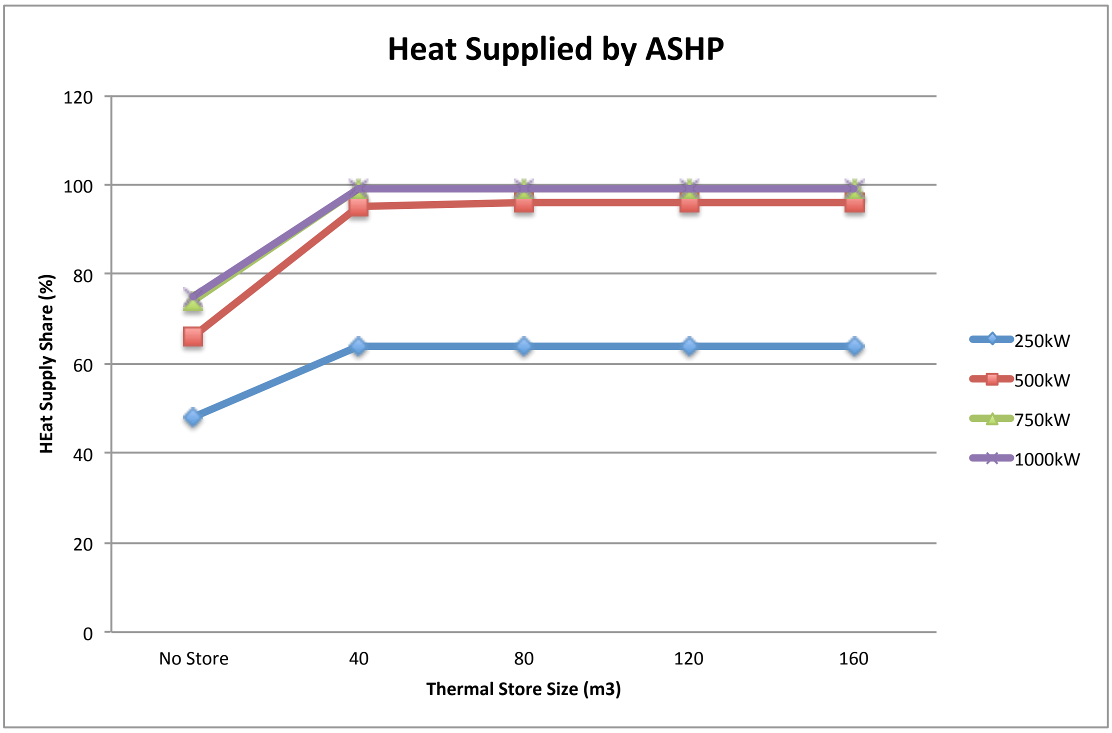


Figure 18: Scenario 1, DHN heat demand met by ASHP

This graph tells us a couple of things; firstly, that a thermal store is vital for increasing the overall heat supplied by the HP. When there is no store there is a drop off for each of the ASHP's modelled. This is consistent as the store allows the ASHP to overproduce heat when demand is being met. This stored heat can be utilized at times of peak demand instead of switching on the electric boiler.

Secondly, the 250kW ASHP is inadequate for meeting the thermal demand for the WWHC. Even with larger thermal storage units these systems plateau around 65% of total heat demand. The other systems modelled follow a similar pattern, producing similar figures. When a thermal store is added to each of them they supply almost the entire heating requirements of the DHN. This is because the demand in summer is rarely over 500kW and in winter ranges between 600kW and 1MW with a peak of 1.4MW. This means that all these systems, with added heat storage, can meet the majority of thermal demand. Overall, increasing the thermal storage volume does not vary this KPI significantly.

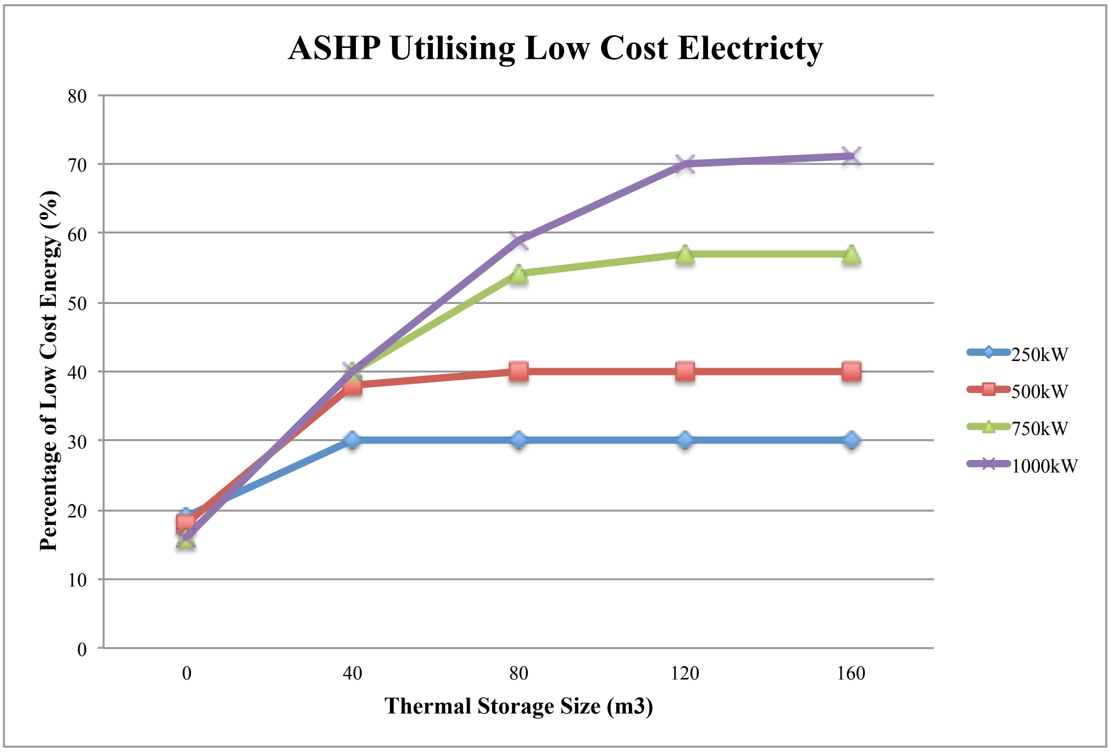


Figure 19: Scenario 1, percentage of low cost energy used by the HP

Figure 19 plots the percentage of low cost electricity used by the HP annually. Through increasing the share of low cost electricity the DHN operational costs will decrease. The graph, expectedly, shows that larger thermal store sizes allow for greater utilisation of low cost electricity that is available during low demand periods. However, this is highly dependent on the capacity of HP installed. The 500kW HP plateaus at 40%; the 750kW system at 57%; and the 1MW at just short of 70%. This data also reaffirms that the 250kW ASHP is not suited to operate the WWHC DHN and that a thermal store is vital for increasing the use of low cost electricity.

4.2.2 Operational Strategy

This section contains the operational strategy that EnergyPRO formulated with an ASHP of 750kW electrical output coupled with a thermal store size of 120m^3. This system was chosen using the KPI outlined above.

The analytical optimisation method that EnergyPRO employs resulted in a system that prioritises using the ASHP over the electric boiler. This purely comes down to the energy intensity of the two energy conversion units, with the boiler requiring more electricity from the grid and is therefore more expensive to operate. Figure 20 shows the priorities that EnergyPRO assigned to the system, showing that for the majority of the year the ASHP has a higher priority of use. The only periods of the year that this graph changes are when demand cannot be met by either the ASHP or stored thermal heat. This graph offers an insight into how EnergyPRO produces the optimal operation.

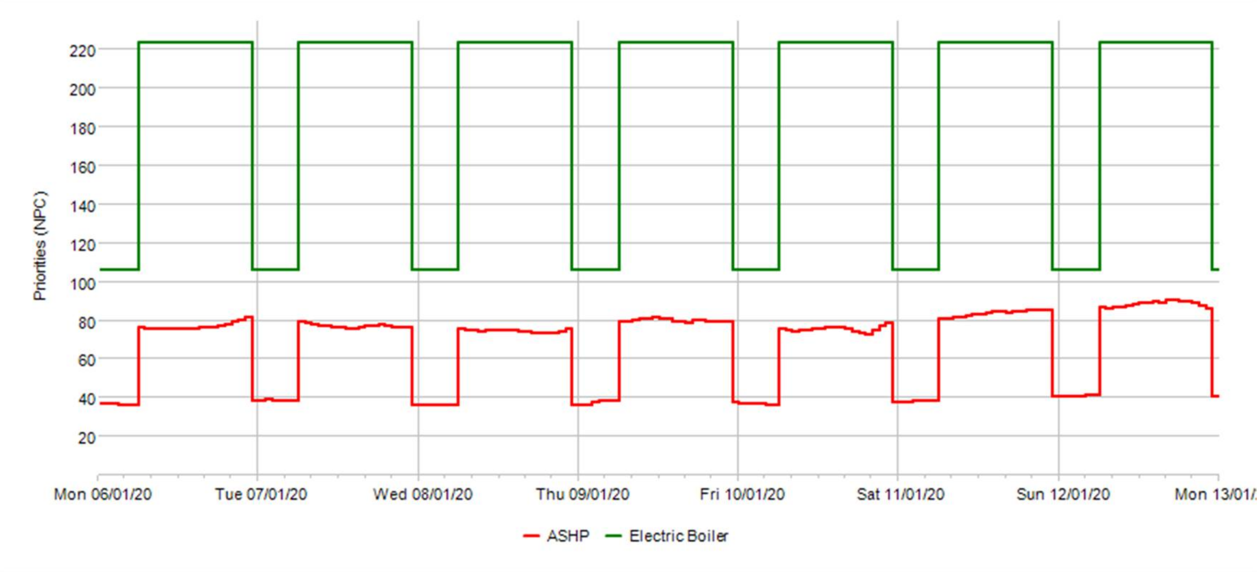


Figure 20: Scenario 1, operational strategy, 750kW ASHP and 120m^3 store

Figure 21 is composed of the heat consumption and thermal store graphs for a typical day in winter. The heat consumption graph shows that demand operational strategy is for the ASHP to overproduce heat during the low demand hours at night, whilst meeting the demand of the DHN. The thermal storage graph corresponds by filling during these hours, reaching capacity at 6am. The DHN uses this heat to meet demand throughout the morning, when the electricity used to operate the HP would be higher. Around 2pm the HP is back in operation as stored thermal energy is dwindling. It operates at a constant rate for the remainder of the day, using the remaining stored heat to smooth the spike in demand in the late evening.

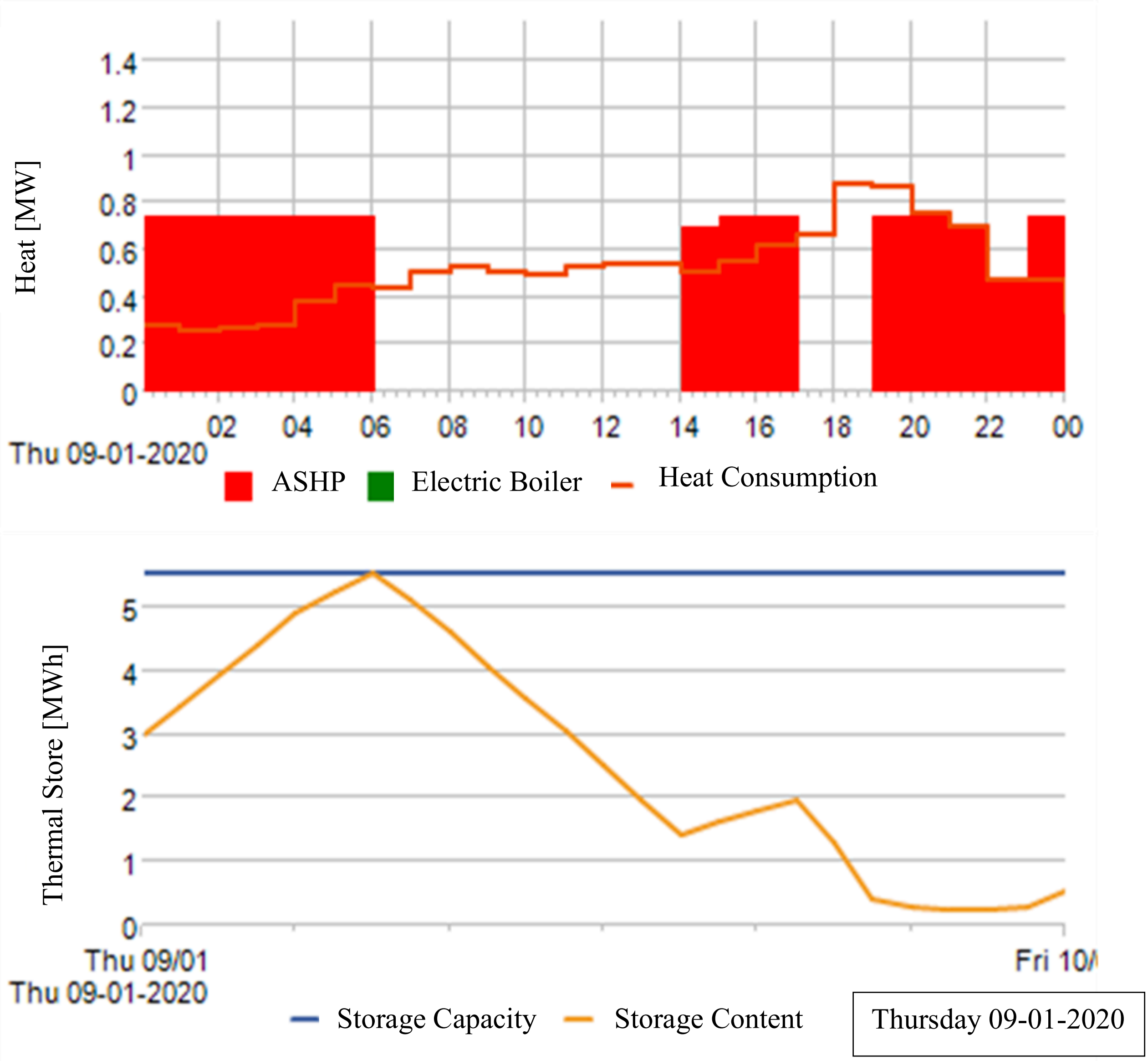


Figure 21: Scenario 1, thermal operational graphs in winter

The operational strategy shifts in summer when demand is lower. The ASHP is used to fill the thermal store during the low demand tariff hours at night. This is then released throughout the day to cover the period when electricity prices are at their highest. If the thermal store does not contain the energy to meet the entirety of the day demand then the ASHP will begin operation again. Figure 22 shows this process for a day in summer.

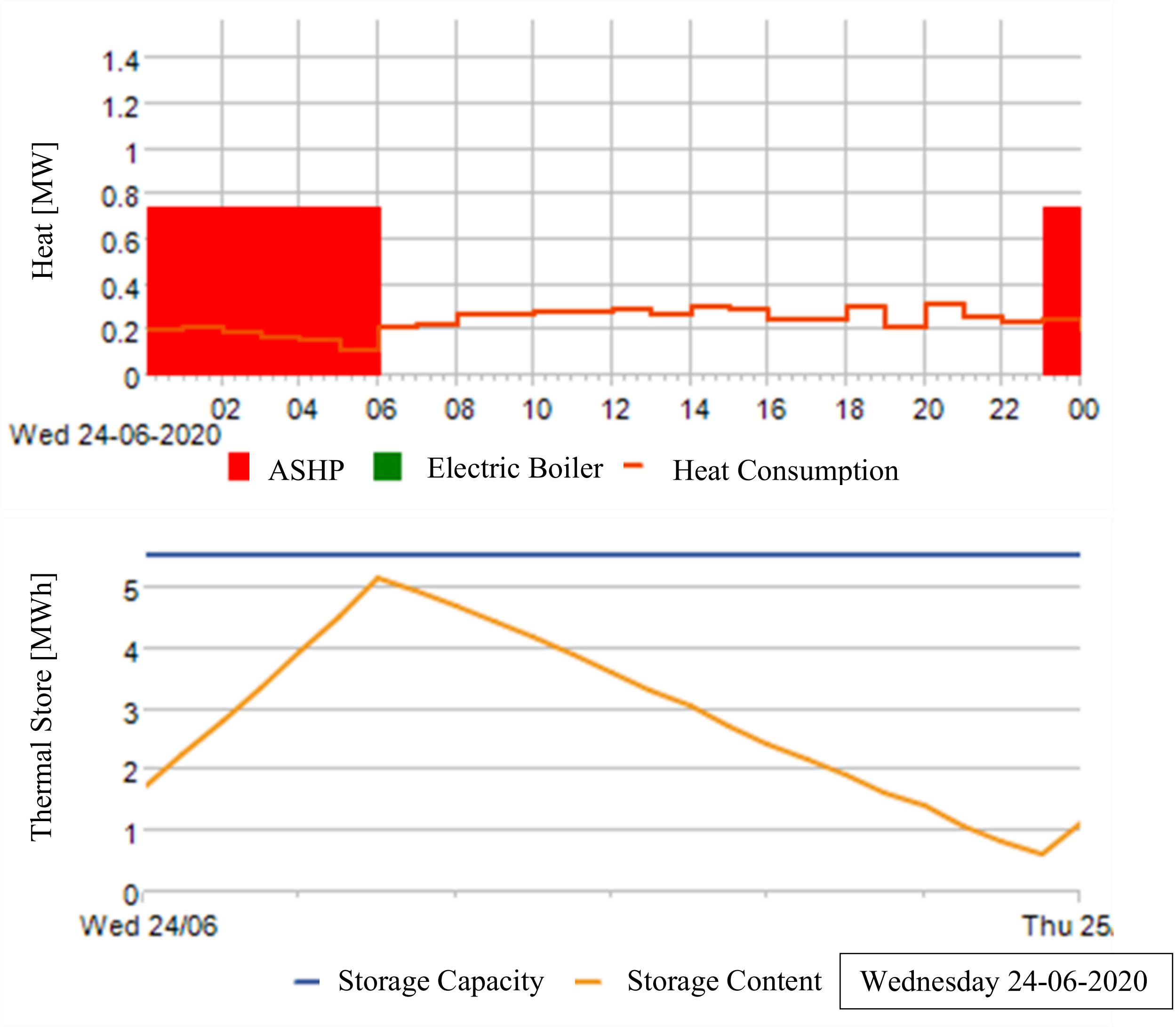


Figure 22: Scenario 1, thermal operational graphs in summer

Overall, the systems modelled in Scenario 1 offer the DHN an operating strategy that is similar to the current model; this being one system that satisfies most of the heating demand through incorporating thermal storage with a boiler system to meet spikes in the thermal demand. The difference between the two is the fuel used to operate these systems. The electricity used in this scenario would make the DHN far more environmentally friendly, but relies heavily on the ASHP and grid electricity is still not 100% renewable.

4.2.3 Storage Loss Analysis

To test the effect of either burying or exposing the thermal storage tank to the external temperature conditions 8 simulations were run that varied the external environment and the thickness of the insulation. These results are plotted below in Figure 23.

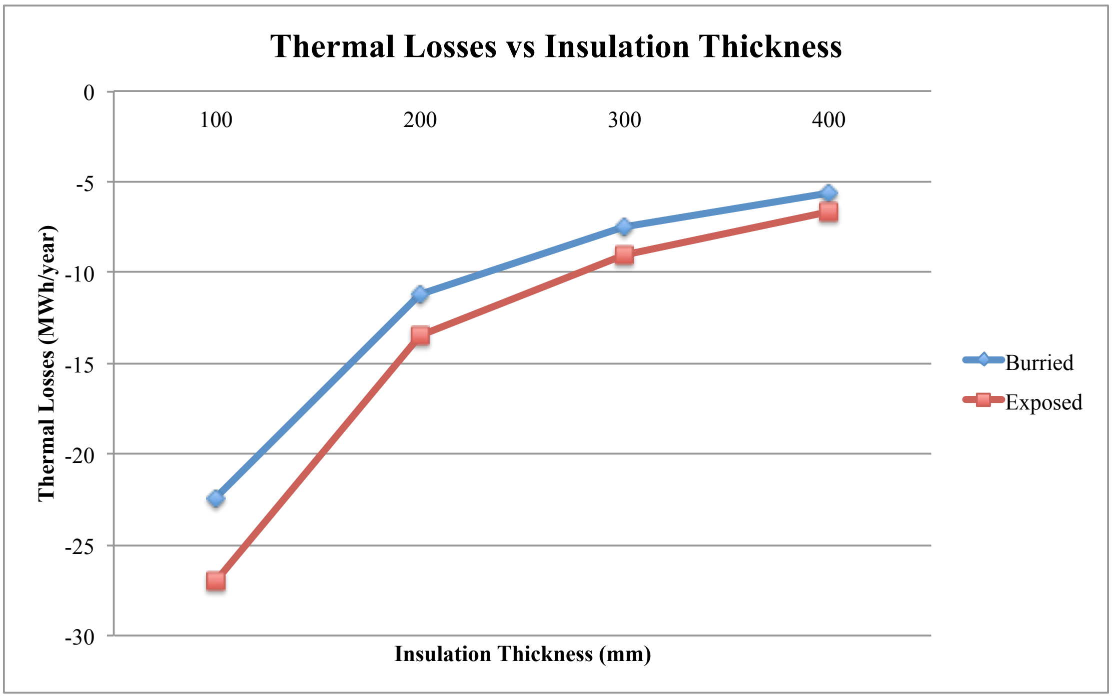


Figure23: Scenario 1, thermal storage analysis graph

The graph shows that there is little difference between the two environments when it comes to thermal losses, with the buried tank marginally more efficient. The change in thermal losses in relation to thickness is more pronounced on this chart. However, annually this accounts for very little energy saved. Excluding the results for 100mm, the difference in losses from 200mm to 400mm is 6MWh/year and 7MWh/year for buried and exposed tanks respectively. EnergyPRO's financial analysis determines that this makes a difference of £400 and £300 in respective annual operational costs for the entire DHN.

This analysis shows us that the external conditions and insulation thickness make little difference in terms of thermal losses, as long as the insulation is a minimum of 200mm. These figures are low and do not change as drastically as expected, suggesting potential inaccuracies in the software or external temperature data. The remainder of the modelling uses a buried thermal tank with 300mm thick insulation.

4.2.4 Financial Analysis

Figure 24 shows the operation costs as calculated by EnergyPRO. As the operational results have shown earlier, the trajectory shown by the 250kW ASHP further proves that the system is not viable as it is far costlier than the others. It also shows that thermal storage, which gives the DHN the ability to utilise cheaper electricity tariffs at night, has an initial drastic effect on the operational costs but then begins to plateau. Scenario 1 offers a base operational cost that can be improved upon in subsequent scenarios through the addition of different heat or electricity producing components.

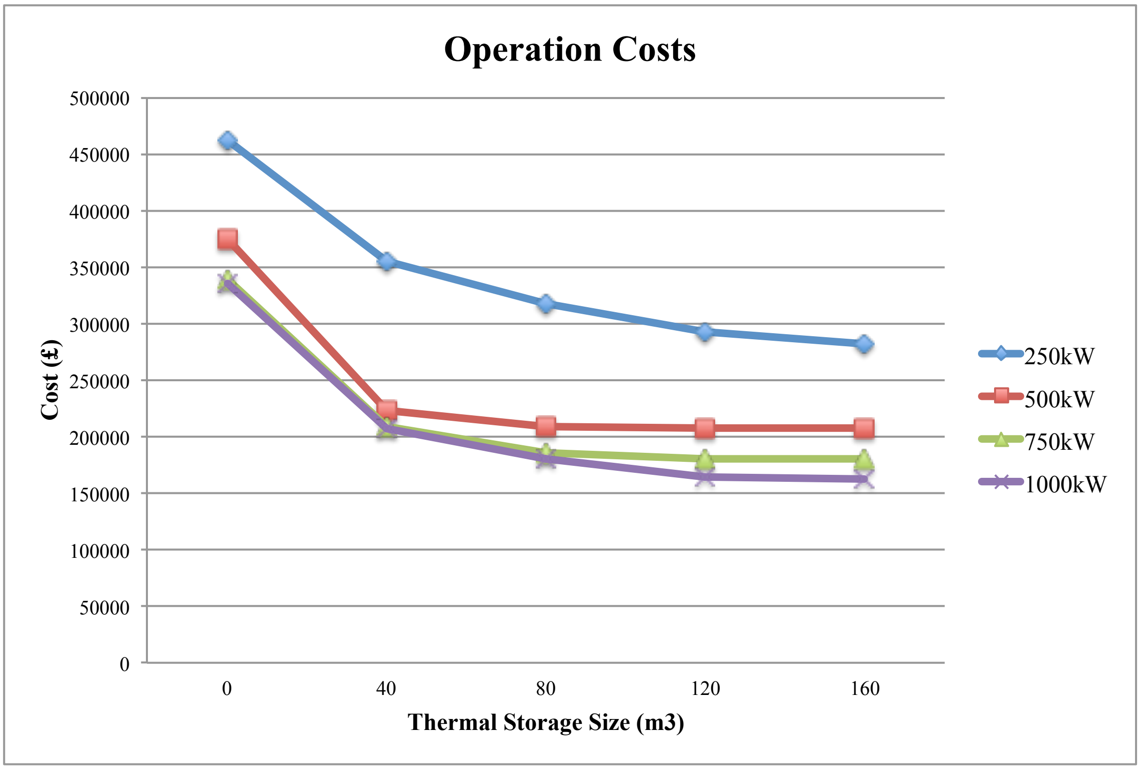


Figure 24: Scenario 1, operational costs graph

4.2.5 Environmental Analysis

As previously stated, the only carbon in a fully electrified system comes exclusively from the grid. Therefore, as the Scottish electricity grid is increasingly less carbon intensive so will a DHN that uses it exclusively for energy. Figure 25 shows the annual CO_2 output in tonnes for the DHN, the base scenario has been outlined previously and the other systems plotted all have a 120m^2 thermal store, the variable factor being ASHP capacity. Through switching to a fully electric system that runs off of the grid, CO_2 output is massively reduced from the 1525 tonnes that the base system produced. There is a slight increase in CO_2 between the 750kW and 1MW ASHP system of 2 tonnes, which goes against the decreasing trend. This could simply be an error in the modelling software or caused by increased storage losses inherent with a higher capacity ASHP. The increase in storage losses from each size of ASHP increases by approximately 1MWh for every 250kW increase in capacity.

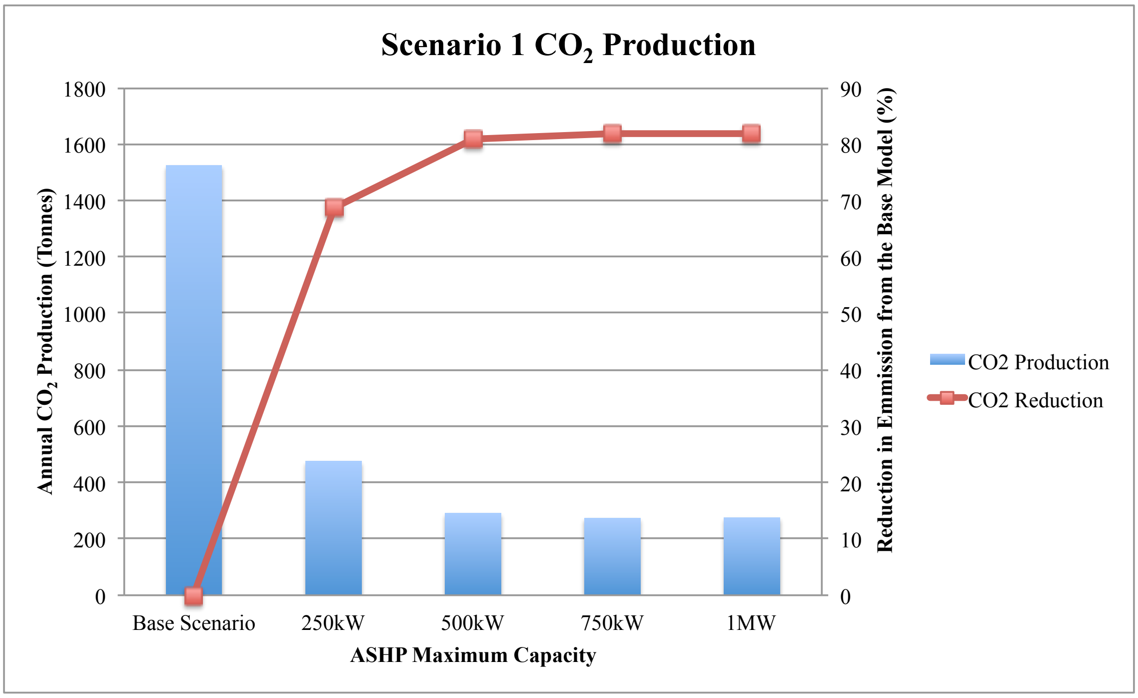


Figure 25: Scenario 1, environmental analysis chart

This analysis shows that Scenario 1 offers a more environmentally friendly way of providing thermal energy for the DHN, with the CO_2 decreasing by 1234 tonnes and plateauing around 291 tonnes which is the 750kW ASHP capacity. This suggests that a 1MW capacity ASHP adds no real improvement for this performance indicator and may even be detrimental.

4.3 Scenario 2: Solar Photovoltaics and Electrical Storage

The results for Scenario 2 outline the impact of adding PV panels with varying installed capacity as well as a battery for electrical storage. The results shown all use a model with a 750kW ASHP coupled with a 120m^2 thermal store, with an electric boiler as a back up. The external, financial and environmental conditions are all uniform with Scenario 1. Selected raw data from EnergyPRO used in Scenario 2 analysis can be found in Appendix B.

4.3.1 Operational Strategy

The first solar energy additions were PV panels; the installed capacity was varied to determine the effect they would have on the operational strategy. The operating strategy is outlined in the figures below and the system schematic is shown in Figure 26.

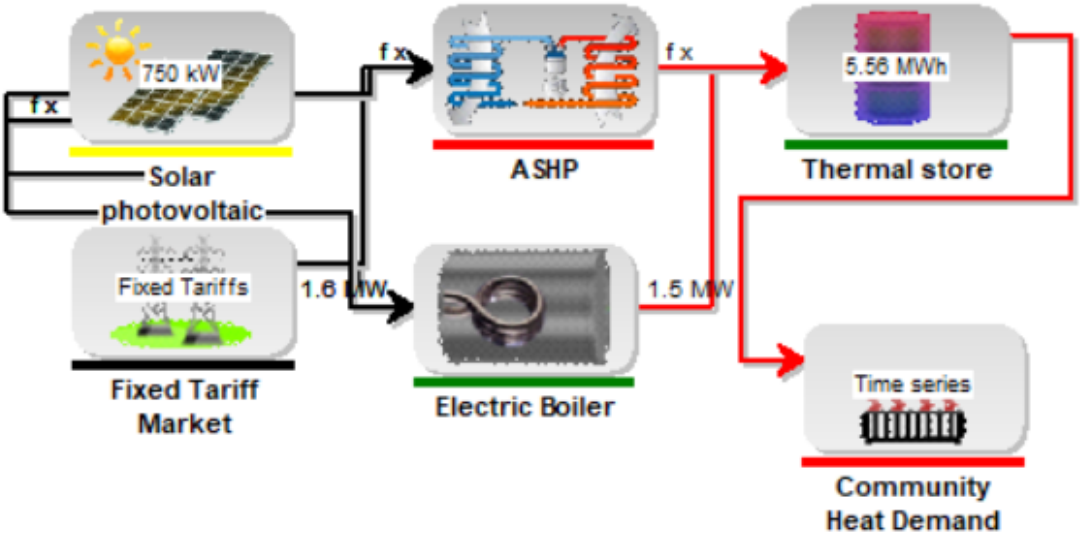


Figure 26: Scenario 2, system schematic

The operating strategy for this model shows us that the most cost effective way to incorporate PV into the existing model is to sell a portion of generated electricity to the grid and use the remainder as a free energy boost for the DHN. The proportion of electricity that is exported or used by the DHN changes when installed capacity varies. This is shown in Figure 27, with the 1MW installed capacity system exporting the highest share of electricity generated. This is because with no electrical store, the surplus energy must be sold or risk being wasted. This is the optimal operating strategy as the cost of importing in this system is higher than potential monetary gains from exporting.

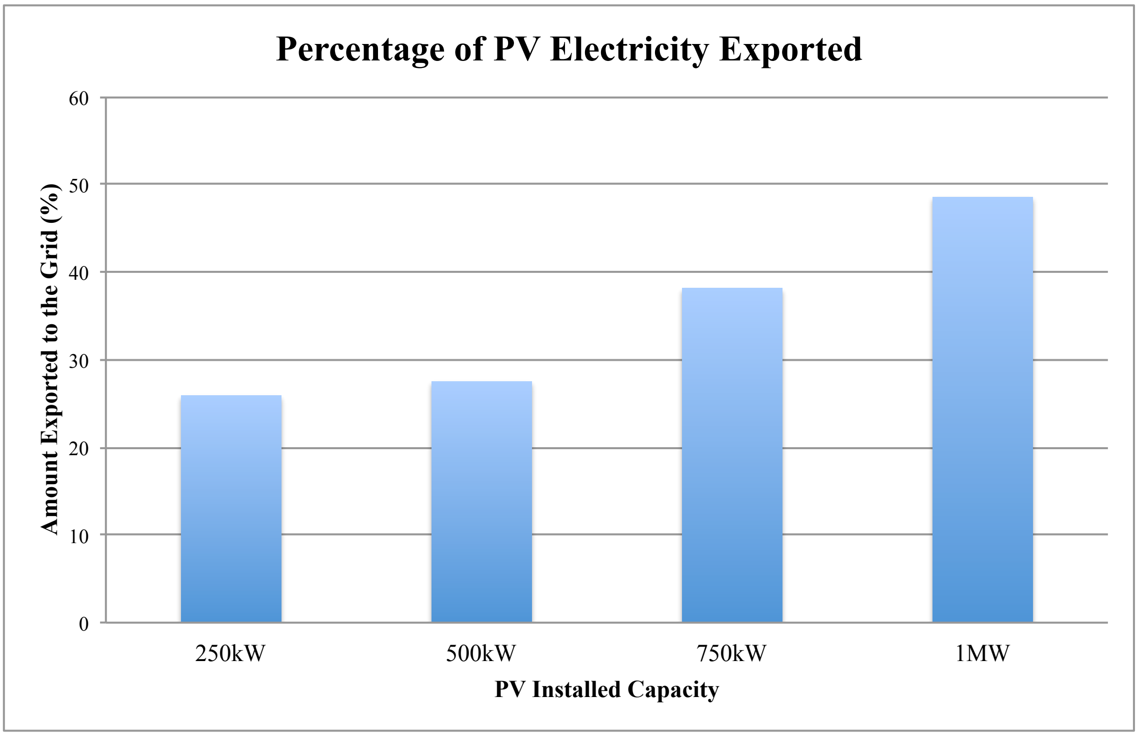


Figure 27: Scenario 2, exported electricity

Figure 28 consists of the operating strategy graphs for this scenario during a day in summer where the majority of heat is generated by the ASHP using night tariff electricity. This time of year was chosen as it best represents the impact that solar energy would have on the system due to the longer daylight hours. The installed capacity for PV panels in Figure 28 is 1MW. This is visualized by the PV production in the electricity graph not corresponding with the operation periods of the ASHP as seen in the thermal graph in Figure 28. This shows a day in which the majority of thermal demand can be met through stored heat generated using night tariff electricity. Therefore, electricity generated by PV is mostly sold to the grid.

This is visualized by the PV production in the electricity graph not corresponding with the operation periods of the ASHP as seen in the thermal graph in Figure 28. This shows a day in which the majority of thermal demand can be met through stored heat generated using night tariff electricity. Therefore, electricity generated by PV is mostly sold to the grid.

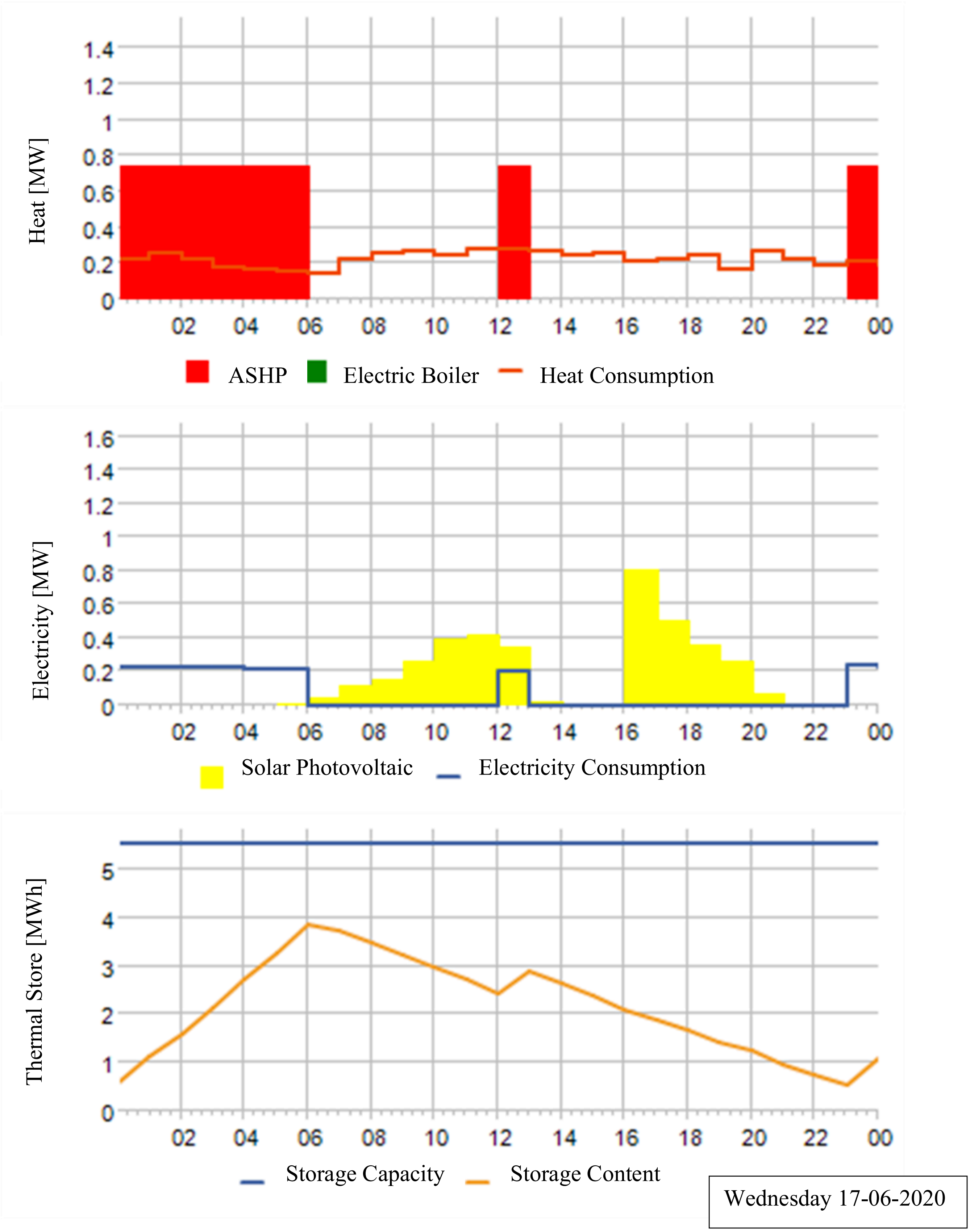


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Figure 28: Scenario 2, operational graphs

Besides the generation and selling of PV generated electricity, the graphs in Figure 28 show that the DHN in Scenario 2 operates in much the same way as Scenario 1 – cheaper night tariffs are used to fill the thermal store which is released during higher demand periods. During the day shown, the ASHP is only required to be switched on for an hour of peak time electricity, between 12:00 and 13:00, as shown in the thermal graph. This was done in order to meet the thermal demand for the rest of the peak electricity period of the day. This switching on corresponds with an electric consumption uptick during the same periods. However, this is shown to be covered by the PV generated electricity, thus avoiding the higher price of grid electricity at that period of the day.

Conversely, colder and darker periods of the year have a similar operating strategy as the Scenario 1 for the same time of year. This is because the PV generates less electricity, so most is imported from the grid. However, the energy that is generated in this period is most often used within the DHN to avoid higher costs during the day; this results in the near 50 – 50 split in PV electricity being used by the DHN and exported as shown in Figure 28. The electric boiler is only ever used when the ASHP and thermal store cannot meet spikes in demand or when the ASHP is not operating on scheduled maintenance days.

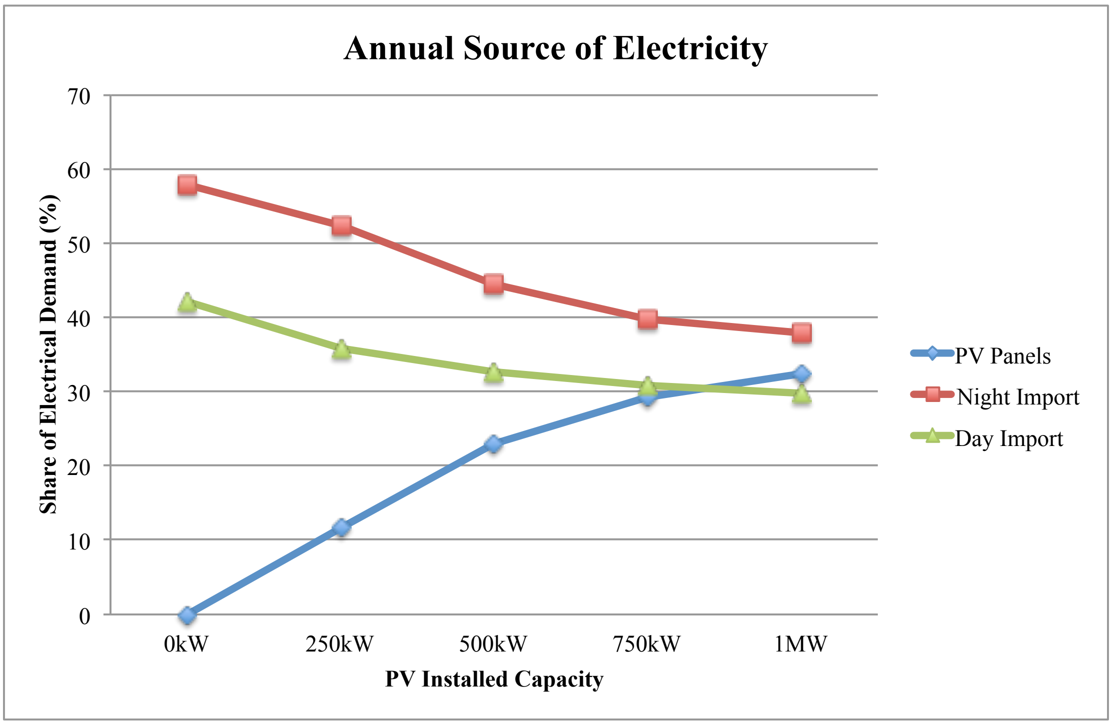

Figure 29: Scenario 2, sources of electricity used by the DHN

Figure 29 plots the share of electrical demand met by on-site PV, night tariff grid imports and day tariff grid imports. As expected, it shows an increasing share covered by PV as installed capacity increases. This lowers the overall share of imported electricity. Both the day and night imports are decreased. The decrease in peak demand imports begins to plateau around 30%; the main reason for this is the lack of electrical storage in the system.

4.3.2 Electrical Storage Addition

Whilst the PV panels reduced the electricity taken from the grid, the operating strategy for Scenario 2 highlights that a greater share of electricity generated on-site can be used by the DHN if a way to store it is added. This scenario outlines the addition of electrical storage to the system outlined in Scenario 2 - the battery specifications are contained in Table 9. The battery was added to the 1MW installed PV capacity model.

Figure 30 shows the thermal operational strategy graphs for Scenario 2 with battery addition. The graphs are plotted over two days in summer to fully show the charging and discharging cycle of the battery during a peak production period of the year. The strategy is to run the ASHP using free, CO2 free electricity produced by the PV panels, with excess heat production stored for periods with insufficient solar radiation.

When these graphs are compared with the electrical operational graphs for the same day (Figure 30), there is a correlation between the periods of ASHP and when output from PV panels is highest. The PV panels provide the energy used to heat the DHN with the surplus being stored, with any remaining electricity being sold to the grid. This strategy is shown in the PV battery energy graph in Figure 31. This graph also shows the battery is discharged to power the ASHP later in the day, which satisfies thermal demand and refills the thermal store.

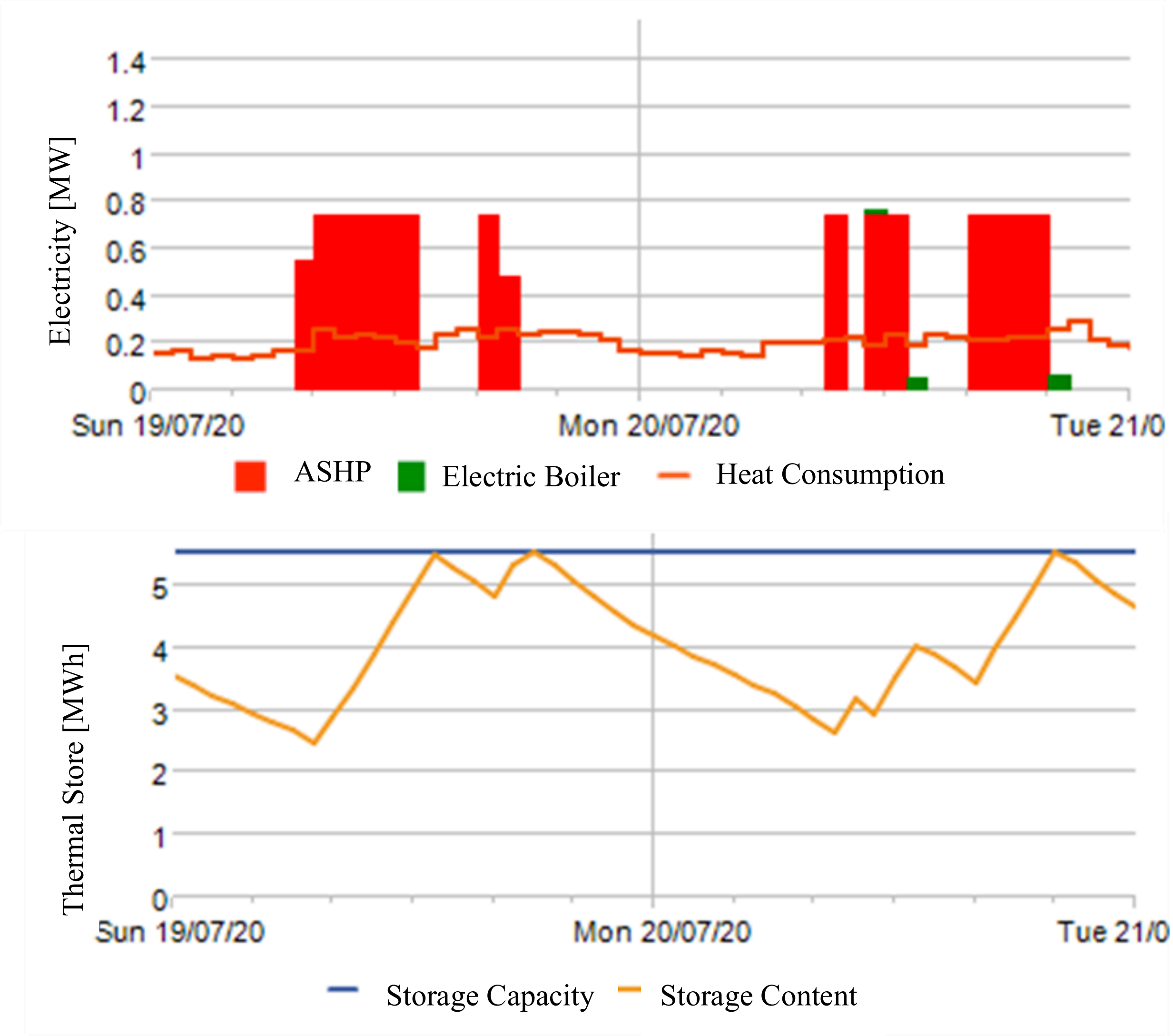

Figure 30: Scenario 2, thermal operational graphs with electrical storage

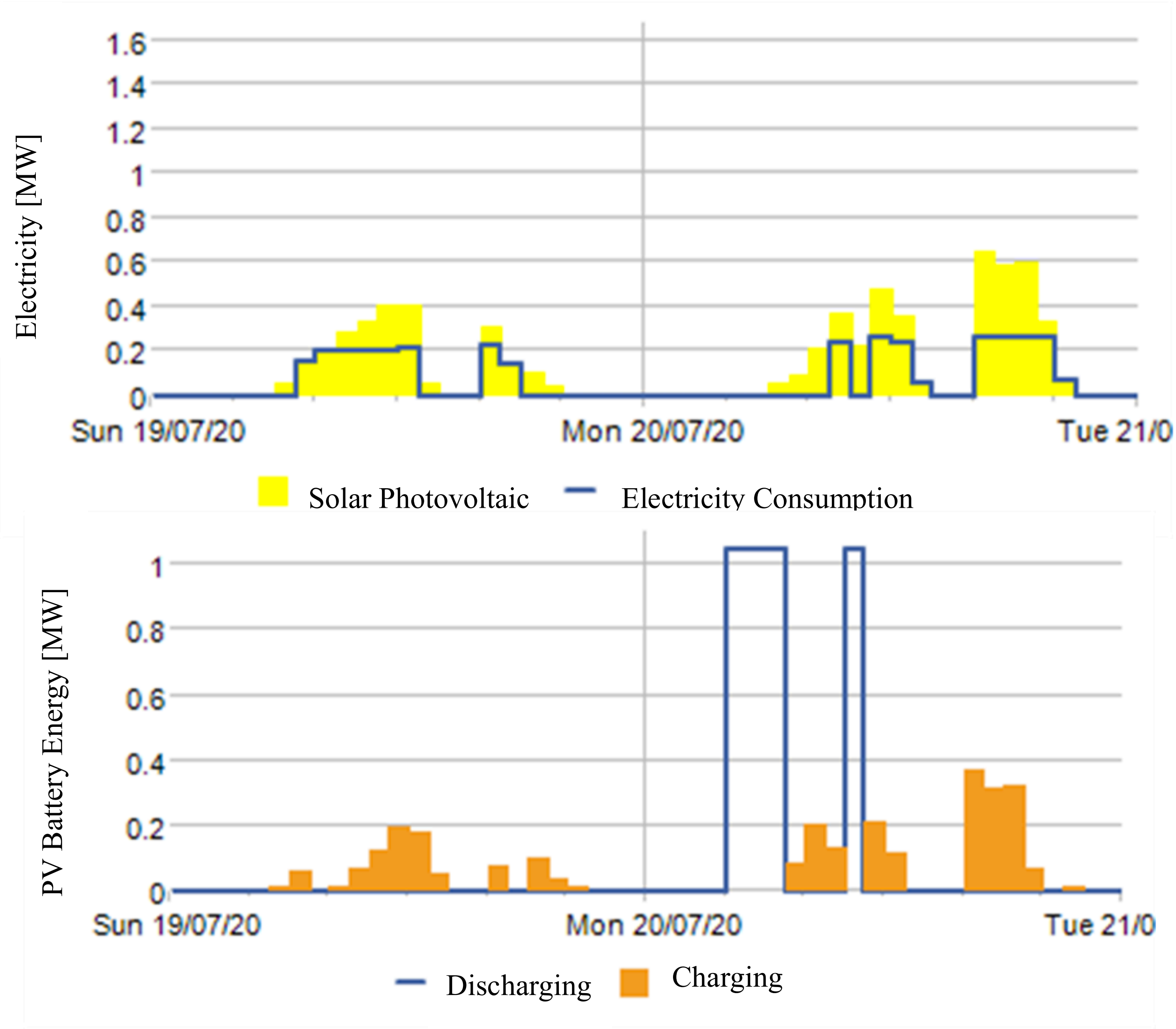

Figure 31: Scenario 2, electrical operational graphs with electrical storage

Overall, the addition of electrical storage to the Scenario 2 model changes the operational strategy of the DHN. Instead of all excess electricity being sold to the grid it is instead stored. This provides the DHN with a cleaner, cheaper source of electricity that can be used to operate the ASHP during periods of no PV output instead of opting for grid imports. Conversely, in winter the PV output is so much lower that the battery does little in the way of reducing the quantity of electricity imported from the grid.

4.3.3 Financial Analysis

The operational cost graph below, Figure 32, shows the approximate savings that can be made when PV is installed. The 0kW capacity system figure is taken from Scenario 1. Ultimately, savings are proportional to installed capacity (as expected) and are therefore dependent on the amount of free space and capital to purchase the panels. Additionally, these results show us that through allowing the excess electricity produced to be stored in an on-site battery more operational savings can be made. However, this would add to the capital cost and batteries have a shorter life cycle than the panels themselves, so they would have to be replaced several times.

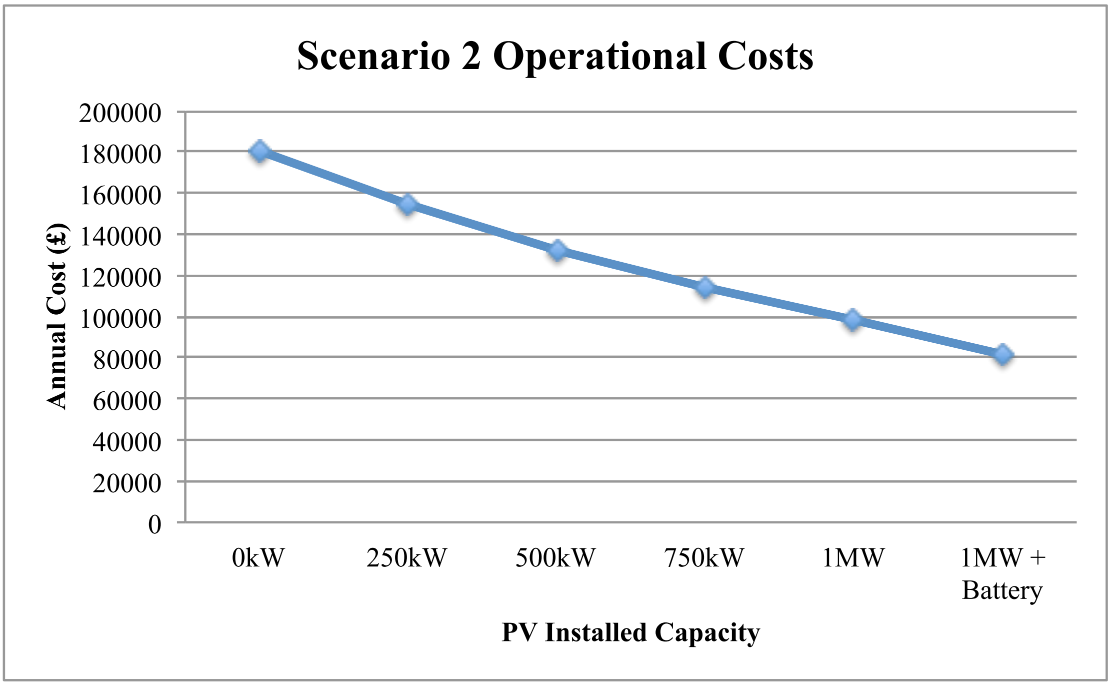

Figure 32: Scenario 2, operational costs graph

4.3.4 Environmental Analysis

Figure 33, the environmental graph for Scenario 2, contains a bar chart of annual CO_2 output and a line graph showing the percentage reduction compared to the base model. Like Scenario 1, the only CO_2 produced in these simulations is from the grid. As such, the more clean electricity produced by the PV panels that is used by the DHN the more environmentally friendly the system is.

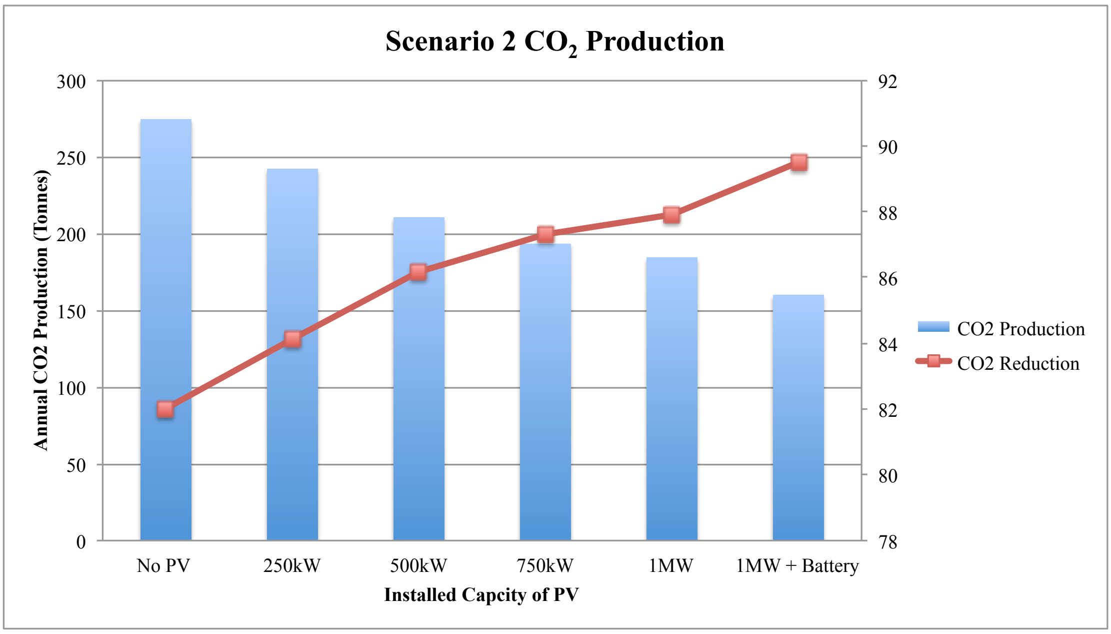

Figure 33: Scenario 2, environmental analysis chart

The graph shows that the PV panels build on the CO_2 reductions achieved by the combination of ASHP and thermal storage in Scenario 1, although not by a lot. The addition of 1MW capacity of PV reduces CO_2 by a further 6% compared to the same ASHP and thermal store combination without PV. The added battery storage allows for a greater amount of the on-site electricity to be used increasing this reduction to 8%, achieving a total of 90% reduction in CO_2 compared to the base scenario.

4.4 Scenario 3: Solar Thermal Collectors

Solar thermal collectors provide hot water for the DHN rather than electricity to power the heat pump or electric boiler. Like PV panels, they operate exclusively during the day when electricity demand and price is high. In this scenario they can produce heat to store and have the highest priority of any component for the operation strategy calculation. The effects of array shading were added for simulations that had 2000m^2 and 2500m^2; this accounts for the shading effects resulting from less space between each FPSC. The approach here was to run simulations with differing areas of flat plate solar collectors and assess the impact their installation would have in reducing imported electricity. Selected raw data from EnergyPRO used in Scenario 3 analysis can be found in Appendix C. Figure 34 shows the system schematic for Scenario 3.

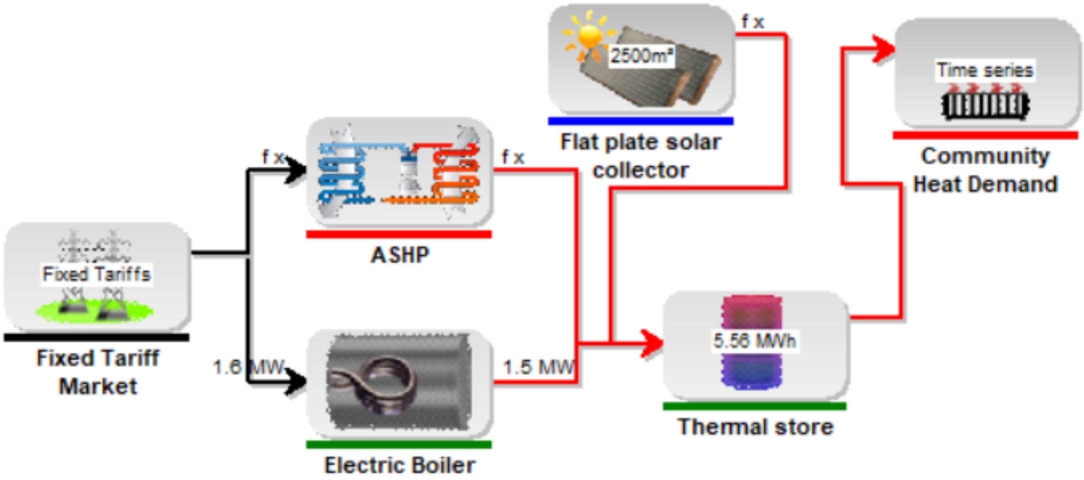

Figure 34: Scenario 3, model schematic

4.4.1 Operational Analysis

Figure 35 shows the annual source of heat for each varying area of FPSC alongside a control simulation that only used an ASHP and boiler. As the FPSC's share of the thermal demand increases, the demand met by the ASHP decreases in unison. This is desirable for a system aiming to achieve net zero emissions as it provides heat with no inherent operational carbon content unlike the ASHP using electricity from the grid. However, as with PV, the share of annual heat demand that FPSC can satisfy is limited by both available space and seasonal variations in solar irradiance.

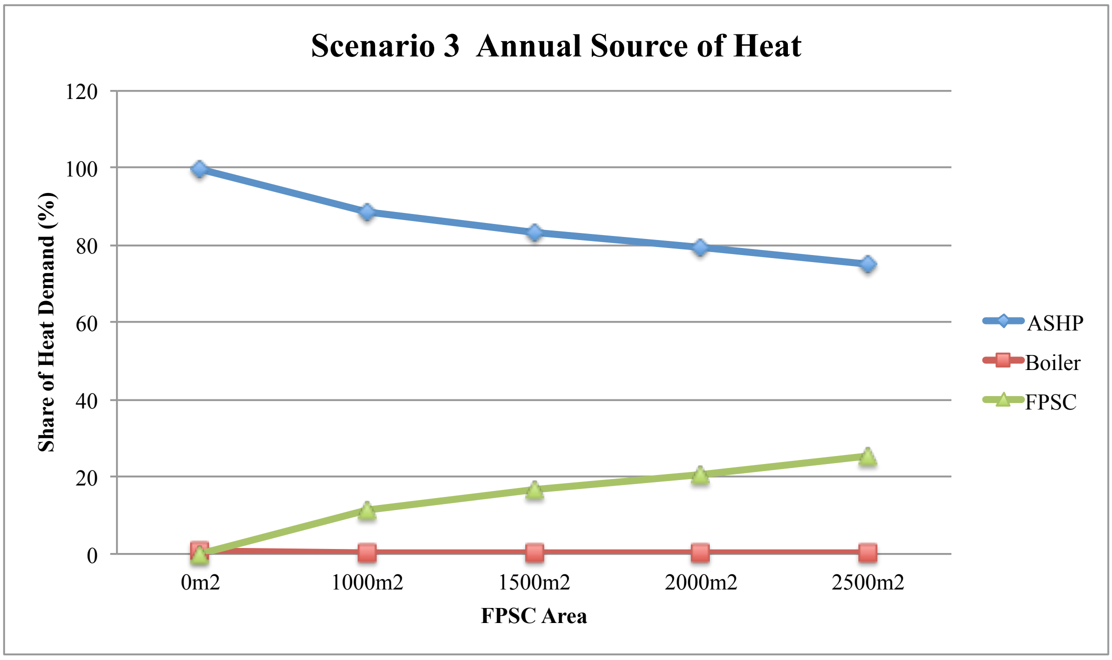

Figure 35: Scenario 3, annual source of heat for the DHN

Figure 36 contains the operational strategy graph for a day in summer, when the FPSC generates the most heat. The thermal graph shows that the ASHP primarily uses cheaper night tariff electricity to overproduce in order to meet demand and fill the store. The heat generated by the FPSC is used to top up the thermal store during the day, thus avoiding peak prices. The thermal energy produced and stored by the FPSC is used to great effect in summer as the DHN can use these stores to satisfy heat demand until the morning. This means less imported electricity, which increases savings and decreases the CO_2 production. The period of no production between 13:00 and 16:00 potentially reflects an error in the solar irradiance data.

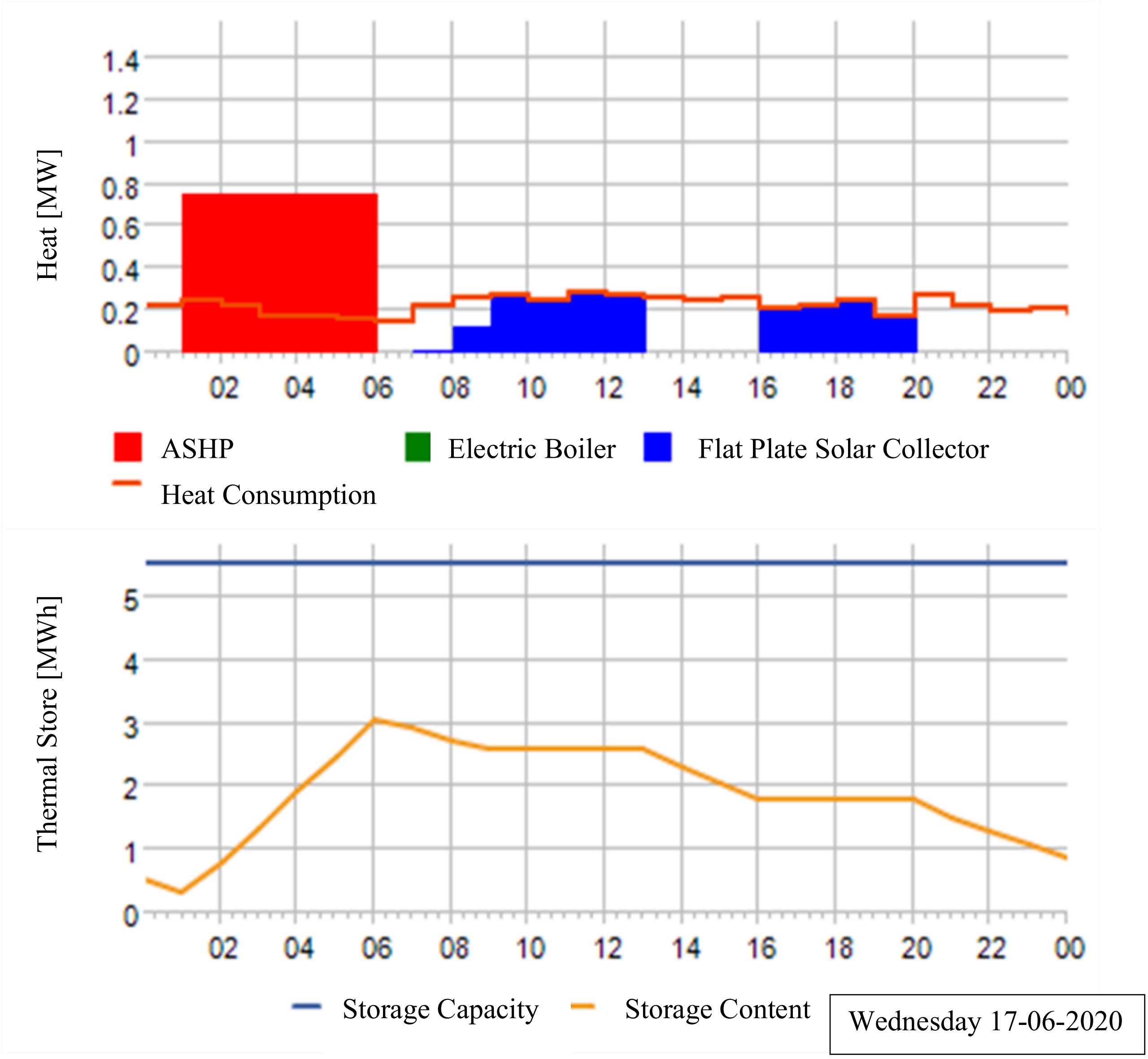

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Figure 36: Scenario 3, operational strategy graphs, day in summer

Figure 37 shows the same scenarios operation strategy but for a day in winter. Here the FPSCs provide very little heat so the DHN is mainly heated by the ASHP, which is in operation for a much longer portion of the day. Again, there is a gap in the middle of the day with no output from the FPSCs; the ASHP picks up the subsequent slack in satisfying the thermal demand. Overall, the FPSCs do very little in the winter, with the DHN mainly using cheap electricity to fill the store in order to use the energy to smooth out peaks in demand, similar to Scenario 1. The FPSCs are merely used for auxiliary heat.

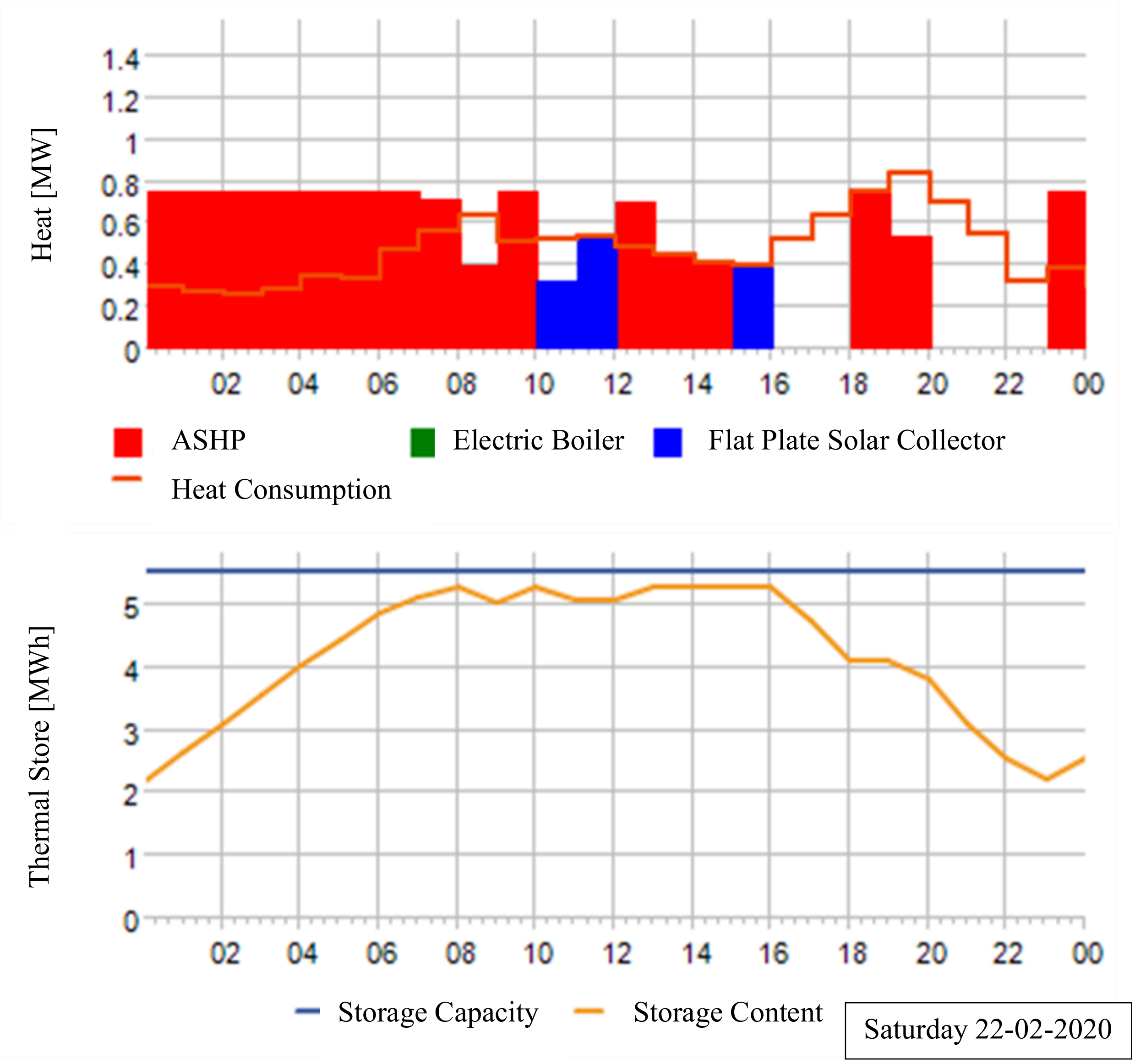

Figure 37: Scenario 3, operational strategy graphs, day in winter

4.4.2 Financial Analysis

As shown in Figure 38, the addition of FPSCs would provide a decrease in the annual running costs for the DHN. The savings made in this scenario derive from less electricity being imported, as there is less demand on the ASHP and boiler to produce heat courtesy of the FPSCs. However, it does not offer the same level of operational savings as Scenario 2. The PV panels have the potential to bring operational costs below £100,000, especially with electrical storage added on, whereas, the FPSCs reach a minimum operational cost of £140,000.

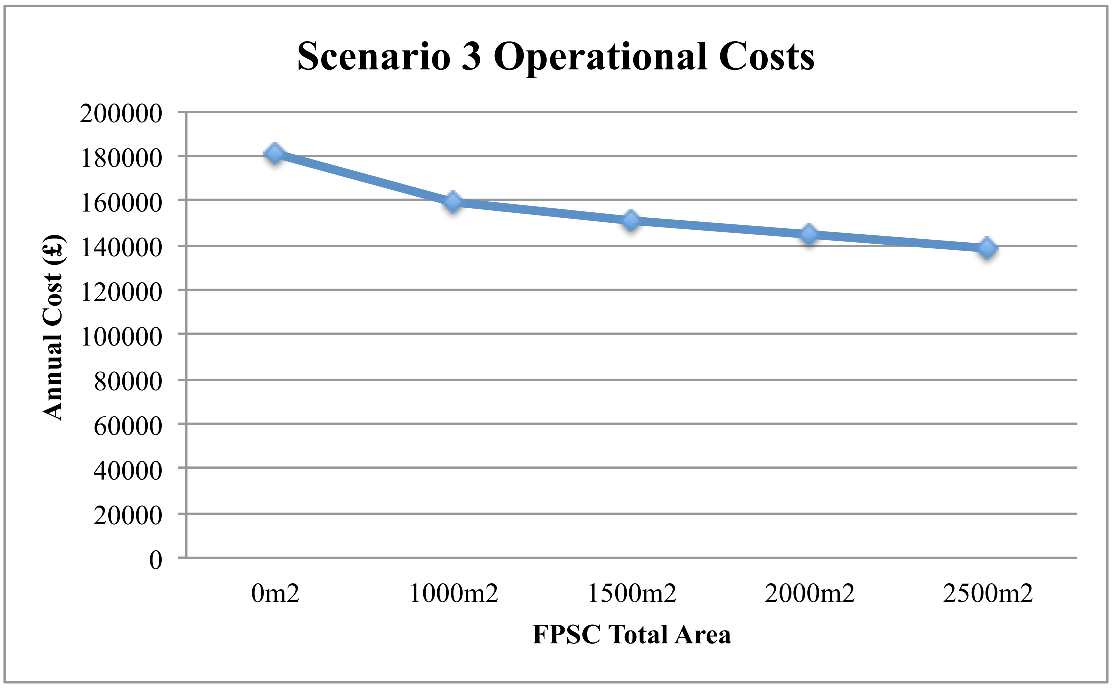

Figure 38: Scenario 3, operational costs graph

4.4.3 Environmental Analysis

The carbon produced in the operation of Scenario 3 comes solely from grid electricity. Therefore, the reduction in electricity imported, as a result of a share of thermal demand being met by the FPSCs, causes a reduction in the operational CO_2 production in the scenario. This is shown in Figure 39, where the annual CO_2 produced is plotted in tonnes on a bar chart alongside the percentage reduction from the base scenario this represents, in a line graph.

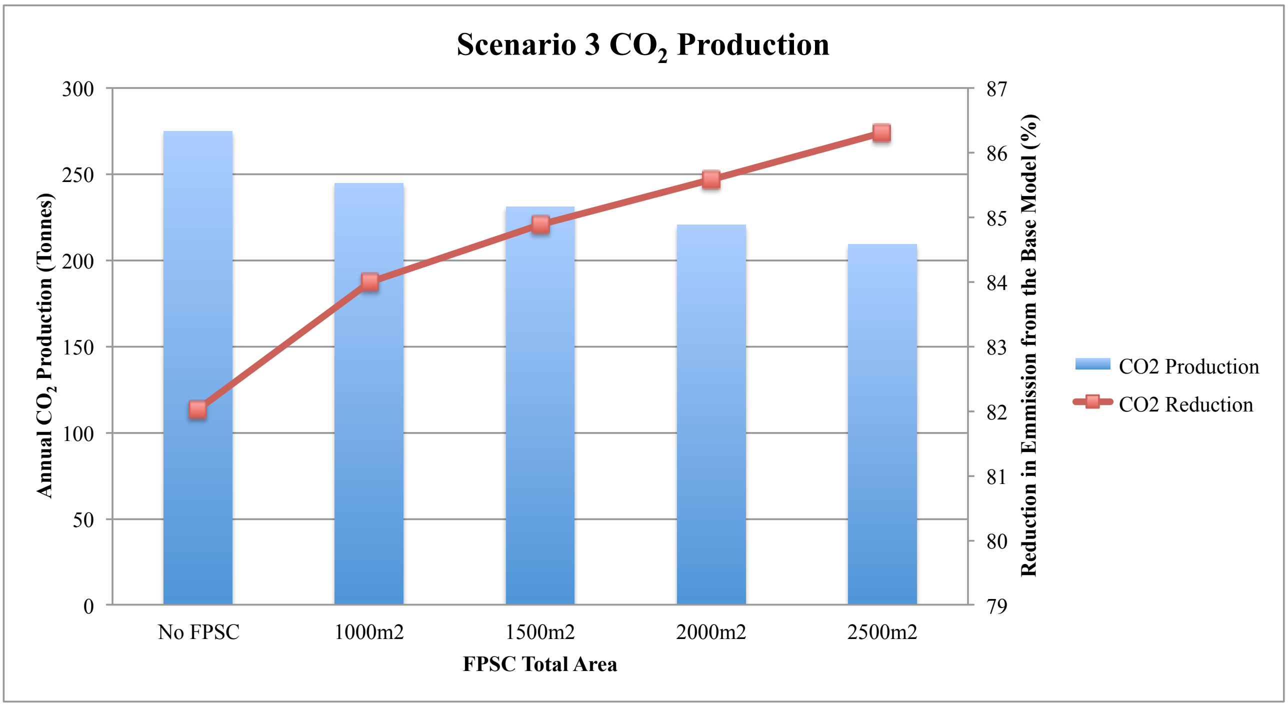

Figure 39: Scenario 3, environmental analysis chart

The reduction in CO_2 ranges between ranges between 10 and 15 tonnes for every 500m^2 of FPSC that is added to the system. The reduction amount is closer to 10 tonnes for the 2000m^2 and 2500m^2 due to the increased effects of array shading. The percentage of reduction from the base scenario that FPSC's offer is included to show the benefits of adding them. It shows that through adding 2500m^2 of FPSC the reduction in CO_2 from the base model is only 4%.

4.4.4 Scenario 4: Wind Turbine

Scenario 4 introduces a private wire connection to a nearby 3MW wind turbine on Cathkin Braes. The turbine specifications and feed in tariff payments are outlined in the methodology. The operational analysis focuses on Scenario 1 system configuration with the wind turbine as the main source of electricity and the grid merely a back up. Selected raw data from EnergyPRO used in the Scenario 4 analysis can be found in Appendix D. The system configuration is shown in Figure 40.

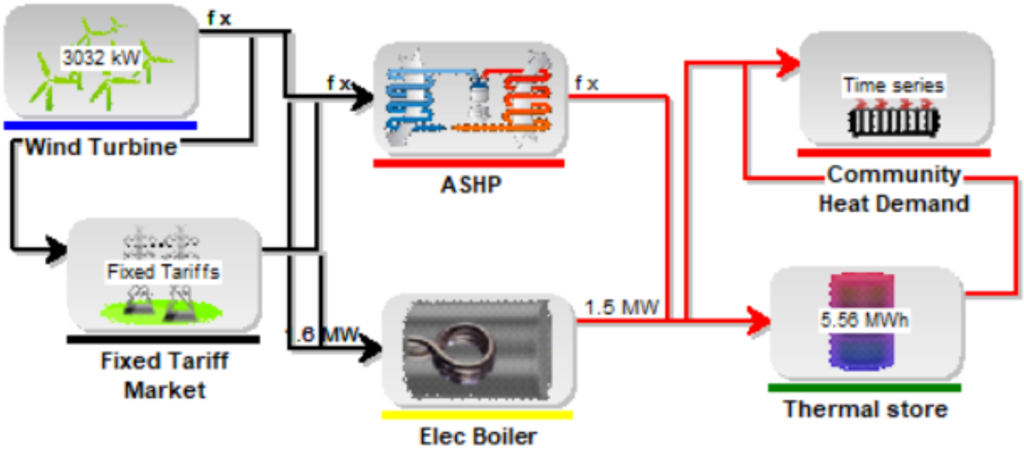

Figure 40: Scenario 4 model schematic

As EnergyPRO calculates the optimum operational strategy based on operational cost, the feed in tariff payments had to be unrealistically altered down to produce an operational strategy that is more likely to become a reality for this configuration. As such, financial analysis is not included for this scenario in as much detail as previous scenarios.

Environmental analysis involves comparing the CO_2 output from Scenarios 1, 2 and 3 with the wind turbine as the primary source of electricity. These results are compiled on the same format of graph as previous scenario results.

4.4.5 Operational Analysis

Figure 41 contains the operational strategy for Scenario 4, over a period of two days. The days chosen do not give an especially high electricity output from the wind turbine; however, they represent how the system would operate when there is no output. This is shown in the electricity graph, with electricity output reaching 1MW before decreasing to no output. Output then increases the following day as weather conditions change.

When the turbine is operating, the ASHP is over producing heat using the electricity generated. The excess heat is used to fill the store and excess electricity is sold to the grid. During periods of no electricity production the store reserve is emptied to satisfy the demand on the DHN. After the stored heat resource is exhausted the network will use electricity from the grid to run the ASHP to meet the demand.

The following day, when electricity production increases again, the ASHP works only to fulfil the demand on the network, using the thermal store a little to smooth a spike in demand later in the day. Through using the electricity produced to use the ASHP to satisfy demand and not fill the thermal store, the system can be more profitable by selling the excess electricity.

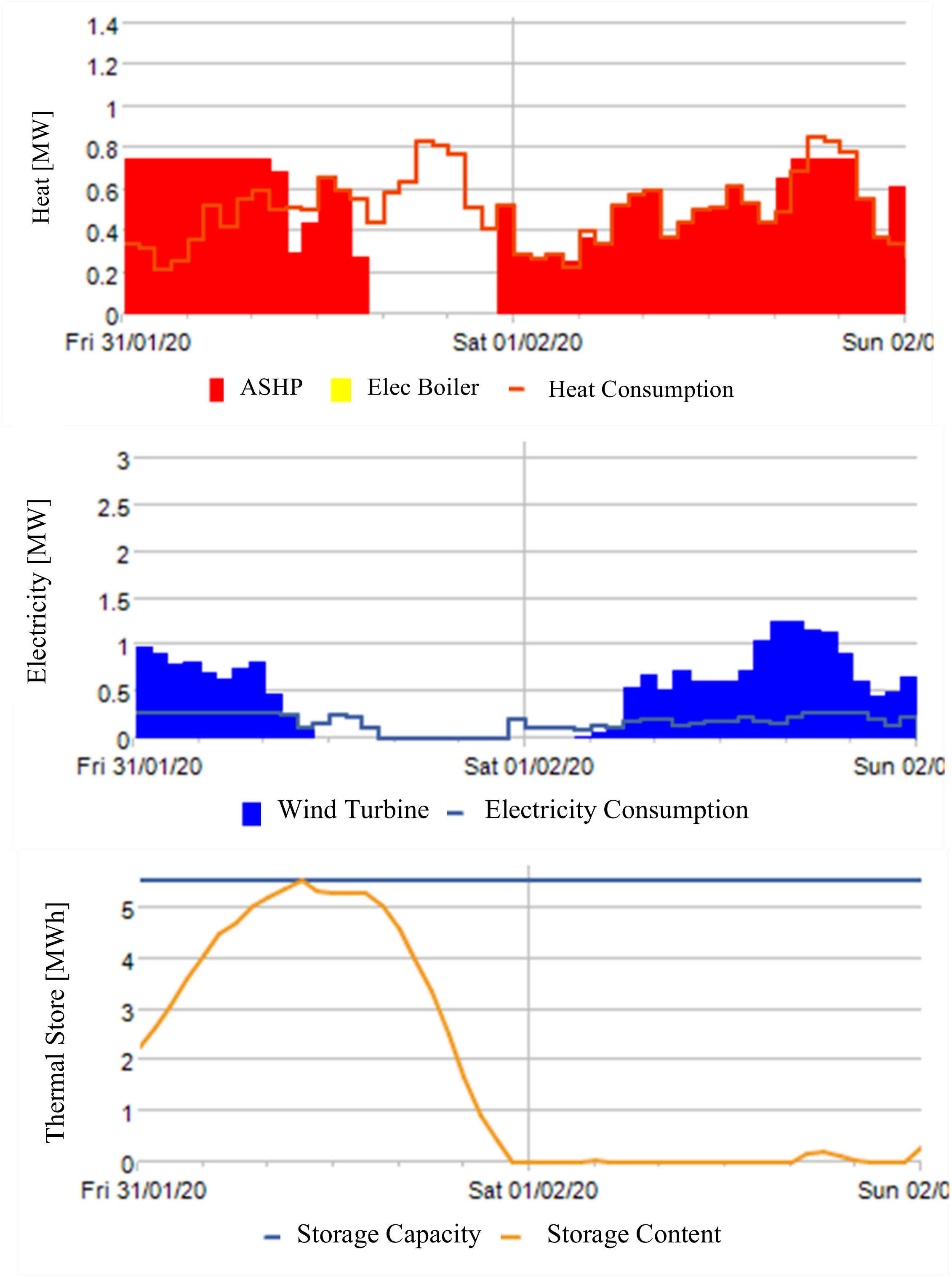

Figure 41: Scenario 4, operational graphs

4.4.6 Financial Analysis

The financial realities of the system are hard to accurately assess as they are based on the assumption that the owners of the wind turbine would agree for the installation of a private wire. This wire is in itself potentially very costly to put in place. If this scenario were to be implemented it can be assumed that the overall heating system would make a profit as most electricity produced would be sold to the grid with the rest used to operate the DHN.

4.4.7 Environmental Analysis

Similarly to previous scenarios, the only operational carbon produced in Scenario 4 comes from grid electricity production. The addition of a 3MW turbine comfortably supplies the majority of the DHN's electricity needs. This equates to most of the electrical demand coming from a completely carbon free resource.

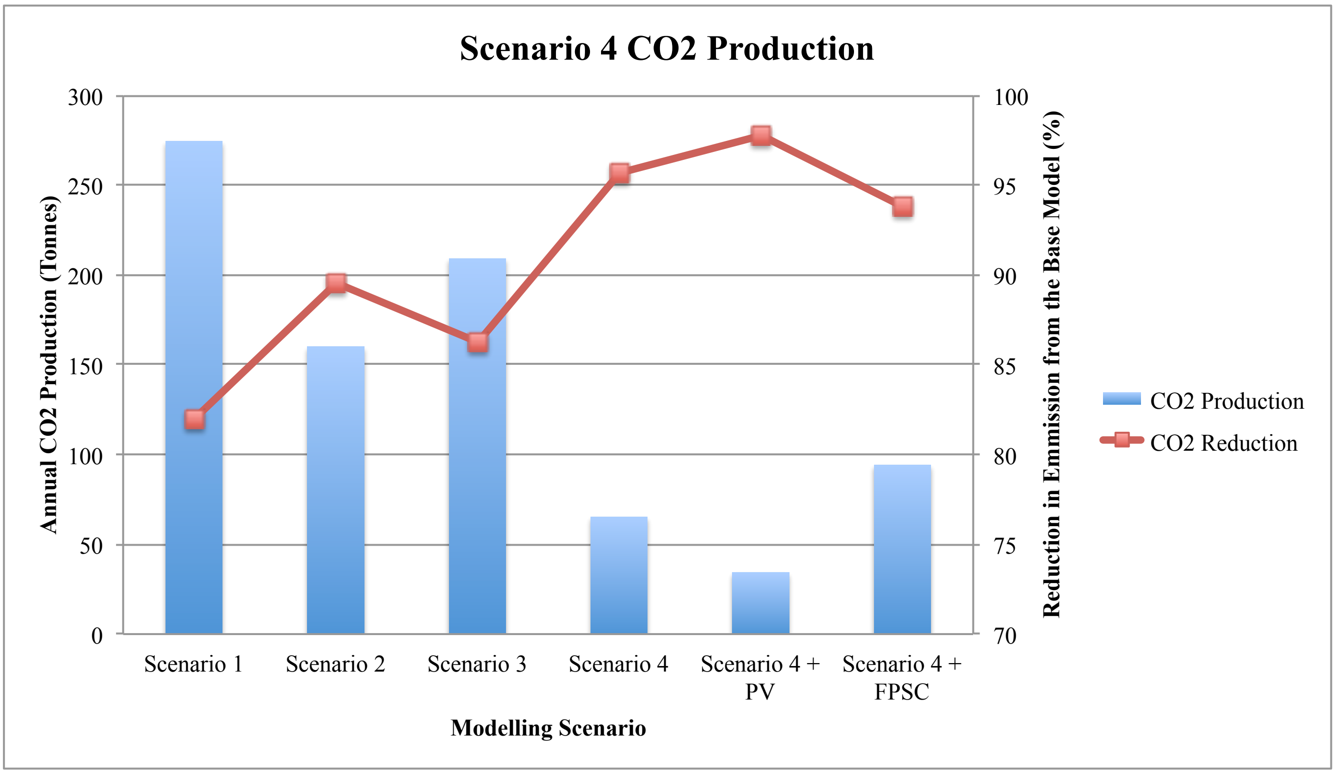

Figure 42: Scenario 4, environmental analysis chart

Figure 42 is the environmental graph for Scenario 4. It contains the CO_2 data for the previous 3 scenarios; the data is from the system configuration which showed the largest reduction in emissions. The other 3 data sets on the graph use the same system configuration with the addition of the 3MW wind turbine from Scenario 4. This graph shows that Scenario 4 further reduces the volume of CO_2 produced. However, when combined with 1MW output of PV from Scenario 2, the reduction in CO_2 from the base model levels reaches its peak of 97%. Conversely, when 2000m^2 of FPSCs are added to Scenario 4 the volume of CO_2 increases. This may be caused by the FPSCs not producing much heat for the DHN when turbine output is low, meaning the DHN has to rely more on grid imports. It could also be caused by an anomaly in the EnergyPRO's operational strategy calculation.

5 Conclusion

In this section the findings that can be extrapolated from this thesis are summarised and the report concluded. Additionally, the limitations of this report are outlined and possible directions for future analysis are summarised.

This thesis aimed to analyse an existing DHN with a view to decarbonising the heat supply method. Different system compositions were modelled to analyse how they would operate at different points in the year, meeting the first two objectives of the thesis; to evaluate the different methods of supplying heat to the DHN and determining their impact on the operational strategy calculated by EnergyPRO. In conjunction with this, the volume of CO_2 that these new systems produced was compared against the existing DHN to determine the potential carbon savings. This satisfies the last of the three objectives set out in this thesis - to assess the environmental impact the modelled scenarios would have, focussing on carbon reduction rates.

The conclusions drawn from Scenario 1 are that the combination of an ASHP and thermal store has the potential to meet the needs of the DHN with minimal back up from an electric boiler. Additionally, by changing the fuel from gas and biomass chips to grid electricity, the volume of CO_2 produced by the system can be reduced by as much as 82%. This system allows for an operational strategy that utilises as much low cost electricity as possible by overproducing heat at night to be stored and released during the day.

Scenarios 2 and 3 show that gains in CO_2 reduction from Scenario 1 can be built upon through the addition of PV panels and FPSCs. These systems utilise solar energy to reduce the amount of imported electricity or the amount of electricity used altogether. The results from these scenarios show that while both reduce CO_2 and operational cost to a lower level than Scenario 1, PV offers a more substantial reduction in both these categories than FPSCs. However, both are ultimately limited by available space within the grounds of WWHC. This is a wider issue with harnessing solar energy for use in DHN, particularly in urban areas.

Scenario 4 showed that a private wire to the nearby wind turbine at Cathkin Braes would both change the way the system operates and reduce the volume of CO_2 produced to its lowest level of just 65 tonnes of CO_2, representing a 96% decrease in emissions compared to the existing system. The energy produced from the turbine is enough to satisfy the majority of the electrical demand of the DHN with the remainder exported to the grid. During periods in which wind output is low, the operational strategy reverts back to Scenario 1, using cheap imports where possible in conjunction with the store to operational costs. The draw back for this scenario is the assumption that a private wire could be implemented.

The results gathered in this report suggest the need for a smart DHN control system to be implemented. This would incorporate weather and demand forecasting to better understand which periods of the year would require thermal energy to be overproduced and stored to meet demand or if electricity can be sold to the grid. This applies to all scenarios but is particularly pertinent for Scenario 4 as wind turbine output varies throughout the year.

Overall, the DHN at WWHC has the potential to be almost completely decarbonised through changing the way thermal energy is supplied whilst maintaining a workable daily operational strategy in both summer and winter. The different scenarios have varying qualities, with the lowest annual CO_2 output coming from Scenario 4 combined with the PV in Scenario 2. However, the impracticalities of implementing the private wire required for Scenario 4 means that Scenario 2 is best placed to decarbonise the DHN at WWHC. The combination of an ASHP and onsite PV with thermal and electrical storage offer the most efficient and realistic system for decarbonising the DHN. In conclusion, this thesis constitutes a necessary step in tackling the climate crisis and shows that ambitious government targets to reduce the CO_2 inherent in our heating systems can be viably achieved using DHNs that are supplied from wholly renewable sources.

5.1 Limitations

Many of the limitations of the study are outlined in the assumptions section of the methodology chapter. However, an additional limitation of this study is that EnergyPRO calculates an idealised operation strategy based on the operational costs of the model. Whilst this is fine for a first look at solutions for decarbonising the DHN at WWHC, in practise these models may operate differently.

The solar data consistently showed a gap in the middle of the day in which no PV or FPSC output was registered. This was despite data values showing output for these periods in both the direct and diffuse solar energy time series. As this anomaly was consistent between models, the PV and FPSC can still be compared despite the error in the calculations undertaken by the EnergyPRO software. Overall, this suggests that the potential benefits of solar energy are perhaps understated within this thesis.

During environmental analysis there are a couple of main limitations. Firstly, with the base scenario model the carbon emitted by the production and transportation of the biomass pellets was not considered, meaning the CO_2 output is potentially higher. The second limitation is that the figure used for gauging electric grid carbon is averaged from UK wide data. The figure for the Scottish grid, that supplies WWHC, is likely to be lower than this figure due to the supply having a greater percentage of renewable sources.

The financial aspect of this report only covers the operational costs of each scenario modelled. Whilst this offers meaningful indicators as to how viable any future DHN would be at WWHC, more work is required in this area. This would involve assessing the capital cost of each scenario and combining it with the operational costs to determine the net present value of the DHN. Additionally, the financial aspect of Scenario 4 is not fully explored due to constraints inherent in the modelling software.

Finally, the lockdown restrictions imposed by the COVID-19 pandemic presented unique challenges that inhibited this thesis, particularly at the beginning. It made initial meetings difficult to organise and made site visits to WWHC to gather first-hand and up to date information impossible. Overall, this impacted the quality of analysis as well as the time taken to complete the report.

5.2 Directions for Future Investigations

Future work in this area could take a number of different directions. An example would be to look at future cooling needs of the buildings supplied by the DHN and then assessing the viability of incorporating a cooling system. This could upgrade the system to a 5GDH network, future proofing it against any changes in climate.

Another option would be to analyse the electricity demand for non-heat purposes alongside the demand from the DHN. This would complete the energy picture in terms of how the entire housing co-operative would operate. This would be particularly useful as the DHN will be entirely electrified under the scenarios analysed in this thesis.

Assessing the opportunity for the deployment of a GSHP could also be beneficial as there is potentially the space to achieve this. The merits and detractions of a GSHP against an ASHP are outlined in this thesis. However, a study into the operational practicality and general sizing of a GSHP for this DHN is a potential area of future study.

Additionally, any future financial analysis must assess the net present value of each different scenario to gauge its long-term financial viability. Operational costs only give an indication of whether or not the system is viable; incorporating capital and staffing costs to form the net present value would offer a more detailed picture.

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Appendices

Appendix A

Scenario 1 Selected Raw Data

Thermal Store Capacity (m3)	0	0	0	0	40	40	40	40	80	80	80	80
ASHP Electrical Capacity (kW)	250	500	750	1000	250	500	750	1000	250	500	750	1000
Heat Demand (MWh)	3309	3309	3309	3309	3309	3309	3309	3309	3309	3309	3309	3309
Heat Production (ASHP)(MWh)	1599	2186	2441	2469	2126	3132	3263	3265	2130	3167	3288	3283
Heat Production (Boiler)(MWh)	1711	1124	869	841	1186	181	50	49	1184	148	27	33
Storage Losses (MWh)	n/a	n/a	n/a	n/a	-3	-4	-4	-4	-5	-6	-6	-6
Hours of Operation												
ASHP	6395	5107	5107	5107	8505	6441	5212	4698	8519	6377	4769	4073
Boiler	8773	5668	4007	3681	3152	643	275	262	2100	247	103	140
% ASHP	73	58	58	58	97	73	59	54	97	73	54	46
% Boiler	100	65	46	42	36	7	3	3	24	3	1	2
Electricty Consumed from Grid												
ASHP Total (MWh)	646	826	927	938	857	1139	1189	1187	858	1149	1202	1199
Boiler Total (MWh)	1825	1199	927	897	1265	193	54	52	1263	158	29	35
ASHP Day (MWh)	521	677	777	788	601	708	717	711	602	690	547	493
ASHP Night (MWh)	125	149	150	150	256	432	472	476	256	459	655	707
Boiler Day (MWh)	1421	871	602	572	690	95	36	37	335	12	7	11
Boiler Night (MWh)	404	328	325	325	575	98	18	15	928	146	22	24
Total (MWh)	2471	2025	1854	1835	2122	1332	1243	1239	2121	1307	1231	1234
Full Load Hours												
ASHP	6395	4371	3254	2469	8505	6265	4351	3265	8519	6334	4384	3283
Boiler	1141	749	579	560	791	121	34	32	790	99	18	22

Thermal Store Capacity (m3)	120	120	120	120	160	160	160	160
ASHP Electrical Capacity (kW)	250	500	750	1000	250	500	750	1000
Heat Demand (MWh)	3309	3309	3309	3309	3309	3309	3309	3309
Heat Production (ASHP)(MWh)	2132	3177	3298	3296	2132	3181	3301	3300
Heat Production (Boiler)(MWh)	1183	140	20	21	1184	137	18	18
Storage Losses (MWh)	-6	-7	-8	-8	-7	-9	-9	-9
Hours of Operation								
ASHP	8529	6377	4547	3645	8529	6376	4517	3470
Boiler	1587	181	43	69	1373	167	32	35
% ASHP	97	73	52	42	97	73	51	40
% Boiler	18	2	1	1	16	2	1	1
Electricty Consumed from Grid								
ASHP Total (MWh)	859	1151	1204	1210	859	1152	1201	1208
Boiler Total (MWh)	1262	149	21	23	1263	146	19	20
ASHP Day (MWh)	603	692	516	351	603	692	514	345
ASHP Night (MWh)	256	459	687	859	256	459	688	862
Boiler Day (MWh)	106	2	1	2	17	1	1	1
Boiler Night (MWh)	1156	147	20	20	1246	146	20	20
Total (MWh)	2121	1300	1225	1233	2122	1298	1220	1228
Full Load Hours								
ASHP	8529	6354	4397	3296	8529	6362	4401	3300
Boiler	789	93	13	14	790	91	12	12

Appendix B

Scenario 2 Selected Raw Data

PV Installed Capacity (kW)	0	250	500	750	1000	1000 + Battery
Heat Production						
Heat Demand (MWh)	3309	3309	3309	3309	3309	3309
Heat Production (ASHP)(MWh)	3298	3297	3297	3295	3292	3292
Heat Production (Boiler)(MWh)	20	20	20	22	25	25
Storage Losses (MWh)	-8	-7	-7	-7	-7	-7
Electricity Produced						
PV	0	193	385	579	770	770
Electricty Consumedfrom Grid:						
ASHP Day (MWh)	516	576	667	717	737	737
ASHP Night (MWh)	687	627	532	480	457	457
Boiler Day (MWh)	1	7	11	17	23	23
Boiler Night (MWh)	20	15	11	7	4	4
ASHP Total (MWh)	1204	1203	1199	1196	1193	1193
Boiler Total (MWh)	21	21	21	24	27	27
Total (MWh)	1225	1224	1220	1220	1220	1220

Appendix C

Scenario 3 Selected Raw Data

FPSC Area	0m2	1000m2	1500m2	2000m2	2500m2
Demand (MWh/year)	3309	3309	3309	3309	3309
Heat Production (ASHP)(MWh)	3298	2925	2756	2625	2481
Heat Production (Boiler)(MWh)	20	12	9	7	6
Heat Production (FPSC)(MWh)	0	380	552	685	831
Losses (MWh)	-8	-7	-7	-7	-7
Electricty Consumedfrom Grid:					
ASHP Day (MWh)	516	444	424	412	399
ASHP Night (MWh)	687	634	596	563	528
Boiler Day (MWh)	1	1	1	1	1
Boiler Night (MWh)	20	12	9	7	6
ASHP Total (MWh)	1204	1078	1020	975	926
Boiler Total (MWh)	21	13	10	8	6
Total (MWh)	1225	1091	1030	983	932
Hours of Operation					
ASHP	8529	4039	3805	3637	3449
Boiler	1587	50	38	41	38
FPSC	0	1591	1591	1591	1591
ASHP %	97	46	43	41	39
Boiler %	18	1	1	1	1
FPSC %	0	18	18	18	18
Operational Cost (£)	180788	159481	151215	145105	138525

Appendix D

Scenario 4 Selected Raw Data

System Configuration	Wind Turbine	Wind Turbine + PV	Wind Turbine + FPSC
Heat Demand (MWh)	3309	3309	3309
Heat Production (ASHP)(MWh)	3297	3299	2482
Heat Production (Boiler)(MWh)	18	18	6
Storage Losses	-5	-7	-7
Electricity Consumed			
ASHP Total (MWh)	1211	1198	919
Boiler Total (MWh)	19	20	6
ASHP Day (MWh)	950	891	566
ASHP Night (MWh)	261	307	353
Boiler Day (MWh)	15	15	4
Boiler Night (MWh)	4	4	2
Total (MWh)	1230	1217	925
Total Imports (MWh)	291	153	420
Day Import (MWh)	128	90	195
Night Import (MWh)	163	63	224