Department of Mechanical and Aerospace Engineering

Assessing the Feasibility of Water Source Heat Pumps Supplied by Renewable Power Generation for Scottish Communities: Isle of Arran Case Study

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Abstract

This project aims to assess the technical, financial and environmental feasibility of using water source heat pumps to provide low-carbon heating for communities living on the Isle of Arran. The investigated technology was designed to function as an alternative solution to high power consumption electric heaters, or conventional fossil fuelled heating systems. The proposed community-owned system could increase the independence and resilience of involved communities, whilst decreasing fuel poverty rate in the area.

The feasibility study concentrated on a small community in Blackwaterfoot with an annual heat demand of 496 MWh, which required a water source heat pump system with a capacity of 105 kW. The energy modelling process with a step of one hour resulted in a seasonal performance factor of 3.7 in one operational year. The rest of the demand was met by heat stored in a thermal storage tank with a capacity of 12,300 litres, and a 15-kW backup immersion heater to ensure reliable heat supply all-year-round.

The hourly based supply-demand phase included renewable power generation through solar PVs that were evaluated as the most feasible solution regarding the Blackwaterfoot community. The PV system with a rated power output of 80 kW supplied more than 50% of heat pump’s annual power consumption, whilst generating additional profit to the community. Government incentives, such as Feed-in-Tariff and Renewable Heat Incentive, were considered in the financial evaluation process.

Finally, the established methodology was tested on a future off-grid community site, expected to be based next to Merkland Burn. This site was designed to harness hydropower potential for heat and power generation, whilst using surplus power for other purposes, such as alternative forms of transport. This procedure proved the applicability and flexibility of the water source heat pump technology even in small-scale applications, while having vastly positive environmental and social impacts.

Acknowledgements

I would like to express my gratitude to Dr Paul Tuohy for supervising this project, providing thorough suggestions and offering continuous support throughout the entire year.

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Nomenclature

ACE	Aberdeen Community Energy
CCF	Climate Challenge Funding
CEH	Centre for Ecology and Hydrology
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DECC	Department of Energy and Climate Change
DG	Distributed Generation
DH	District Heating
ECSC	Edinburgh Community Solar Co-operative
ESP-r	Environmental System Performance-renewable
ESRU	Energy Systems Research Unit
EU	European Union
EV	Electric Vehicle
FDC	Flow Duration Curve
FIT	Feed-in-Tariff
GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HDPE	High-Density Polyethylene

HFC	Hydrofluorocarbon
HIU	Heat Interface Unit
HOMER	Hybrid Optimization Model for Electric Renewables
ISO	International Organisation for Standardisation
LPG	Liquefied Petroleum Gas
NRFA	National River Flow Archive
ODP	Ozone Depletion Potential
OFGEM	Office of Gas and Electricity Markets
PAT	Pump as Turbine
PEX	Cross-Linked Polyethylene
PU	Polyurethane
PV	Photovoltaic
RETScreen	Renewable Energy Technologies Screen
RHI	Renewable Heat Incentive
ROR	Run-of-River
SEPA	Scottish Environment Protection Agency
SNH	Scottish Natural Heritage
SPF	Seasonal Performance Factor
UK	United Kingdom
USA	United States of America
WSHP	Water Source Heat Pump

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1. Introduction

Scotland is one of the world leaders in terms of implementing renewable energy systems into their electricity network, which is heavily driven by national targets and policies. In 2016, the last Scottish coal-fired power station Longannet was officially closed, whilst 54% of gross electricity consumption was sourced from renewables, which is nearly three times greater than ten years ago (Scottish Government, 2017a). Furthermore, Scotland has set an ambitious target of meeting 100% electricity consumption from renewable sources by 2020.

Although these electricity generation statistics and targets are remarkable milestones, non-renewable heat generation remains the main obstacle of moving towards a more sustainable, low carbon future. Heat generation is currently responsible for more than half of Scotland’s total energy consumption, whereas only 5.5% of non-electrical heat demand was generated from renewable sources in 2015 (Scottish Government, 2017b). Unlike in the electricity sector, Scotland has one of the lowest percentages of renewable heat generation in the entire EU (Scottish Government, 2017b). Therefore, the implementation of low carbon heating systems is expected to increase rapidly in the upcoming years, which has also been confirmed in the draft Scottish Energy Strategy published in 2017. This enhancement of space and water heating technologies within the UK domestic and non-domestic sectors is crucial if the 2050 target of reducing greenhouse gas (GHG) emissions to 80%, compared to the 1990 levels, is to be met.

One of the key players in the low carbon heating transition are water source heat pumps (WSHPs) that have gained momentum in recent years, especially due to numerous successful installations across the country. A new Code of Practice for surface water source heat pumps prepared by the Chartered Institution of Building Services Engineers (CIBSE) has been recently launched to boost uptake of this technology in the UK. The code is supported by the Department of Energy and Climate Change (DECC), and introduces the best practice procedure and the minimum requirements for the whole life of the system to meet ambitious national targets (CIBSE, 2016).

The expansion of renewable heat generation should, however, not only ensure the reduction of emissions but also decrease fuel poverty, which remains a major issue especially in rural areas of Scotland. Thus, this project seeks to evaluate the feasibility of using water source heat pumps supplied by renewable power generation for Scottish communities situated on the Isle of Arran. The island represents a typical rural location out with the national gas grid, which leads to an increased risk of fuel poverty due to the use of insufficient electric heaters and expensive fossil fuels that must be imported from the mainland.

1.1. Overall Aim and Objectives

Scottish communities in rural areas often use non-renewable sources such as coal and kerosene to heat their dwellings, as they are not connected to the national gas network. Alternatively, electric heaters are installed in the houses which lead to expensive bills, therefore increased risk of fuel poverty. This project aims to assess the technical, financial and environmental feasibility of using water source heat pumps (supplied by renewable power generation) that could provide low carbon space heating and hot water for communities living on Scottish islands, particularly on the Isle of Arran. This technology could function as an alternative solution to fossil fuelled heating systems and/or high power consumption electric heaters, which could increase the independence and resilience of involved communities, whilst decreasing fuel poverty rate in the area.

The key objectives of the individual project are following:

1. Describe the function of both conventional and state of the art water source heat pumps.
2. Include a brief overview of small-scale renewable power generation technologies with an emphasis on innovative systems and community owned schemes.
3. Prepare a concise methodology that could be replicated in other communities situated on Scottish islands, mainland or even abroad.
4. Establish the heat demand in the selected community and determine how it is currently being met.
5. Establish potential renewable energy resources in the selected area.
6. Design the system in computer based energy modelling programs.
7. Discuss the technical, environmental and social feasibility of the proposed system and determine related barriers to deployment.
8. Recommend the type and system design to the community on the island if evaluated as feasible.
9. Study the potential applicability to a future off-grid site that could follow the established methodology to demonstrate its flexibility.

1.2. Overall Approach

Since there are many low carbon heating systems that could be investigated, this project concentrates primarily on water source heat pumps. Therefore, the second chapter identifies fundamental principles of the technology, and describes the latest improvements and scientific findings. To ensure that real-world insight is provided, case studies from different countries are investigated.

To guarantee that heating is provided from renewable sources, the possibility of small-scale renewable power generation systems, to meet the required electricity consumption of the heat pumps, are to be part of the project. The third chapter includes a brief overview of micro hydropower and solar PV systems, whilst putting emphasis on the most recent innovations in the system design, as well as focusing on those schemes owned by local communities in Scotland.

Design approach and software evaluation is the core of the fourth chapter that aims to find the best possible methods and tools for the analytical section. This should ensure that a wide range of options were taken into consideration before selecting the tools that were used to design the proposed system. As this project seeks to address a real-world problem, many different computer-based tools came into play to ensure the robustness of the recommended outcomes.

The fifth chapter focuses on developing a detailed methodology that could be replicated elsewhere in the future. The provided methodology concisely states all of the important steps that were undertaken throughout the project. Other communities within, and out with, Scotland, could eventually follow this procedure.

The analysis, results and discussion of technical, environmental and social aspects related to the proposed development are the backbone of the sixth chapter. This section also briefly introduces the renewable energy projects on the Isle of Arran, which has been chosen as a case study. To assure the robustness of the project, a specific location on the island was selected to model the system and run numerous simulations. Furthermore, this section concentrates on barriers to deployment, and how those could be overcome by various incentive programmes. The last part of the chapter is focused on testing the established methodology on a potential off-grid site on the island to demonstrate its applicability and flexibility that could be replicated elsewhere.

The last part of the thesis is concentrated on a final discussion and conclusion that brings all the researched outcomes together, whilst recommending the best solution to the investigated sites. Finally, further work that arose when working on this project that could be executed in the future is concisely outlined in the last section of the thesis.

2. Literature Review Part I: Heat Pumps

The fundamental principle of a heat pump is to extract low temperature heat from a given source, and transfer it to a high temperature sink. It was Lord Kelvin who first came up with the idea of using heat pump system to provide heating for dwellings, with the first UK officially reported installation at the Norwich Corporation building (Singh, et al., 2010). Although the system design has clearly changed significantly since this milestone, the underlying concept has remained unchanged.

The second law of thermodynamics discovered by Clausis states that heat cannot freely flow from a cold object to a hot one without external force being applied on the system. This means that, in the case of a heat pump, electrical power is required to run the compressor. The same principle is used in a conventional fridge, where heat is being removed from the internal space, and dumped to the surrounding environment. This operation keeps the interior at a desired temperature, whilst the back of the fridge is warming up. Heat pumps used for space heating and hot water essentially work as a reversed fridge. Although electricity is necessary throughout the process, the amount is significantly lower compared to the heat delivered. The ultimate difference between the refrigeration cycle and the heat pump cycle is captured in *Figure 1*.

The required heat can be taken from different sources, such as air, ground or water, where each comprises of unique physical properties. Although heat pumps, especially the ones using ground as a heat source, are occasionally called geothermal devices, the main heat source is solar energy (65mW geothermal vs 100W solar) (Clarke, 2016). This gives the technology a substantial advantage compared to other heating systems, as solar energy is abundant and entirely renewable.

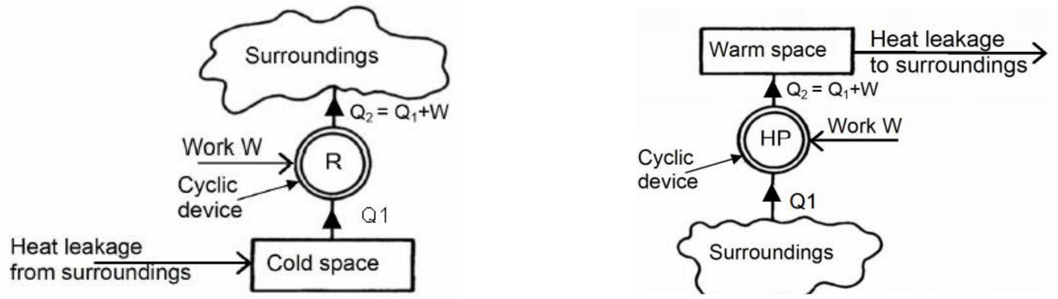


Figure 1. Fundamental difference between refrigeration cycle (left) and heat pump cycle (right) *(Tuohy, 2016)*

2.1. Vapour Compression Cycle

A heat pump consists of four main stages where each is represented by a unique component. These include compressor, condenser, expansion valve and evaporator. Firstly, a refrigerant is passed through a compressor which leads to increased pressure and temperature. Condensation occurs in the second stage, where compressed vapour turns into a liquid state whilst pressure remains unchanged. This is where heat is delivered to the building. Afterwards, high pressurised liquid experiences a pressure drop which causes the evaporation. In case of space heating and hot water generation, the evaporator is placed outside to gain heat from the source, as heat always flows from hot object to a cold one. Low pressure refrigerant in a gas state is then passed through the compressor, and the cycle is completed. The identical cycle can also be used for air-conditioning, in which case the condenser is placed outside to dump the heat and the evaporation process occurs inside to cool down the internal rooms. This flexibility illustrates one of the many advantages compared to other conventional heating systems. A schematic of the heat pump cycle can be seen in *Figure 2.*

Although a heat pump is a low carbon technology that uses renewable heat sources, external force must be applied on the system, to ensure that energy is transferred to the heat sink. This external work is delivered in a form of electricity that is consumed by the compressor. The change of pressure and enthalpy in each stage of an ideal vapour compression cycle is shown in *Figure 3.* In reality, the curves are not linear due to various heat losses and natural imperfections.

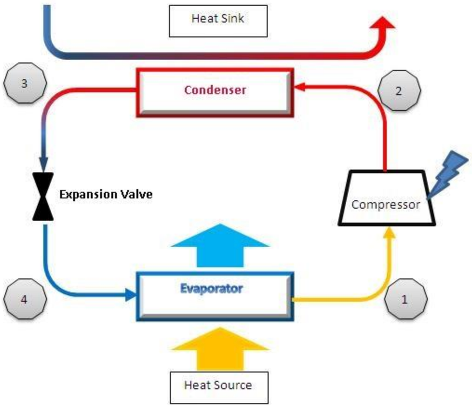


Figure 2. Four main stages of a typical heat pump cycle *(ESRU, 2011)*

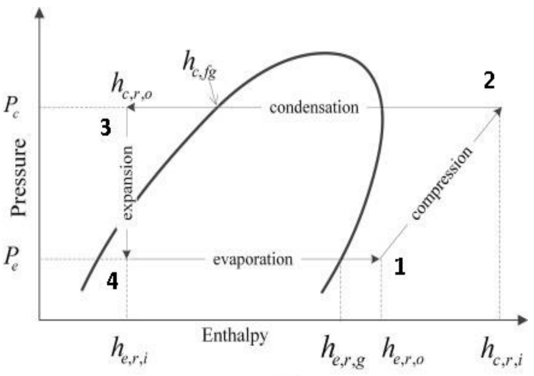


Figure 3. Pressure-Enthalpy diagram of an ideal vapour compression cycle *(Ruz, et al., 2017)*

2.2. System Performance

The main indicator to recognise performance of a heat pump is the coefficient of performance (COP). It is stated as a ratio of the net heating capacity to the effective power input, and should be officially measured according to ISO 13256-2:1998, which includes international standards for testing and rating for performance of water source heat pumps (ISO, 2015). Therefore, COP of a heat pump can be accurately measured by taking the amount of heat transferred to the heat sink (Q), and dividing it by the amount of electricity power dragged by the operating equipment (W), as shown in *Equation 1*:

$$\mathrm{COP} = \frac{\mathrm{Q}}{\mathrm{W}} \qquad \textit{Equation 1}$$

Alternatively, there is a relationship between temperature of refrigerant in condenser ($\mathrm{T_c}$), and evaporator ($\mathrm{T_e}$). This solution has the advantage of requiring only two thermocouples to calculate the COP of the ideal Carnot cycle, as shown in *Equation 2*:

$$\mathrm{COP_{Carnot}} = \frac{\mathrm{T_e}}{\mathrm{T_c - T_e}} \qquad \textit{Equation 2}$$

It can be seen that the highest COP is achieved when the temperature of condensation is the closest to the temperature of evaporation. This is why the performance of an air source heat pump decreases with lower outdoor bulb temperature. This often leads to a poor air source heat pump performance when the heat demand peaks, and generally unstable performance throughout the year, especially in countries such as the UK. Moreover, heating is usually required during the evening and night when the outdoor bulb temperature is the lowest. On the other hand, ground and water, both at sufficient depths, are represented by relatively stable temperatures not only during the 24-hour period, but also throughout the whole year.

Although COP is an important characteristic of the system, it does not provide any information about how the heat pump performs in a long term. By contrast, seasonal performance factor (SPF) reflects a more realistic view of performance, as it is measured and calculated over an entire season (Morton, 2013). In the UK, every heat pump must be designed with a COP of 2.9 or higher and SPF must achieve a minimum of 2.5 to receive government incentives for low carbon heat generation (OFGEM, 2014). Therefore, these values could be used as an indication of a ‘good’ performance.

In 2016, the Department of Energy and Climate Change published a report dedicated to monitoring performance of ground and water source heat pumps installed around the UK. The overall SPF ranged from 1.3 to 4.2 with an average of 2.7 (Hughes, 2016). This statistic demonstrates that the majority of heat pumps are designed and installed correctly these days.

The performance of heat pumps is relatively stable throughout the system lifetime, although regular maintenance is required. The expected working life of commercial heat pumps is estimated at 25 years which gives this technology significant advantage in terms of lower replacement rate, since conventional domestic boilers have an expected lifespan of only 15 years (Singh, et al., 2010).

2.3. Heat Exchangers

The core principle of a heat pump is to transfer heat from one place to the other, which requires the use of a heat exchanger. Low temperature heat extracted from the primary source is passed through the cycle and highly pressurised into a vapour before entering the condensation stage. At this stage, heat is transferred from the refrigerant to the water circuit which distributes heat around the building. To ensure that heat transfer is maximally efficient, a counter-flow heat exchanger with numerous shell passes should be used (Tuohy, 2016). Both cycles are completely separated, and therefore water and working fluid are never physically mixed.

Inside the building, heat transfer is mainly executed through natural convection. The cheapest and most common practise is to use of radiators that are mounted to the wall. Underfloor heating has been becoming increasingly popular in the past decades, as it provides higher comfort to the residents, while the water temperature in the pipes can be significantly lower, which decreases heat losses thus saving money. According to the OFGEM research paper from 2015, an average Scottish 3-bedroom household using a heat pump as a primary heating source would save approximately £200 per year if an underfloor heating system is installed instead of a conventional radiator (OFGEM, 2015). Upgrading to underfloor heating is, however, very expensive, and therefore is usually installed only in new builds.

2.4. Refrigerants

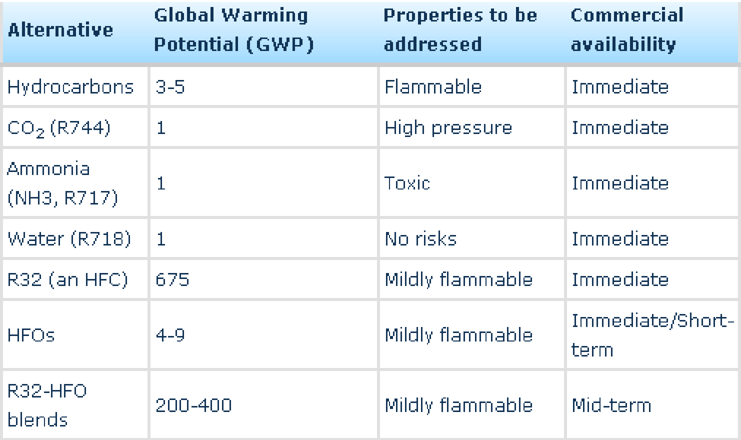
An appropriate selection of a refrigerant type is a crucial aspect that has to be addressed when designing any heat pump system. Refrigerants significantly affect the technical performance of a heat pump due to different physical properties at different pressures. Fluids that are ideal for transferring heat from the source to the heat sink are, however, often highly environmentally unsuitable. These negative impacts have been overlooked in the past, when fridges contained toxic substances that were released to the atmosphere and contributed towards ozone depletion and global warming (Bolaji & Huan, 2013). Therefore, a recommended working liquid should provide high COP, while having minimal impact on the environment.

There are numerous refrigerants that are banned or at least regulated by international agreements. Hydrofluorocarbons (HFC) and hydrochlorofluorocarbons (HCFCs) are typical examples of man-made working fluids that have been used in many industrial processes, including heating and cooling technologies, whilst having a substantial impact on the environment. In October 2016, Montreal protocol adopted the Kigali Amendment that adds HFCs to the list of controlled substances. This amendment has been strongly supported by the European Union to regulate use of refrigerants that are harmful for the atmosphere. Following this action, the European Commission published official papers that provide relevant information about alternatives to those regulated greenhouse gases (European Commission, 2017a). Some of the possible substitutes are shown in *Table 1*.

To evaluate environmental suitability of different refrigerants, Global Warming Potential (GWP) measure has been established. Water has a GWP of 1 which represents the most climate-friendly solution. By contrast, the GWP values of many HFCs are in thousands, which clearly demonstrates the urgency to find appropriate alternatives. Working fluids that often replace HFCs are ammonia and $\mathrm{CO_2}$ due to their low GWP values and high potential to achieve good technical performance. $\mathrm{CO_2}$ must be, however, highly pressurised to meet sufficient COP, and ammonia is toxic which increases the health and safety costs related to the prevention of potential leakage.

Moreover, the production of ammonia is a highly energy intensive process, which often means higher usage of fossil fuels.

Table 1. Climate-friendly alternatives to HFCs and HCFCs *(European Commission, 2017a)*



Alternative	Global Warming Potential (GWP)	Properties to be addressed	Commercial availability
Hydrocarbons	3-5	Flammable	Immediate
CO_2 (R744)	1	High pressure	Immediate
Ammonia (NH3, R717)	1	Toxic	Immediate
Water (R718)	1	No risks	Immediate
R32 (an HFC)	675	Mildly flammable	Immediate
HFOs	4-9	Mildly flammable	Immediate/Short-term
R32-HFO blends	200-400	Mildly flammable	Mid-term

There is not a universal refrigerant that is ideal for all types of heating and cooling technologies that would also be environmentally acceptable. Therefore, each application should be considered individually, and the conclusion will vary according to given circumstances. The technical performance of working fluids with low GWP value that could be used specifically for high temperature heat pumps has been investigated at the Royal Institute of Technology KTH, where six different fluids are evaluated (Palm, et al., 2016). The authors concluded that DR-2 is a refrigerant with a very high critical temperature, whilst having a GWP value as low as 2. This means that DR-2 seems like an ideal climate-friendly solution in cases where high temperatures are required. The relationship between the vapour pressure and temperature of studied working fluids is shown in *Figure 4.* In reality, other aspects including financial feasibility or health and safety issues need to be considered before the refrigerant is finally selected.

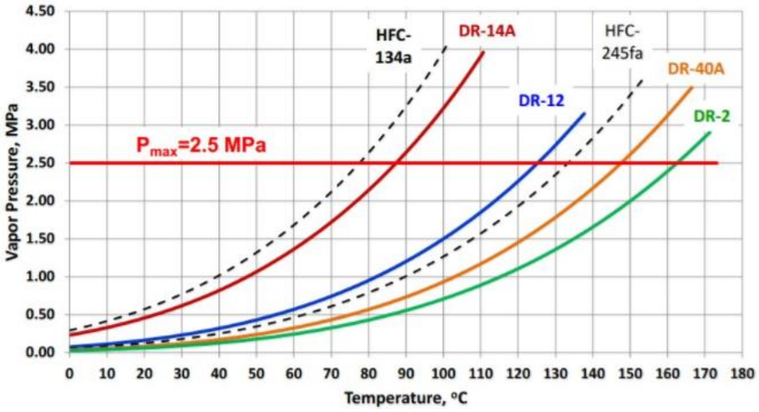


Figure 4. The relationship between vapour pressure and temperature of investigated refrigerants *(Palm, et al., 2016)*

2.5. Heat Distribution and Losses

Heat distribution and related losses are important aspects that significantly influence the overall performance of any heating system, which also applies to domestic and non-domestic heat pump technology. In single buildings, radiators or underfloor heating are primarily responsible for heat distribution as discussed in Chapter 2.3. Since heating systems are usually placed within a short distance from the buildings, or even inside them, heat losses are generally low. On the other hand, heating systems that feed multiple buildings must take into consideration heat losses that occur in the underground pipes. The concept of using a heating system from a centralised location to deliver heat into more buildings is called district heating (DH), which is currently gaining momentum in Scotland as a part of the draft Scottish Energy Strategy published in 2017.

2.5.1. District Heating

District heating is not a new concept, as the first system was implemented already in 1880 in the USA, and a similar design was used for 50 years (Stevenson, 2016). Although district heating schemes have become a backbone of heat distribution in many European countries, UK has been left behind with the lowest deployment of DH in the entire EU. Many European countries have implemented heat networks that supply towns or even entire cities, whereas in Scotland, individual boilers heating each building or flat are the main source of heat (Scottish Government, 2017a). Nevertheless, this trend has started to change, and many DH projects across Scotland have been proposed in recent years. All the planned and built DH schemes in Scotland can be seen in *Figure 5.*

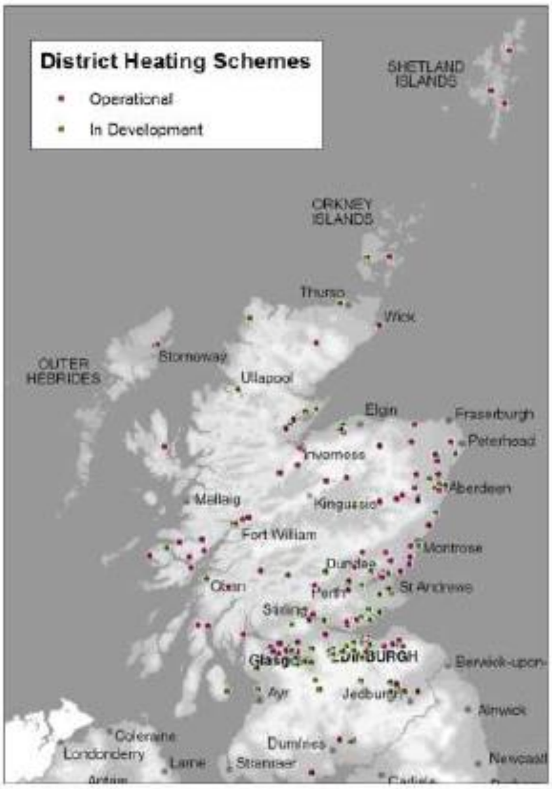


Figure 5. Planned and existing district heating sites across Scotland *(Scottish Government, 2017a)*

It can be seen in *Figure 5* that most schemes are situated within towns and cities, where population density is relatively high, which leads to lower heat losses in the pipes. Application of DH systems in rural areas might be more problematic, especially in places where individual buildings are dispersed. In these cases, DH schemes are usually not technically and financially viable option. However, even small rural communities can benefit from the district heating concept, if distances between the dwellings are relatively short to minimise heating losses that occur during heat distribution. Indeed, the Scottish Government has been supportive through incentives and grants to increase the deployment of DH schemes not only within its largest cities, but also in rural areas to decrease fuel poverty and meet ambitious renewable heating targets.

Although Scotland is moving in the right direction with regards to deployment of DH, there are countries which have already reached remarkable achievements. There are more than 10,000 DH systems installed in the EU, which distributes heat to approximately 70 million EU citizens. In particular, Scandinavian countries are the leaders in implementing DH schemes. More than 50% of heating demands of Sweden and Denmark are supplied through DH schemes, including fast evolving systems that use 4th generation district heating concept (European Commission, 2017b).

While conventional district heating schemes often use gas boilers and other fossil fuels powered systems, the new concepts move towards more sustainable solutions, such as biomass boilers, industrial waste heat recovery, large-scale heat pumps and solar thermal collectors, or geothermal energy (Lyden, 2015). The 4th generation district heating concept has several advantages that increase efficiency and integration of renewable energy technologies. Many conventional DH systems use steam for heat distribution, which results in higher losses compared to low temperature water distribution system. Moreover, fourth generation district energy networks are built from prefabricated materials, use the smart storage concept, and are controlled and monitored through advanced systems (ESRU, 2017).

These advanced control systems function not only as time and temperature regulators, but also as metering and billing devices of energy use in individual buildings within the district heating scheme. All the aforementioned aspects can be controlled by a heat interface unit (HIU), also called ‘heat box’, that follows the official UK standards given by CIBSE. The HIU should be installed within each house of the community to provide a user-friendly platform for residents to serve their requirements (CIBSE Journal, 2011).

2.5.2. Piping

Conventional pipes are made from prefabricated materials and consist of three main elements; carrier pipe, appropriate insulation and outer jacket to protect the pipe from undesirable damage or bending. Heat losses in pipeline networks can be considerably reduced by using insulation materials. However, achieving minimal heat losses by using an excessive amount of insulation is neither technically nor financially feasible. Thus, energy savings and capital costs should be balanced to find an optimum solution. A schematic of a commonly used pipe is shown in *Figure 6.*

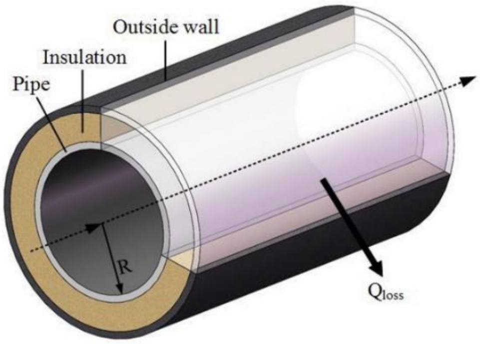


Figure 6. Schematic of a conventional pipeline used for heat distribution *(Zhang, et al., 2017)*

There are many types of pre-insulated pipes that can be used for heat supply. To keep the capital cost and space required as low as possible, twin pipes should be used in the case of heat distribution provided by heat pumps to allow circulation of input and output water in the same piping. Steel pipes generally have a longer lifespan and resistance against hostile conditions, whereas drawbacks include lower bending flexibility, challenging jointing and higher lambda value which negatively influences heat losses. High-performance polymer pipes with polyurethane (PU) foam are ideal for large systems over long distances, due to high level of insulation. Polymer pipes with cross-linked polyethylene (PEX) foam are defined by excellent flexibility due to corrugated outer jacket. Both types of polymer pipes can be purchased from UK manufacturers, which can result in a CO_2 reduction of 29% (Rehau, 2017). The three discussed types are shown in *Figure 7*.

Figure 7. Pre-insulated twin pipes; steel pipe (left) *(Vital, 2017)*, polymer pipe with PU foam (middle), polymer pipe with PEX foam (right) *(Rehau, 2017)*

2.5.3. Thermal Storage

Energy storage should be an integral part of any heat pump system, due to the stochastic nature of electricity prices, and intermittency of renewable energy sources that are used to generate electricity. Without any energy storage implemented, a heat pump system would have to rely completely on current electricity available by the grid. Such a solution would be neither economical nor secure in areas of national grid supply, and impossible in sustainable off-grid areas where individual houses or whole communities are dependent on renewable energy power generation. Nevertheless, energy storage in the case of heat pump systems is usually provided by hot water storage tanks that are appropriately insulated to avoid undesirable heat losses.

Sensible heat, latent heat or chemical reactions are the three main forms of thermal storage that can be used. Recent years experienced a significant evolution of new thermal storage technologies that include phase change materials, cryogenic storage or molten salt for concentrated solar systems (Bonanos & Votyakov, 2016). Although generated heat can be stored in many ways, which will certainly improve in the future, insulated hot water storage tanks are expected to be appropriate for the purpose of this project. This technology is well established, thus represents a reliable and financially affordable solution that can be purchased with a secure warranty, which is often a very important factor for vulnerable rural communities.

The type and size of hot water tank depend on each individual situation. Small tanks with negligible stratification (hot water travels up and cold water stays down) are represented by low inertia and ability to respond to heating demand very quickly (Varga, et al., 2017). Water inside of the small tanks can be heated up fast and supply heat almost immediately. On the down side, such a system might be unable to generate and store heat when the electricity prices are the lowest, or when conditions for renewable energy generation are favourable. By contrast, large storage tanks are able to harness renewable energy potential and store heat for later use; this is especially necessary for district heating schemes to meet demand of multiple dwellings. Large storage tanks tend to be however, more expensive and cannot respond as quickly to variable heating demand. Therefore, most hot water storage tanks are designed to be a compromise of these features, and should be assessed on a case-by-case basis.

Figure 8 shows a typical domestic heat pump system with implemented hot water storage tank. It can be seen that hot water storage tanks take up a significant amount of space compared to other heat pump components. With regards to the piping connections, colder water is taken from the bottom part of the tank and passed through heat exchangers in the condenser. Hot water gathered in the tank travels to the top, thus the pipe distributing hot water around the building(s) is placed in the top part of the storage tank.

Figure 8. Hot water storage tank as a part of a conventional heat pump system *(Solo Heating Installations, 2017)*

2.6. Types of Systems

Heat pumps are part of renewable heat technologies that are supported by the Scottish Government. Although heat pumps have been gaining momentum in the recent years, they currently supply only 6% of all renewable heat generated in Scotland, which corresponds to 236 GWh (Scottish Government, 2017a). Most common are air source heat pumps that have the advantage of low capital cost and uncomplicated installation. However, their COP varies significantly throughout the year, especially in cold and humid climates such as the UK (Clarke, 2016). Ground source heat pumps (horizontal or vertical) provide more stable performance all year long, but higher capital cost and cumbersome building procedure are the main drawbacks that slow down deployment of this technology. Water source heat pumps benefit from high conductivity of water, and provide a relatively stable COP throughout all seasons. Moreover, nearly one quarter of domestic heat demand in Scotland lies within one kilometre of a major river and 22% within one kilometre of the coastline (Scottish Government, 2017a). These statistics demonstrate an enormous potential that has remained untapped, which is the main reason why the Scottish Government is investing into feasibility studies to install WSHP systems across the country to decarbonise Scotland’s energy sector. All three types of heat pump technology can be seen in *Figure 9.*

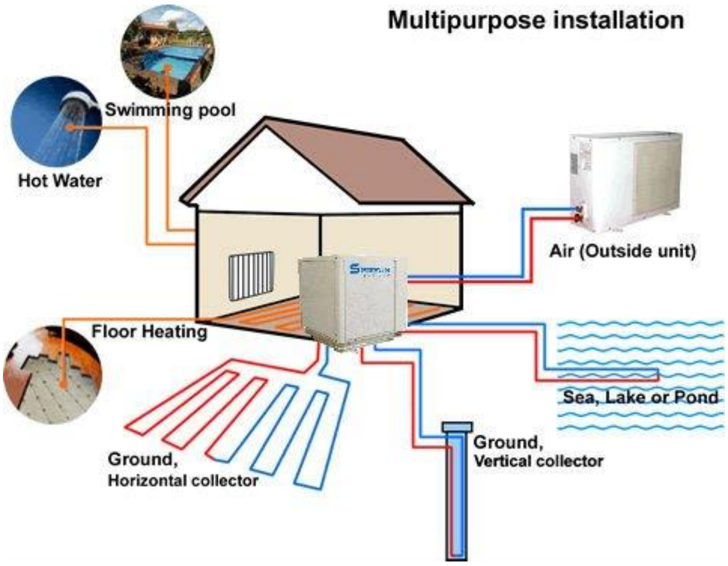


Figure 9. Schematic of different heat source for multipurpose usage *(Heat Pump Critique, 2017)*

WSHPs are designed to transfer heat from the water source, such as river, lake, pond, man-made reservoir or sea, to the heat sink. The mass of water must be large enough to be prevented from freezing. This technology is generally restricted to areas, where the water source is relatively close to the heat demand side to ensure that heat losses are minimised. Fortunately, many Scottish communities, towns and cities are situated within a short distance from large water source. WSHPs can be divided into two main categories; open-loop and closed-loop. Each type has its own advantages and drawbacks, thus there is not a universal rule regarding which type is more feasible to implement. The fundamental difference between open-loop and closed-loop systems can be seen in *Figure 10.*

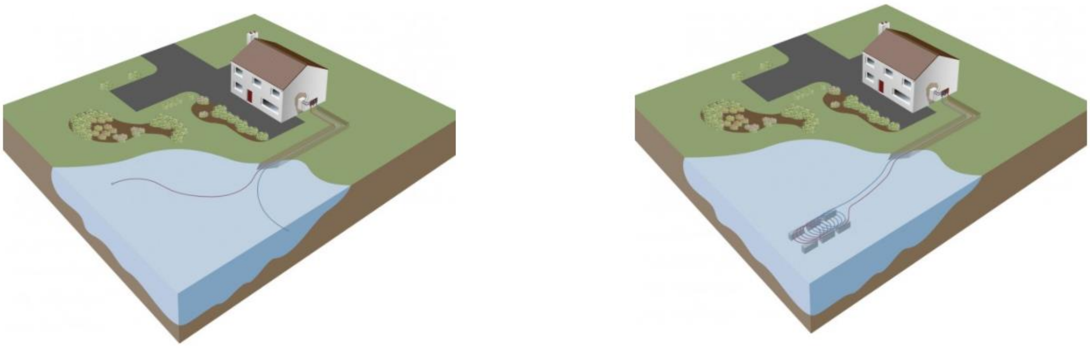


Figure 10. Graphical schematic of an open-loop (left) and closed-loop (right) WSHP system *(Kensa Heat Pumps, 2017)*

2.6.1. Open-Loop

Open-loop systems, also referred to as ’indirect’, rely on an additional pump that draws water from the source, passes it through the heat exchangers, and then pumps the water back to the source where it was taken from in the first place. This means that power consumption of these systems is generally higher, compared to the closed-loop systems. On the bright side, undesirable heat losses are avoided, as water passes directly through the heat exchanger. Open-loop WSHP systems can be used in residential or commercial buildings, and in district heating and cooling systems. Due to economic reasons, open-loop systems tend to be used for large scale applications (Spitler & Mitchell, 2016).

Additional capital costs are not linked only to the water circulation pump. Appropriate prevention against corrosion needs to be considered, especially in those systems that must withstand seawater conditions, which are generally more expensive due to the necessity of special anticorrosive materials. If high volumes are extracted from the primary heat source (more than 20 cubic meters per day), an official abstraction licence from a relevant authority is required (Environment Agency, 2016). Moreover, appropriate protection of water creatures needs to be considered to prevent any animals or debris being sucked into the system. In Scotland, these conditions are supervised by the Scottish Environment Protection Agency (SEPA). Finally, additional maintenance is required compared to the closed-loop systems. The evaporator should be cleaned frequently, as the heat transfer can decrease by 75% within only five months of operation without regular cleaning (Rosen, 2015). All these aspects are projected into the capital cost of the system, hence the larger scale usage. An example of a large-scale water source heat pump with an open-loop system installed in Drammen by Star Refrigeration is shown in *Figure 11*.

Figure 11. Large-scale river source heat pump with an open-loop system manufactured by Star Renewable Energy *(Star Refrigeration, 2016)*

Despite the fact that open-loop systems use another pump to circulate the water from the source, these systems can achieve high COP values even on a long-term basis. 19 open-loop WSHP systems, with nominal capacities from 35 kW to 6.8 MW, were investigated in Norway. During the operational time, an average seasonal heat pump heating COP was 3.1, ranging between 2.1 and 4 (Spitler & Mitchell, 2016).

2.6.2. Closed-Loop

Closed-loop systems are fundamentally very similar to ground source heat pumps, except that fact that the thermal exchange is made between water sources rather than earth. In closed-loop systems, heat transfer fluid, which is usually water with added antifreeze substances, absorbs heat from the water source, and passes it through the heat exchanger which is placed in the evaporator. These systems experience greater heat losses compared to the open-loop schemes, as the fluid has to be transferred from the water source to the evaporator. On the other hand, the overall power consumption is generally lower, as water does not have to be pumped from the source. Since there is not a direct contact between the evaporator and water body, a risk of corrosion is eliminated. This is advantageous especially in seawater installations where advanced and more expensive anticorrosive materials would be otherwise required. In addition, there is no danger of the evaporator being frozen, although attention must be paid to the heat transfer fluid, hence the antifreeze solution requirements (Morton, 2013).

The type of thermal transfer fluid plays an important role in terms of environmental considerations. This is due to the reason that any potential leakage from the closed-loop system would immediately affect the water ecosystem. Thus, the eco-toxicity of the used antifreeze solution is highly important before designing the system. Ethylene glycol is often used in ground source heat pump installations due to its low viscosity, however it is poisonous, therefore not recommended for water source applications. Although propylene glycol or ethanol have higher viscosity, they could be possible used as reliable alternatives due to their lower level of toxicity (Banks, 2012). Other alternatives that are available on the market and claim lower toxicity than previously mentioned substances are thermal transfer fluids based on vegetable extracts or organic salts (Environment Agency, 2011).

Heat exchangers placed in a water body are either coiled high-density polyethylene (HDPE) pipes or flat plate heat exchangers. The former is more feasible in cases of lower water depth available, which includes smaller rivers and areas with shallow coastline. Coils are arranged in slinky overlapping patterns, which are often used to install ground source heat pumps to reduce the overall area. The latter represents a more solid solution, which takes up more space, however is less likely to be damaged by external factors, such as floating objects in the water. Both types of heat exchangers that are used to extract heat from the body of water are shown in *Figure 12*.

Figure 12. Heat exchangers used for closed-loop systems; coiled HDPE pipes (left) *(Kensa Heat Pumps, 2017)* and flat plate heat exchangers (right) *(Aweb, 2017)*

Closed-loop systems generally require less maintenance than open-loop systems, although they are more vulnerable to high flow rates in rivers, as they can float away. Moreover, they can be damaged by passing boats when placed in the river or sea (Lyden, 2015). These risks can be, however, eliminated by adequate field research that should be followed by appropriate design and precise installation.

2.7. Real-World Implementation

Water source heat pumps have become a successful technology supplying heat in domestic and non-domestic sectors not only in Europe, but also worldwide. Although the majority of applications are used for either large commercial buildings, social housing, or multiple dwellings as a part of district heating schemes, a small fraction of the total number of installations in the UK are installed in individual family homes (mainly in rural areas). An example of a small scale WSHP utilisation is the River House in Cambridge, where the system provides heating to a family house of four members. Heat is taken from the nearby lake, and buried underground pipes transfer heat to the evaporator that is placed in the building. The closed-loop system with coiled HDPE pipes took less than three weeks to install, and resulted in significant financial savings compared to the previous situation when gas boiler was used. This is largely due to the support from the Government through the domestic Renewable Heat Incentive scheme (Kensa Heat Pumps, 2017).

Moving from the small-scale application to the other extreme, the world largest open-loop WSHP system is used for a district heating scheme in Stockholm, which includes six seawater heat pumps with a total capacity of 180 MW. This system was originally installed in the middle of 1980s, and has gone through numerous upgrades including refrigerant replacement in 2003 from working fluid R22 to R134a. Taking into consideration a heat pump COP of 3.75 during the winter time, it can be seen that WSHP is a technology with long durability and relatively stable long-term performance (Friotherm, 2015). The enormous size of the system is shown in *Figure 13*.

Figure 13. The largest water source heat pump scheme in the world - 180MW capacity operating in Stockholm, Sweden *(Friotherm, 2015)*

The vast majority of WSHPs are installed in places within the national electricity grid coverage. Off-grid installation with renewable power generation on site would be more complicated due to stochasticity of renewables. Nonetheless, the technology could provide a reliable heating supply, if appropriate thermal storage was implemented. In such a case, a heat pump would drag generated electricity when the weather conditions were favourable and heating demand was low, and store this heat for later use. The system size, including thermal storage technology, would have to be designed individually for each specific case.

The technology has proven to be successful in both cities and rural areas. Cities generally benefit from more densely populated areas, which means lower heat losses in the system. On the other hand, rural areas in Scotland are often not connected to the main gas grid, thus heat pumps are capable of providing a financially and environmentally attractive alternative to electric heaters and systems fuelled by coal or kerosene. Loch Ness Shores Foyers Camping Site in Foyers represents an example of a rural community that benefits from a small-scale WSHP district heating scheme. A 60 kW hybrid system consists of a WSHP and solar thermal collectors that are installed on the roof of the building to supply heating and hot water for the visiting customers. This successful eco-camp project created local jobs, and supported local businesses in the area. The project has been successfully running since 2013, and was subsidised by the Scottish Government's Energy Saving Trust (Helping It Happen, 2017). The camping site during the construction process and the implemented heat pump system are captured in *Figure 14*.

Figure 14. Loch Ness Shores Foyers Camping Site in Foyers; district heating construction process (left), successfully installed heat pump system (right) *(Kensa Heat Pumps, 2017)*

High flexibility of WSHP systems in terms of various application is a crucial advantage that should not be overlooked. The same system can provide space heating during the colder months of the year, and air-conditioning during the warmer periods of the year. In addition, hot water can be supplied throughout the entire year, if the system is designed for it. In that case, the hot water temperature must exceed a temperature of at least 55 °C to avoid a Legionella bacteria that extensively grows in man-made water systems operating at temperatures between 20 °C and 45 °C. This type of bacteria can cause the Legionnaires' disease (LD), and appears especially in lower temperature water storage tanks (Collins, et al., 2017). Therefore, hot water systems, such as the one installed in Foyers, are designed to achieve temperatures of around 60 °C to prevent any risk of Legionella contamination. The relationship between the growth rate of Legionella bacteria and water temperature and time is shown in *Figure 15*.

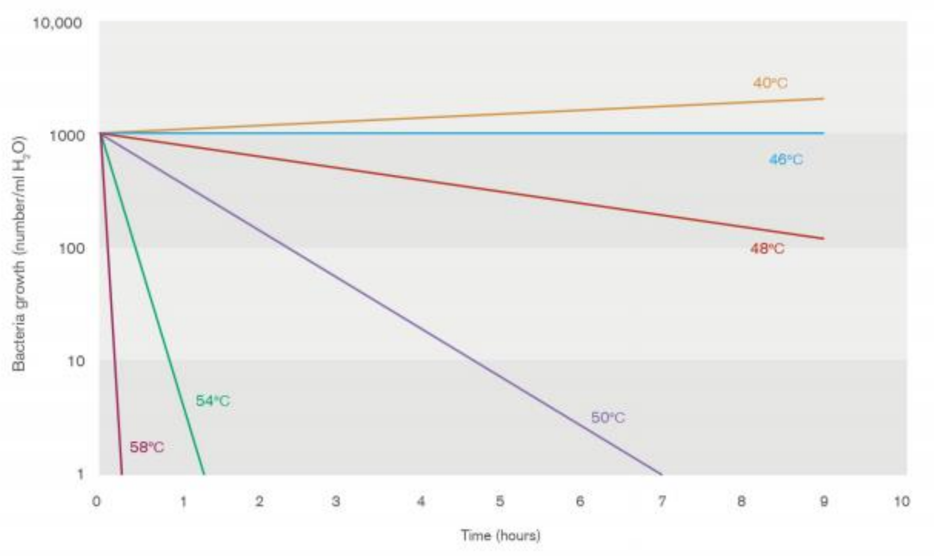


Figure 15. The growth rate of Legionella bacteria related to water temperature and time *(Greater London Authority, 2014)*

2.7.1. Crucifers Convent in Venice Case Study

Many countries in the world are currently experiencing fast economic growth and enhancement of living standards, which consequently leads to increased heating and hot water demand, and especially cooling demand during summer months. Indeed, WSHP technology can tackle all of these aspects, which is demonstrated in the research paper focused on experimental analysis of the performance of a surface water source heat pump system installed in Venice that was designed to meet all three critical demands (space heating, hot water and cooling) (Schibuola & Scarpa, 2016).

A seawater-based open-loop heat pump system was installed as a part of a retrofit project of the Crucifers Convent historical building, which is captured in *Figure 16.* The Venetian lagoon (the largest wetland in the Mediterrean Sea) provides an ideal heat source for WSHP application, especially due to the proximity of the buildings and surrounding lagoon. The heat pump has a nominal capacity of 610 kW in a heating mode, and 580 kW in a cooling mode, respectively. R113a was selected as a working fluid, which has favourable physical properties for cooling systems, however extremely high Ozone Depletion Potential (ODP) value (0.9) and Global Warming Potential (GWP) value (6,130), thus a more environmentally friendly solution could be considered as an alternative in the future (Riemer, 2014).

Appropriate water filtering was a critical challenge that had to be addressed, as the lagoon water tends to be dirty due to numerous scarce sewers and refuse spills in the city. Moreover, the presence of algae, sludge and urban waste related to the frequent boat traffic negatively affect the water purity. The installed self-cleaner filter is shown in *Figure 16.*

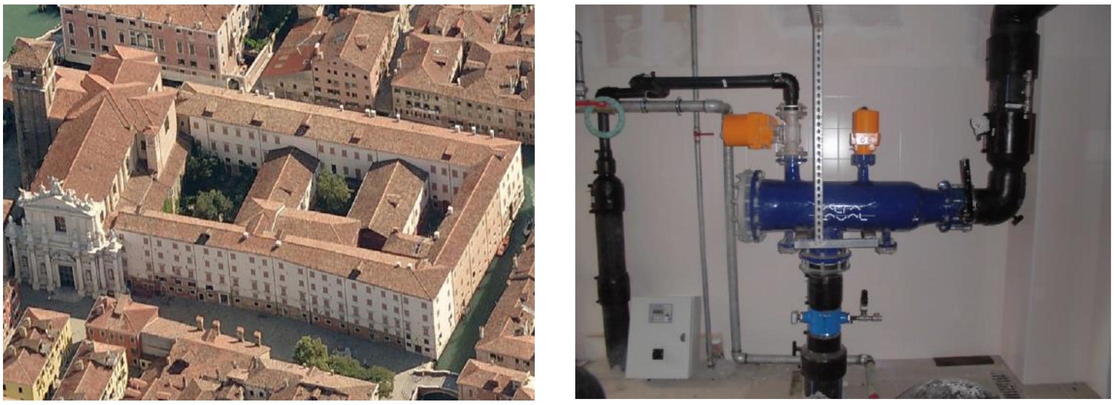


Figure 16. The Crucifers Convent complex in Venice, Italy (left); self-cleaning filtering device (right) *(Schibuola & Scarpa, 2016)*

The applied seawater heat pump system achieved a winter COP of 3.66 between October and April, and a cooling COP of 4.13 during the rest of the year. The power consumption of the suction pump, which is necessary for any open-loop system, was considered when calculating the COP value. This experimental analysis has proven the flexibility of the system that has a capability to work reliably throughout all seasons of the year.

3. Literature Review Part II: Renewable Power Generation

To ensure that heat generated through a water source heat pump is completely renewable, the required power consumption of the system needs to be met from renewable sources. Although the heat pump power consumption is significantly lower compared to conventional electric heaters, that are often used in areas outside of the main gas network, they still a require reliable electricity supply to transfer heat from the heat source to the heat sink. The core of the project is not to provide an overview of all renewable power generation technologies that could be considered, however the increased power demand related to the operation of heat pumps should not be completely overlooked.

Micro hydropower is one of the technologies that could be considered when implementing any river source heat pump technology. It applies especially to places with abundant hydro resources and a high concentration of environmentally protected areas that would not be suitable for any large-scale projects, including large dams or wind farm developments. This is also the case of Arran, which is very limited in terms of potential wind generation due to restrictions from Scottish Natural Heritage and protected wildlife areas (Calderwood & Logan, 2016). In the areas with insufficient hydropower resources, the possibility of using solar PV panels instead was assessed. All in all, this project will investigate the feasibility of using micro hydropower and/or solar PV systems to supply power consumed by the low carbon heating system. The reason why even small wind turbines were excluded from the feasibility study is provided in Subchapter 4.1.

3.1. Micro Hydropower

Hydropower is a reliable source of electricity that accounts for a quarter of renewable generated electricity in Scotland. Although the majority of this electricity comes from large hydropower schemes built mainly in the second half of the 20th century, the Scottish Government currently supports mostly small and community-owned hydropower projects instead of proposing large-scale schemes. The 2020 hydro targets are to have 1 GW of community and locally-owned energy, which means that at least half of newly consented projects should include shared ownership. Wider deployment of small and micro hydro projects has been continuously supported through various funds and loans (Scottish Government, 2017b). Their cost distribution between civil engineering on site, required mechanical and electrical equipment and preliminary planning documentation is significantly more uniform compared to large-scale schemes, where enormous capital must be dedicated to the construction stage as seen in *Figure 17.*

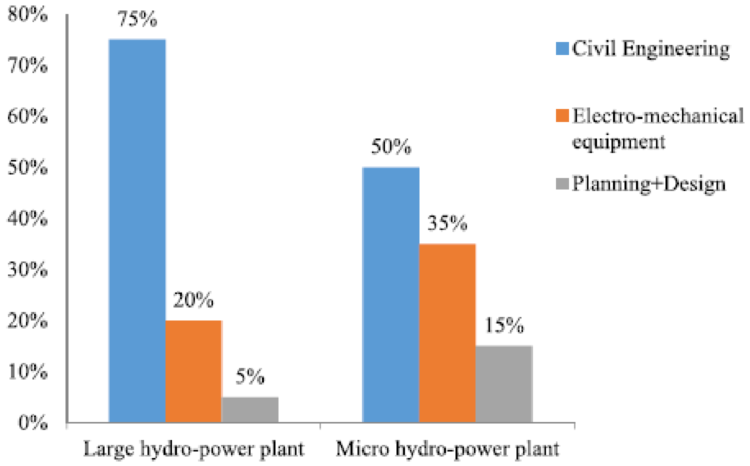


Figure 17. Cost distribution of large and micro hydropower schemes *(Binama, et al., 2017)*

The vast majority of micro hydro systems are run-of-river (ROR) schemes with a capacity between 5 and 100 kW. Other types include dam-based and pumped storage schemes, however these are more common for large-scale developments. ROR schemes can be divided into two main types. Upland schemes are characterised by high head and low flow, whereas lowland schemes are typically situated on more mature, lower reaches of the river that benefit from the opposite characteristics with the head usually created by a small barrage (Prophet, 2015). A typical small run-of-river scheme is presented in *Figure 18.*

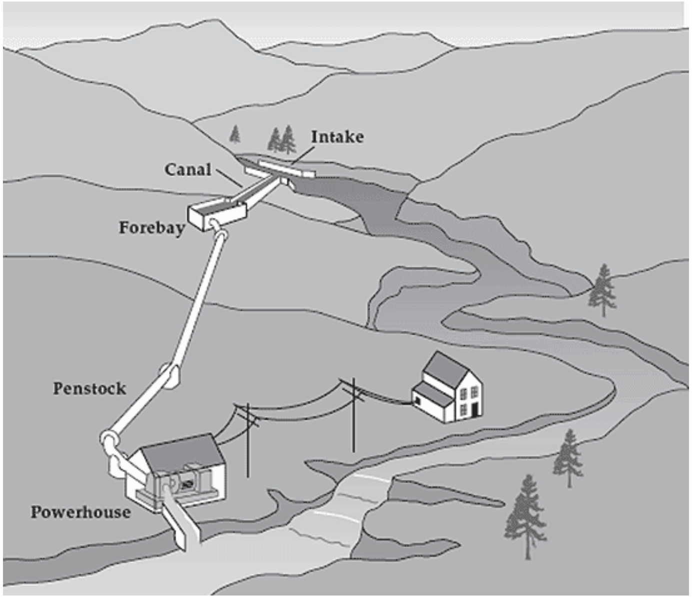


Figure 18. Small run-of-river system landscape schematic *(TEEIC, 2017)*

Most environmental and socio-economic concerns related to large hydropower plants are practically negligible when it comes to micro hydro systems. Schemes with a capacity under 100 kW do not flood useful land, damage local ecosystems, affect seismic activity or cause population displacement. Micro hydro projects are often designed and built in an environmentally friendly way to fit into the surrounding landscape, whilst generating electricity to meet local demand without the need of using large transmission lines. Moreover, micro hydro systems are suitable for places with abundant fish presence, which is an important aspect in many parts of the world, including Scotland (Botelho, et al., 2017).

Hydropower turbines can be divided into two main categories; impulse and reaction. The selection of suitable type largely depends on available head and flow rate. These are the main aspects that should be considered throughout the initial assessment. Related capital costs and expected efficiency during operation are more detailed aspects that should also be considered before the final decision is made. Both main types of turbines have been widely used across the world, and there is not one uniform type that would be ideal for any situation.

Impulse turbines use the water velocity as a kinetic energy before moving the runner and discharging at atmospheric pressure. Therefore, these turbines cannot function as a part of pumped storage schemes, as they are not submerged, thus cannot work in a reversed mode. Impulse turbines are mainly used for high-head low-flow applications to gain enough kinetic energy that can be squirted in the jets. A Pelton wheel is characterised by blades that are symmetrically split into two parts to transfer most of the kinetic energy to rotate the runner. A variation of this type is a Turgo wheel that is based on a similar principle except the incoming water passes from one side to the other, and it is manufactured exclusively by Gilkes in England (EERE, 2017). The last type is a Cross-flow turbine, also known as Banchi or Ossberger. This turbine is represented by a cylindrical runner, which is often made from sheet metal, and allows incoming water to pass twice through the blade ring. Cross-flow turbines are often used for micro hydro applications in the UK, and especially at sites with higher heads available (Renewables First, 2015). Basic schematic of each impulse turbine is captured in *Figure 19.*

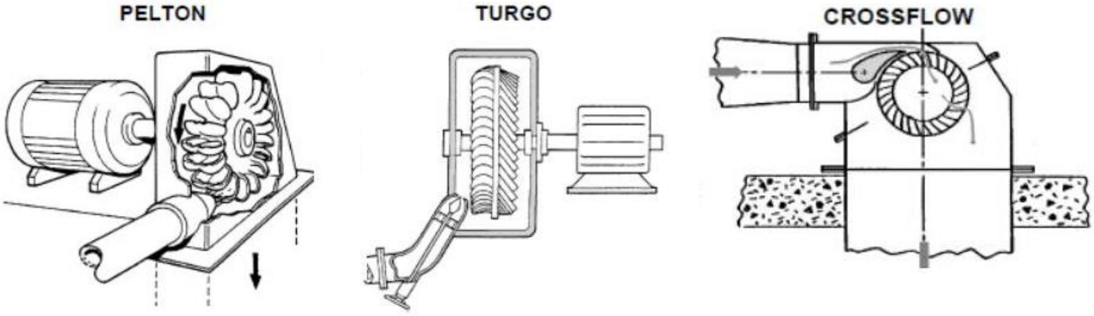


Figure 19. Basic schematic of widely used impulse turbines *(HydroBPT, 2017)*

Reaction turbines benefit from the gained pressure to move the runner. The turbine is fully submerged, therefore can be used in a reversed mode as a motor in pumped hydro schemes. Reaction turbines are suitable for sites with higher flow rates and lower heads. A Francis turbine is fed by water from spiral casing, and includes a runner with fixed blades. Francis turbines have been a core part of many large hydropower schemes, however are also occasionally used in micro hydro applications. A Propeller turbine is an axial-flow system that usually comprises of guide vanes. These turbines have between three to six blades that are constantly in contact with flowing water. *Figure 20* shows basic schematics of the two main types of reaction turbines. A variation of this type is a Kaplan turbine which was invented by Czech scientist Viktor Kaplan. Kaplan turbines have automatically adjustable blades to achieve high efficiencies at different flow rates, thus are often a feasible solution for low-head micro hydro applications. Another option for small hydro projects can be pump as turbine (PAT) system that has been successfully proven especially in developing countries as a low-cost solution with a simple structural design. PAT systems are feasible even for very small flow rates and heads (Binama, et al., 2017).

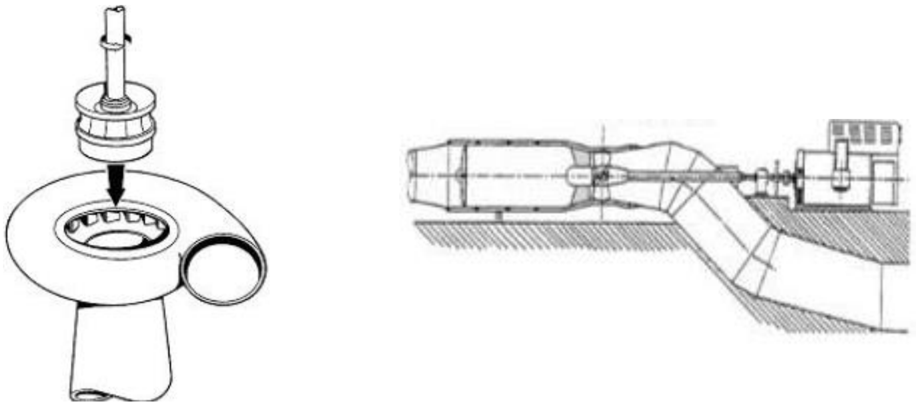


Figure 20. Basic schematic of two main reaction turbine types; Francis turbine (left) and Propeller turbine (right) *(Clarke, 2016)*

The suitability of specific turbines regarding available head and flow rate is shown in *Figure 21*. Turbines recommended for micro hydro projects are generally placed towards the bottom left area of the graph. It can be seen that the hydro resource in the given location must be evaluated first to narrow the scope of possible options that can be further investigated.

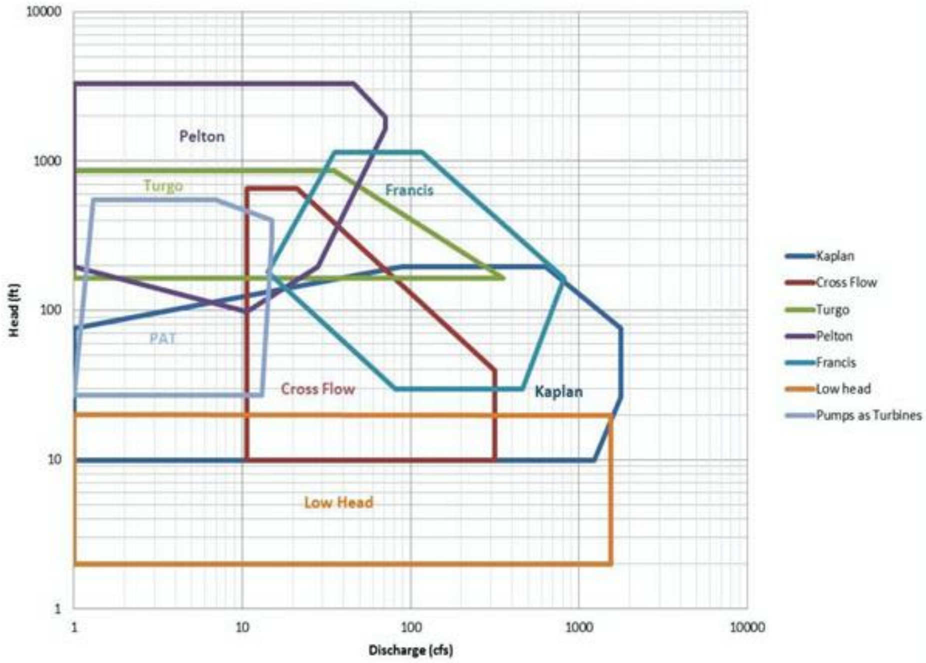


Figure 21. Turbine selection regarding available head and flow rate *(Wyoming Renewables, 2017)*

Although the vast majority of hydropower schemes are built with reaction or impulse turbines, other types have also been successfully demonstrated in projects across Scotland. An Archimedes Screw is a gravity-based turbine that is suitable for extremely low-head applications. The Archimedes Screw with a head of two meters was installed near Aberdeen as a part of Donside Hydro Community project in 2016 to generate electricity for the village (rated capacity of 100 kW), whilst providing an interesting site for tourists. The Aberdeen Community Energy (ACE) project required a capital investment of £1.25m, and became the first urban community hydro development in Scotland (Power-Technology, 2017). The system in operation is shown in *Figure 22.*

Another state of the art concept which has been tested in Scotland is the Water Engine system that uses hydraulic rams to convert water motion into high pressure fluid to generate electricity. This system is suitable for ultra low-head applications, whilst being environmentally friendly to fish that can swim through the system without getting harmed. The Water Engine demonstration project is proposed to be built by Water Engine Technologies as a part of Energise Galashiels Trust community project to harness the untapped hydro potential on the Scottish Borders (Water Engine Technologies, 2016). The proposed development received a funding of £24,000 from Local Energy Scotland – Challenge Fund, and is expected to supply 400 kW of electricity to the town (Local Energy Scotland, 2017). The Water Engine concept design model is shown in *Figure 23.*

Figure 22. Archimedes Screw as a part of Donside Hydro Community project *(Power-Technology, 2017)*

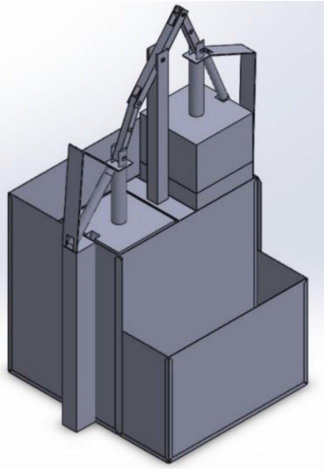


Figure 23. The Water Engine concept design *(Water Engine Technologies, 2016)*

3.1.1. Harlaw Hydro in Balerno Case Study

The Balerno Village Trust set up Harlaw Hydro Ltd in 2012 to install and operate a community owned micro hydro system to generate green electricity for the village situated near the capital of Scotland. The Francis turbine with a rated capacity of 95 kW is placed at the outlet of Harlaw reservoir to generate electricity for about 56 homes, whilst saving approximately 130 tonnes of CO_2 emissions annually (Schiffer, 2014).

A feasibility study was financed through the Scottish Government's Community and Renewable Energy Scheme (CARES), and strongly supported by dedicated local team members that volunteered to develop the project, which is often the ultimate characteristic of any community-based project. The proposed development originally raised £313,000 through stakeholders' investments, however an additional £50k was raised afterwards, as the rated capacity was increased from 65 to 95 kW. The hydro plant was designed to benefit from the Feed-in-Tariff (FIT) payments, which were guaranteed at a fixed rate of 20 pence per kWh for 20 years at the time of construction process of the micro hydro system (Schiffer, 2014). The scheme was successfully built and officially opened by the Minister for Business, Energy and Tourism, Fergus Ewing, on the 1st of September 2015 (Harlaw Hydro, 2017).

The system was installed with a power meter that measures real-time data at the site, and automatically uploads them every hour on the Harlaw Hydro website. This includes current water flow (l/s), guide vane angle (%), total hours of run (h), inlet valve pressure (bar), and many other technical data including statistics of generated power since the project was launched (Harlaw Hydro, 2017). The fact that anyone within and out with the community can see the real outcomes of the micro hydropower scheme, including how many homes are supplied by green electricity, is a very important aspect that should be replicated in any community owned development. This gives the stakeholders real credibility that small-scale renewable energy systems are able to provide a reliable electricity supply, whilst generating valuable income for the community. The construction and operation stages of the micro hydropower project are captured in *Figure 24.*

Figure 24. Harlaw micro hydro project in Balerno; construction phase (left) and installed Francis turbine with other mechanical and electrical equipment (right) *(Harlaw Hydro, 2017)*

3.2. Solar PV Panels

It is hard to think of a more rapidly developing technology than electricity generation from photovoltaic panels (PVs). The world leader in producing and installing PVs is China with 15.2 GW added capacity in 2015. Similarly, the PV industry in the UK has enormously progressed in the past two decades. The expansion has been noticeable especially in the past several years with the peak in 2015, when the UK installed PVs with a rated power output of 3.5 GW, which was the largest achievement in the entire European market (International Energy Agency, 2015). This 'boom' was caused mainly due to the introduction of the Feed-in-Tariff by the UK government, which encouraged many people to install solar panels on their roofs to produce green electricity. Even though the FIT rates were significantly altered recently, the uprising trend of PVs installation is likely to continue. This prediction assumes that the prices of PVs will keep falling down, as we could have seen in the past number of years.

The PV technology has been introduced to convert solar energy (direct and diffuse solar radiation) directly into electricity. The most common PV cells are built from silicon which is one of the most abundant elements in the world (Boyle, 2012). Other materials have been researched already, however silicon seems to be the most financially feasible solution so far when manufacturing PVs.

Silicon cells are made either from mono or poly crystalline. Monocrystalline silicon cells are used still commonly used, although new types of cells have been recently introduced. The Czochralski process is used to manufacture monocrystalline silicon cells, however this method is relatively expensive. Therefore, PV cells are more frequently made from polycrystalline (multicrystalline) silicon, which is more financially feasible, whilst achieving sufficient efficiencies. Another crystalline material that can be used is gallium arsenide, also called compound semiconductor. Currently, the use of these cell types is increasing rapidly, due to their low prices and adequate efficiencies. A cheaper but less effective option is using thin film PV cells, which are usually made from amorphous silicon, copper indium diselenide, or cadmium telluride. These types might become more common in the future, as they are still undergoing laboratory research (Boyle, 2012). The three main PV types are shown in *Figure 25.*

Figure 25. Three main types of commercially used solar PV panels *(Advanced Solar Technology, 2013)*

The solar PV technology has been successfully used not only in the domestic sector, but also in many community-based projects across Scotland. One example is the Edinburgh Community Solar Co-operative (ECSC) scheme that manages 25 solar PV systems installed on roofs of buildings owned by Edinburgh City Council. The public buildings include primary schools, and community and leisure centres with an overall rated capacity of 1 MW (the largest project of its kind in the UK) (Schiffer, 2014). Generated electricity is primarily harnessed by the public buildings, and any surplus is sold to the National Grid. The gained profit is then invested locally through the Community Benefit Fund that has been created to support new projects in each involved area. Moreover, each building is equipped with a real-time data display that helps pupils to better understand renewable energy systems, which is crucial in the long term run when moving towards a low carbon future. This innovative project produces a significant amount of zero-carbon electricity, whilst contributing to the Edinburgh Council's 2020 target to reduce CO_2 emissions by 42% (ECSC, 2017). Some of the projects can be seen in *Figure 26.*

Figure 26. Solar PV installations as a part of ECSC scheme; Davidson mains primary school 35 kW (left) and Ratho primary school 80 kW (right) *(ECSC, 2017)*

3.2.1. Isle of Eigg Case Study

The Isle of Eigg is a small island located on the west coast of Scotland as a part of the Inner Hebrides that became the world's first off-grid site that generates electricity from a combination of three renewable energy resources; micro hydropower (100 kW, 6 kW and 5 kW), four small wind turbines (6 kW each) and solar PV panels (50 kW). The integrated system also includes battery storage to provide a reliable power supply 24 hours a day, and two 80 kW diesel generators that function as a backup system. The Eigg Electric project required a financial cost of £1.6m including all renewable power systems and required grid connections. A large proportion of the capital was gathered from EU grants and other government incentives (Schiffer, 2014).

The photovoltaic array has a rated output of 50 kW, and is situated in on the south-facing hill in the southeast of the island. The tilt of installed PVs is 20° from the horizontal axis, which was evaluated as an optimal all-year-round solution for a static assembly. The PVs generate a direct current that is converted to an alternative current through inverters that are placed on the nearby control building before entering the electrical grid. The control building includes not only inverters, but also batteries that store any surplus electricity generated on the island. To ensure that the diesel generators do not have to be switched on frequently, each building is restricted to use 5 kW of power at any time of the day, and commercial buildings are allowed to drag a maximum of 10 kW at any time (Eigg Electric, 2017).

The combination of three small-scale renewable power systems has been proven as a very effective approach to overcome the stochastic nature of renewables. There is rarely a situation where either sun, hydro or wind resource would not be available to generate electricity, and even in this case battery storage comes into play. Therefore, diesel generators have not been frequently used since the system was installed in 2008.

The Eigg community keeps innovating their system, which currently also includes new solar PVs installed on the roof of the primary school that help to meet power demand of the building. The Eigg Electric project has successfully demonstrated that solar PVs can provide a reliable electricity supply even in remote Scottish off-grid areas, if they are combined with appropriate storage technology. The Eigg PV array and panels installed on the primary school's roof are shown in *Figure 27*.

Figure 27. Solar PV panels on the Isle of Eigg; community owned PV array (left) and PV panels installed on the roof of the primary school (right); pictures taken during a field trip on April 4, 2017

4. Design Approach and Software Evaluation

The potential implementation of any community owned renewable energy project is a complex process that requires a multi-disciplinary approach, often supported by engineering tools and software packages. As this project seeks to address not only technical aspects of the water source heat pump technology in a combination with renewable power generation, but also financial, environmental and social issues, numerous sources must be used to deliver an all-round solution. This means that different scientific approaches and specific design tools must be evaluated before selecting the most appropriate ones that are thereafter used in the detailed analysis section.

Sustainable heating systems can be generally designed in two ways. The first approach starts with a selection of a specific community, and then evaluates all different heating systems that could be considered. The scope is then narrowed down to a given number of options, which are further investigated throughout the appropriate analysis. The second approach is to look at a specific technology first, and then choose a potential site afterwards. The specific location can be selected with regards to established heating demand, geographical location, annual occupancy, or other unique aspects.

Annual heat demand of buildings in Scotland can be gathered from the Heat Map tool that is officially provided by the Scottish Government, and shown in *Figure 28.* In 2016, the heat map dataset has been offered to every local authority in Scotland to collect relevant data that can be used to establish suitable locations for future low carbon heating projects (Scottish Government, 2016). Alternatively, heat demand data can be gathered through different software packages dedicated to building design upgrades. This includes the HEM tool that is primarily designed to map the possible energy performance of a dwelling, however it also has pre-defined results that are embedded in the tool (ESRU, 2010). There are multiple options to select within each determinant tab, which can lead to a reliable estimation of annual heat demand. The main determinants are shown in *Figure 29.* Another way to establish yearly heat demand is to find information in the CIBSE standards. Detailed guidance on the calculations procedure of heat load in a typical UK dwelling is provided in the GVB1/16 CIBSE Guide B1 (CIBSE, 2016). Finally, the most accurate solution would be to visit each building, and gather exact annual heat demand from the residents. Nonetheless, such approach is very difficult to apply in the real-world, especially due to time constraints and confidentiality, thus not likely to be practically viable.

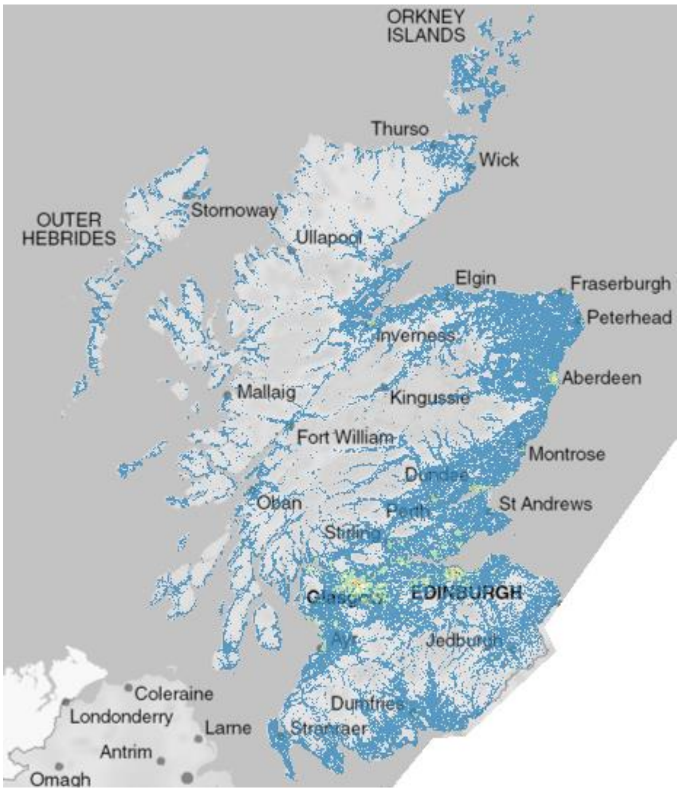
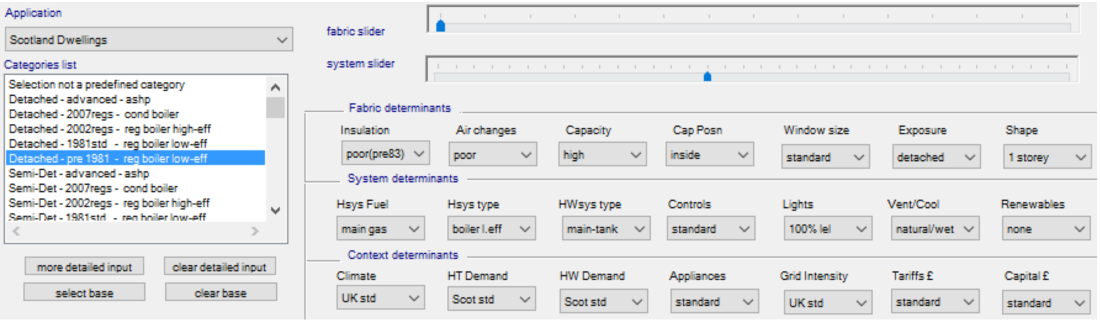


Figure 28. Scotland’s Heat Map *(Scottish Government, 2016)*



Application

Scotland Dwellings

Categories list

Selection not a predefined category
Detached - advanced - ashp
Detached - 2007regs - cond boiler
Detached - 2002regs - reg boiler high-eff
Detached - 1981std - reg boiler low-eff
Detached - pre 1981 - reg boiler low-eff
Semi-Det - advanced - ashp
Semi-Det - 2007regs - cond boiler
Semi-Det - 2002regs - reg boiler high-eff
Semi-Det - 1981std - reg boiler low-eff

Fabric determinants

Insulation	Air changes	Capacity	Cap Posn	Window size	Exposure	Shape
poor(pre83)	poor	high	inside	standard	detached	1 storey

System determinants

Hsys Fuel	Hsys type	HWsys type	Controls	Lights	Vent/Cool	Renewables
main gas	boiler l.eff	main-tank	standard	100% lel	natural/wet	none

Context determinants

Climate	HT Demand	HW Demand	Appliances	Grid Intensity	Tariffs £	Capital £
UK std	Scot std	Scot std	standard	UK std	standard	standard

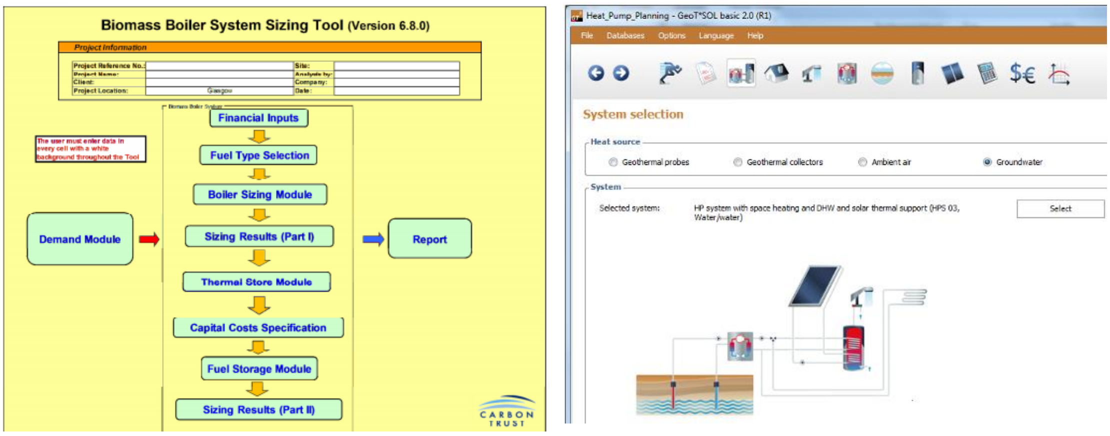
Figure 29. Snapshot of the HEM tool designed to map energy performance of buildings *(ESRU, 2010)*

Water properties in the selected area must be evaluated when assessing any WSHP technology. In case of seawater-based systems, water temperature is the crucial property that needs to be analysed (salinity is important mainly for open-loop systems to avoid corrosion), whereas designers of river-based systems should consider water flow, also called velocity, temperature and available depth.

In Scotland, the Hydrometry team is responsible for collection of data from surface water systems (rivers, streams and others). This data can be collected from SEPA that publishes up-to-date statistics on their website including water levels and quality. Data is collected from more than 400 ‘gauging’ stations in Scotland, which are regularly checked by hydrologists through computer based systems to ensure that instrumentation is calibrated to meet mandatory standards. The gauging method is a fast-evolving process that can be carried out by numerous devices. SEPA hydrologists often use Flow Trackers, which are sonar devices mounted on a long metal rod. The top of the rod is connected to three sensors which then provide data to an electronic device that calculates river flow by measuring the velocity of particles that pass through the sensors. A more sophisticated method is to use cableways devices that can measure data more accurately, however these devices are significantly heavier and require at least two people for operation. Both types of gauging methods are shown in *Figure 30.* The collected data are useful not only for the scientific community within the local authorities, but also for planners, policy makers and other users to plan their activities on the Scottish rivers (SEPA, 2017). Otherwise, National River Flow Archive (NRFA) run by the Centre for Ecology and Hydrology (CEH) can also be used for this purpose and/or to validate results gathered from other sources (CEH, 2017). A field survey including individual gauging process might be required especially when assessing the water properties of smaller rivers and streams in rural areas. Alternatively, software tools dedicated to hydropower resources can be used, which is further discussed later in this chapter.

Figure 30. Gauging devices used by hydrologists; Basic Flow Tracker (left) *(SonTek, 2017)* and advanced cableways device (right) *(SEPA, 2017)*

The WSHP system design can be executed in numerous engineering programs dedicated to low carbon heating systems. The Biomass System Sizing Tool developed by Carbon Trust has been designed to help design engineers and biomass installers during the decision-making procedure (Carbon Trust, 2013). Although this tool is primarily devoted to design biomass systems, the basic sizing of a heat pump system including thermal storage can be completed only with several minor adjustments in the tool's interface. The tool also enables the user to create a heat demand profile that is necessary when designing a low carbon heating system. Software dedicated specifically to space heating and hot water systems including WSHP has been developed by Valentin Software company based in Germany. GeoT*Sol is a user-friendly tool for the design of heat pump systems that takes into consideration heat losses and electricity consumption as a result of the dynamic simulation with steps as short as one minute. The software also calculates the COP, SPF and financial costs associated with different tariffs and variable electricity prices, and evaluates the overall efficiency of the heat pump system (Valentin Software, 2015). Graphical interfaces of both design tools are captured in *Figure 31*. Other tools, such as Heat Pump Design Software provided by The Easy Renewable Software Solutions, are often dedicated only to air and ground source systems (RSS, 2017).



Project Location: Glasgow

Heat source: ○ Geothermal probes ○ Geothermal collectors ○ Ambient air ● Groundwater

Selected system: HP system with space heating and DHW and solar thermal support (HPS 03, Water/water)

Figure 31. Low carbon heating system design tools; Biomass Boiler Sizing Tool (left) *(Carbon Trust, 2013)* and GeoT*Sol (right) *(Valentin Software, 2015)*

The basic layout of a heat pipe network as a part of any district heating scheme can be created through Google Maps interface, and ideally validated by field survey on the site. This is due to the reason that online data might not be up-to-date, especially in more remote rural areas. A more detailed sketch can be executed in the Digimap tool that has been developed at the University of Edinburgh for UK academia to analyse maps and geospatial data (Digimap, 2017). The piping design to provide reliable heat distribution with minimal heat losses should follow best practice procedure set by CIBSE Guide C, Chapter 4, which is dedicated to Flow and Fluids in Pipes and Ducts (CIBSE, 2016). The selected pipe should include detailed information provided by the manufacturer that can be used to estimate thermal losses in the piping network. This also applies to the pipe producer REHAU that publishes a comprehensive description of each pipe regarding pressure drop and thermal losses related to the flow rates (Rehau, 2017). Extremely detailed and accurate thermal losses could be evaluated through computational fluid dynamics (CFD) analysis that is based on the Navier-Stokes equations, however this would be tremendously time consuming, and in most cases not necessary when designing district heating projects.

A wide range of tools can be used to assess the hydropower resource if the WSHP system is to be river-based, or within a relatively short distance to a running water source. Different software tools developed for planning and designing of small-scale hydropower plants at a feasibility stage have been investigated by Punys et al. (2011). Many advanced tools are integrated with Geographic Information System (GIS), which can provide very accurate results even when evaluating complex projects in remote areas. Different types of design tools to assess hydropower resource are shown in *Figure 32.*

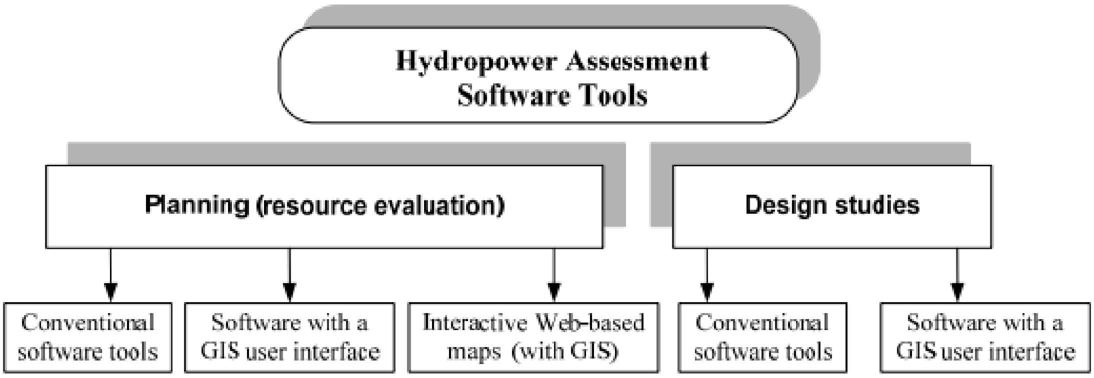


Figure 32. Five software types used for hydro resource assessment *(Punys, et al., 2011)*

A number of countries, such as Canada, Italy, Norway, USA and Scotland, re-assessed their hydro resource based on spatial information of their water catchments, combined this data with GIS mapping tools, and developed their own hydro-site identification tools, so called Atlases. In Scotland, such tool is called Hydrobot, which has been commissioned by the Forum for Renewable Energy Development, and officially acknowledged by the Scottish Government. Hydrobot functions not only as a GIS tool to identify potential micro hydropower schemes, but also to evaluate the financial feasibility of the site. This unique tool, which uses flow duration curve (FDC) hydrology model, is based on accurate data gathered from 10 m x 10 m grid across the whole of Scotland, and calculated water velocity was validated by data gathered at SEPA gauging stations (Punys, et al., 2011). Other hydropower estimation tools, including CatchmentsUK and LowFLows 2, have been developed by the Wallingford Hydro Solutions (WHS). The former tool is designed to define water catchments in the UK within precise catchment boundaries, whereas the latter software is dedicated to the estimation of natural and influenced flow regimes in ungauged catchments. Although LowFlows 2 was primarily developed by CEH and Environment Agency of England and Wales (EA), the program was extended to the rest of the UK with data gathered from SEPA, thus can be reliably used to model projects in Scotland (WHS, 2011). Hydrometric area divisions of the whole UK and an example of a specific catchment boundary are captured in *Figure 33.* Appropriate use of all these tools can become convenient when assessing not only micro hydropower resources, but also running water properties necessary to design WSHP systems.

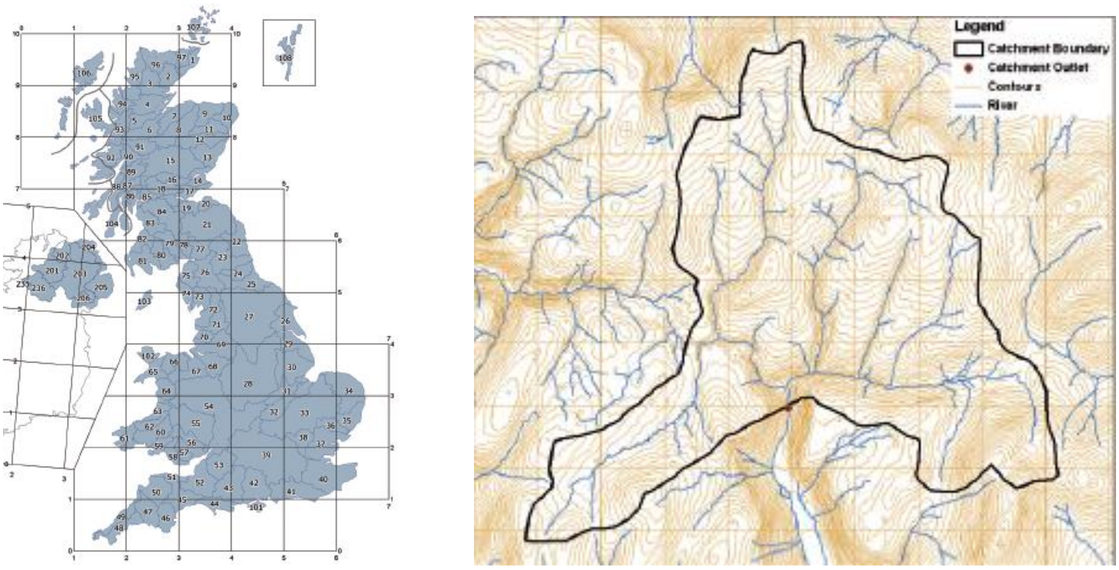


Figure 33. Hydrometric area divisions in the United Kingdom (left) and an example of a catchment boundary (right) *(WHS, 2011)*

In case of insufficient hydropower resources in the selected area, PV panels can be implemented instead to generate the required electricity consumed by the heat pump. Numerous software tools can be used to assess the solar radiation and design of PVs. Software package PVsyst has been widely used in many academic and industrial projects. The tool is design for sizing, simulation and data analysis of PV systems. PVsyst is defined to be user-friendly with embedded meteorological data from various sources. A thorough system design in PVsyst can be evaluated in a performance analysis mode with a simulation step of one hour. Another option to design and analyse system performance is PV F-Chart that has been developed at the Solar Energy Laboratory of the University of Wisconsin. This software can estimate long-term system performance, and is capable of modelling off-grid projects, as it includes pre-defined battery storage systems that can be adjusted according to user requirements. Researchers often choose Environmental System Performance-renewable (ESP-r) tool, which has been developed at the University of Strathclyde, and has many state of the art simulation features. This innovative tool enables user to take into consideration more realistic conditions, such as air moisture or heat gain, thus providing reliable outcomes based on real-world circumstances. If shading effect represents a major issue in the selected area, PV*SOL Expert should provide a thorough estimation. This tool offers a 3D visualization, and simulation steps can be set to as low as 10 minutes (Sharma, et al., 2014). A 3D model showing shading animation in PV*SOL Expert is captured in *Figure 34.* Although there is a wide range of other engineering tools that could be evaluated, it is not core of the project to focus strongly on the PV design.

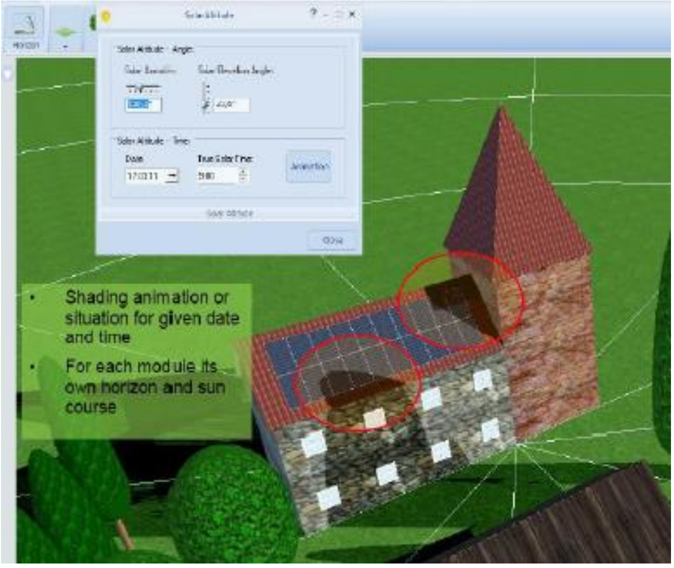


Figure 34. 3D shading animation for given date and time in PV*SOL Expert tool *(Sharma, et al., 2014)*

Supply-demand matching is a critical aspect that needs to be addressed if WSHP system is to be supplied by electricity generated from renewable sources. There is a limited number of tools that can deliver appropriate outcomes. A possible solution to this complex problem is Merit, which was developed at the University of Strathclyde as an open source dynamic supply-demand matching simulation tool. This tool gives an opportunity to combine renewable energy technologies, such as PV panels, heat pumps, batteries or thermal storage to meet heat or power demands. Merit contains climate data from many UK areas which is highly beneficial when evaluating the system performance based at a specific location. The degree of supply-demand match is described by statistical parameters that are calculated for the exact chosen specifications with an example shown in *Figure 35* (ESRU, 2017b). Industrial supply-demand projects are often modelled in a software called Hybrid Optimization Model for Electric Renewables (HOMER), which has a user-friendly interface to design distributed generation (DG) systems. HOMER allows users to analyse the technical and financial feasibility of many technological options, whilst taking into consideration variations of electricity prices and renewable energy resource availability. Another tool that can be potentially used for this purpose is Renewable Energy Technologies Screen (RETScreen) that has been developed under the Canadian Government. This free tool is available in 36 languages, and stands out by offering emission analysis (Sharma, et al., 2014). Finally, energyPRO developed by EMD is an advanced and flexible energy modelling software that is widely used for techno-economic optimisation purposes (EMD, 2017). This tool stands out especially on the thermal side compared to other commercially available tools, which is advantageous for modelling sustainable heating systems, such as a community WSHP.

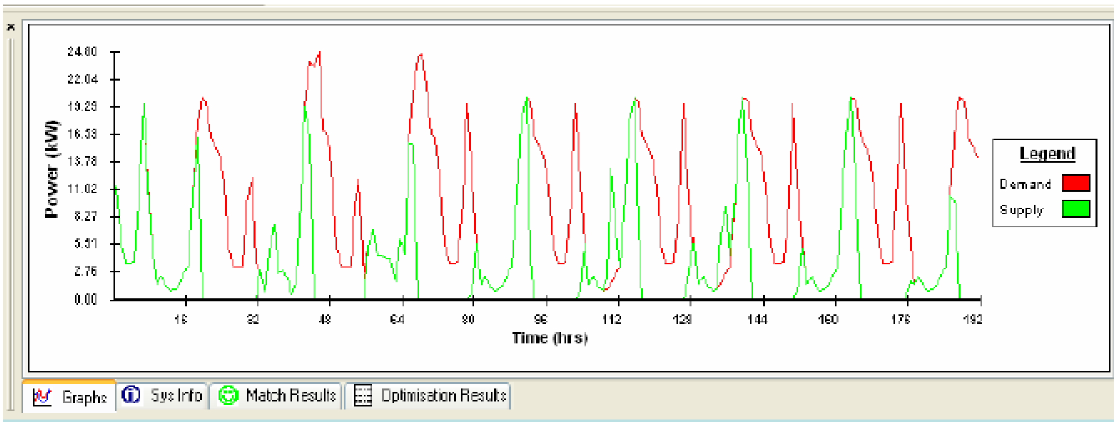


Figure 35. Example of supply-demand matching graph simulated in Merit design tool *(ESRU, 2017b)*

5. Project Methodology

The creation of project methodology is an important part of the thesis that could be eventually used in other future projects that concentrate on community-owned sustainable heating systems. The project has been divided into numerous core stages that have been evaluated as the most essential steps that should be followed. Each stage contains many different subsections that are more thoroughly described in this chapter. The main steps that have already been executed or will be further developed are shown in *Figure 36.*

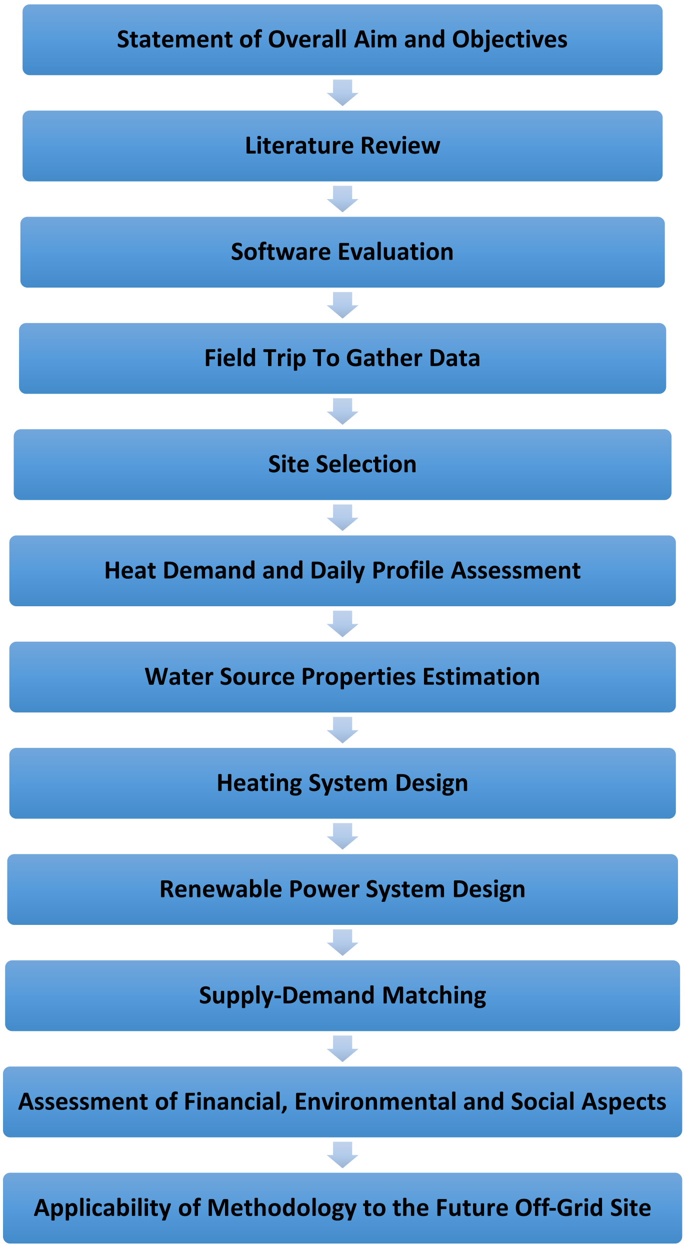


Figure 36. Project methodology summarised in the core steps

This project seeks to assess the feasibility of using water source heat pumps supplied by renewable power generation to provide low carbon heating for Scottish communities. Therefore, a thorough literature review was executed to describe the main technical components and state of the art concepts of WSHP technology, followed by a brief overview of micro hydropower and PV systems. Since this project aims to design a community-owned system, appropriate case studies were selected to demonstrate socio-economic benefits related to such schemes. Renowned international journals, technical books and official reports published by the Scottish Government were central to the literature review, with appropriate illustration included to demonstrate the appropriate clarity of specific system components or similar low carbon projects. The literature review has been a major step to introduce all important aspects that will need to be considered in the following parts of the project.

To ensure the robustness of selected design methods and computer-based tools that will be used in the analytical section, appropriate design approaches and a comprehensive software evaluation should be introduced in any engineering feasibility study. This guarantees that various design options were taken into consideration before selecting the most favourable ones. Moreover, similar projects might not be able to access the same software tools that will be selected during the design process, due to restricted accessibility or limited knowledge of a specific tool. Therefore, the software evaluation was completed not only to choose the best possible tool for this project, but also to present other possible options that might be more favourable for other feasibility studies.

The Isle of Arran has been selected as a case study for this project, thus a brief introduction of renewable energy systems already installed on the island will be presented. Most of this data will be gathered from the Energy Audit that was prepared and published by the local council in 2016. The official report will be an important source of information, validated by a field survey carried out on the island. The survey can provide a more thorough insight to systems that are already implemented, as well as give an opportunity to make an illustration that will be used later in the thesis. The field survey should also be very supportive in terms of identifying a specific site on the island with a nearby water source that will be further investigated.

After the selection of a specific site, the annual heat demand will be established, which is required before creating a daily demand profile. Annual heat demand will be obtained from the Scotland’s Heat Map that is provided by the Scottish Government. The HEM tool will be used to model all houses that will be part of the community-owned WSHP scheme to validate data gathered from the Heat Map. The key input determinants that are required by HEM will be estimated from Google Street View and the site survey. Afterwards, the validated annual heat demand will be used to establish daily heat demand profiles of the dwellings to size the WSHP system. Daily profiles will be modelled in Merit, where thermal demand profile of a pre-defined 3-bedroom house will be adjusted to the actual annual demand gathered from the Heat Map. This method will also identify daily peak demands that will be crucial for the system sizing phase.

A comprehensive investigation of water source properties will be assessed to guarantee that the WSHP system can collect enough heat from the source and transfer it to the heat sink, which are in this case residential houses. Daily water temperature could either be sourced from data measured by SEPA, or another reliable data measuring source, and flow velocity and depth gathered either from SEPA or NRFA. Alternatively, hydro resource data can be collected from CatchmentsUK or LowFlow 2 that will be used to assess hydropower resources. A sound hydro resource assessment will also be necessary to estimate the water temperature drop caused by the WSHP system, and the potential daily water intake to investigate the suitability of an open-loop system. Both aspects must follow official regulations set by SEPA.

The next stage will be concentrated on the system design that will start with the system sizing in the Biomass System Sizing Tool to find the ideal capacities of WSHP and thermal storage tank. This stage will be followed by detailed system design executed in the GeoT*Sol software that has been developed to model ground water source heat pump systems. Heat demand profiles and water properties which have already been obtained will be used as input data to the design tool. The outputs will not only include weekly COPs of the system and an overall SPF value, but also calculate the river temperature drop of the selected water source. The hot water storage tank size might be altered in the supply-demand matching stage to provide a technically and financially ideal solution. The system design outcomes from GeoT*Sol will be validated by the Biomass System Sizing Tool including heat losses of the system. The piping layout will be sketched in AutoCAD by extracting accurate geographical data of the selected site from Digimap.

Renewable resource evaluation and the consequential basic system design will be a core focus of the following phase. Firstly, a hydropower assessment will be established in CatchmentsUK and LowFlow2. If the selected site is evaluated as suitable for a micro hydro power generation, the system will be designed in energyPRO, which should provide satisfactory outcomes. PV system modelling will be considered if hydropower resource is evaluated as insufficient. The PV system will be designed in PV*Sol and the data validation will be analysed in Global Solar Atlas developed by the World Bank Group.

The last stage of technical analysis of the low carbon heating system is to model the entire system in a supply-demand matching tool. For this purpose, energyPRO will be used to optimise the sizing of all the necessary components. The supply-demand model will consider not only renewable resources to generate electricity on the site, but also daily variation in electricity prices to guarantee space heating and hot water availability in times of high demand and low renewable power supply.

The financial, environmental and social aspects related to the proposed low carbon heating scheme will be studied in the following stage. Although the financial analysis will be primarily analysed in energyPRO, different funding and incentive schemes will be evaluated separately. Environmental considerations during construction and operation phases will be discussed with regards to SEPA and SNH regulations. Furthermore, social aspects, such as job creation and enhancement of community spirit, will be discussed.

Finally, the methodology that was prepared for the existing site will be tested on the future off-grid site. This will be a high-level assessment to detect the main obstacles related to the potential community project that might go ahead in the future. Moreover, this process can uncover imperfections that might be altered in the established methodology, which could be used in similar projects within and out with Scotland.

6. Analysis and Results Discussion

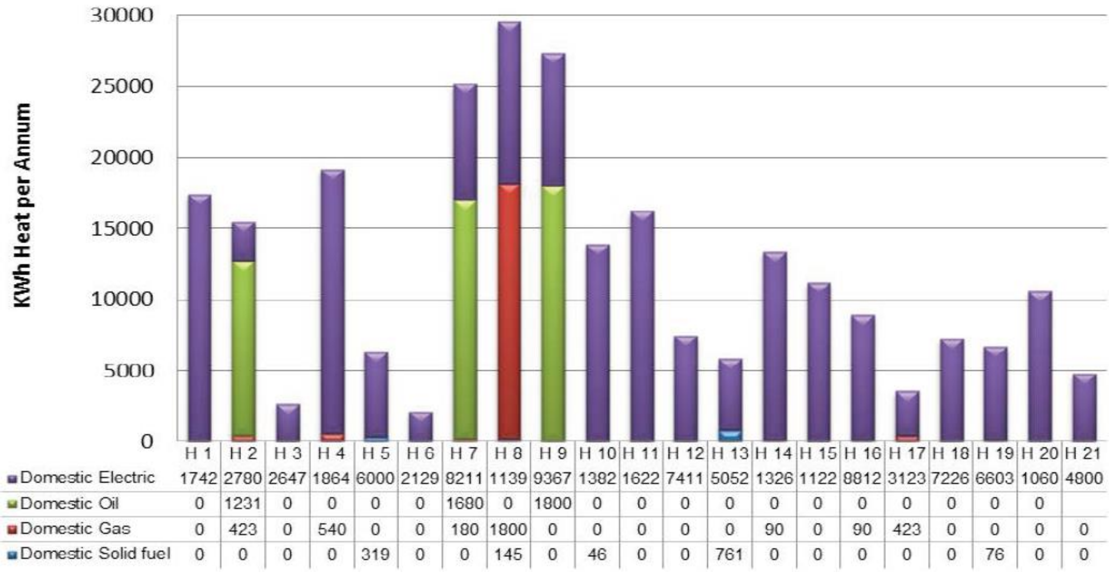
6.1. Energy on the Isle of Arran

The Isle of Arran has been selected as a case study for the feasibility analysis of WSHP system to provide affordable low carbon heating for a small community. Arran is the seventh largest Scottish isle, and home to approximately 5300 permanent residents. It is the largest island in the Firth of Clyde, and can be reached by two ferry routes operated by CalMac which is a service provider subsidized by the Scottish Government (Calderwood & Logan, 2016). Arran is connected to the national electricity grid by subsea cables from Kintyre, however is not part of the national gas grid network. This leads to an increased risk of fuel poverty that residents on the island are often exposed to. The map of the island gathered from Digimap is shown in *Figure 37.*

Figure 37. Geographical map of the Isle of Arran *(Digimap, 2017)*

The major electricity supplier on the island is Scottish and Southern Energy (SSE), whilst other fuel types are provided by both island and mainland suppliers. Although the majority of energy demand is met by non-renewable sources, several projects have been successfully implemented on the island, including micro hydro schemes, small wind turbines or large biomass boilers to heat domestic and non-domestic buildings. The National Trust and dedicated community groups are eager to develop proposals for more renewable energy projects to increase the resilience of the island, and decrease the level of fuel poverty, as the fuel costs on Arran are amongst the highest in the whole of Scotland (Calderwood & Logan, 2016).

Both domestic and non-domestic heating consumption on Arran is predominantly met by electric heaters, with a number of buildings supplied by bottled and LPG gas, coal or kerosene, that represent an overall fuel consumption fraction of 1, 2 and 5 per cent, respectively (Calderwood & Logan, 2016). More than a half of all domestic buildings on the island are detached homes, which generally require more space heating compared to flats as a part of apartment buildings. Since electric heaters are one of the least efficient heating system types, winter utility bills must be significantly high for many families on the island. The domestic heating consumption by fuel type can be seen in *Figure 38.*



	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	H 9	H 10	H 11	H 12	H 13	H 14	H 15	H 16	H 17	H 18	H 19	H 20	H 21
■ Domestic Electric	1742	2780	2647	1864	6000	2129	8211	1139	9367	1382	1622	7411	5052	1326	1122	8812	3123	7226	6603	1060	4800
■ Domestic Oil	0	1231	0	0	0	0	1680	0	1800	0	0	0	0	0	0	0	0	0	0	0	
■ Domestic Gas	0	423	0	540	0	0	180	1800	0	0	0	0	0	90	0	90	423	0	0	0	0
■ Domestic Solid fuel	0	0	0	0	319	0	0	145	0	46	0	0	761	0	0	0	0	0	76	0	0

Figure 38. Domestic heating consumption by fuel type divided into 21 different building categories *(Calderwood & Logan, 2016)*

Although micro hydro schemes and solar PV systems have been installed across many parts of the island and generally receive positive feedback from the residents, wind energy projects are exposed to environmental limitations from SNH and the presence of protected wildlife areas. Moreover, considerably strong public resistance, even against small wind developments, has been discovered during a field trip, which has been an important part of the project methodology. There are currently three small wind turbines installed in the southern part of the island, however there have been several objections raised due to visual impact and increased noise pollution. Therefore, after an all-inclusive consultation with Arran Community Council and several residents of the island, it has been decided to exclude wind energy assessment from the feasibility study. This is due to the reason that any wind energy project would most likely be disregarded due to public perception in any community on the island. Small wind turbines which are already installed are shown in *Figure 39.*

Figure 39. Wind energy systems on Arran; Small wind turbine next to Kilmory primary school (left) and turbine as a part of farm land in the south (right); pictures taken during a field trip on June 23, 2017

6.2. Site Selection

The purpose of this project is to prove that WSHP technology is a reliable low carbon heating solution applicable not only for large-scale industrial sites, but also for small rural communities. Therefore, the three main towns on Arran, which are Lamlash, Brodick and Lochranza were excluded from the case study locations. Moreover, the feasibility of WSHP application has been investigated in most of these towns already, although the outcomes remain confidential. Ideally, the selected community would be placed close to both coast and river or burn to evaluate all possible water sources. Furthermore, the community should have a relatively uniform heat demand distribution to minimise heat losses in the piping. After considering all important aspects, a small village called Blackwaterfoot has been selected as a case study for this project.

Blackwaterfoot is situated within the Kilmory parish, and is famous for its unique 12-hole golf course. The village has an apparent community spirit, thus should be willing to consider a potential development of community-owned WSHP scheme combined with renewable power generation on site. The recent field trip discovered that there are already several houses in the village that have PV panels installed on the roofs, and residents are generally pleased with the technical and financial outcomes resulting from sufficient solar radiation and the FIT scheme.

Numerous specific locations in Blackwaterfoot have been considered and evaluated with the help of Google Maps followed by the site survey. It has been discovered that the largest heat consumer in the village (Blackwaterfoot Lodge Hotel) is already using a biomass boiler to provide space heating and hot water in the building, thus was excluded from the analysis. It has been decided that the detailed analysis of the community district heating scheme will be focused on 20 detached houses that are situated in the north west of Blackwaterfoot within a short distance from a small river called Black Water. According to the site visit, the vast majority of these houses are occupied all-year-round. Both village and selected site are shown in *Figure 40.*

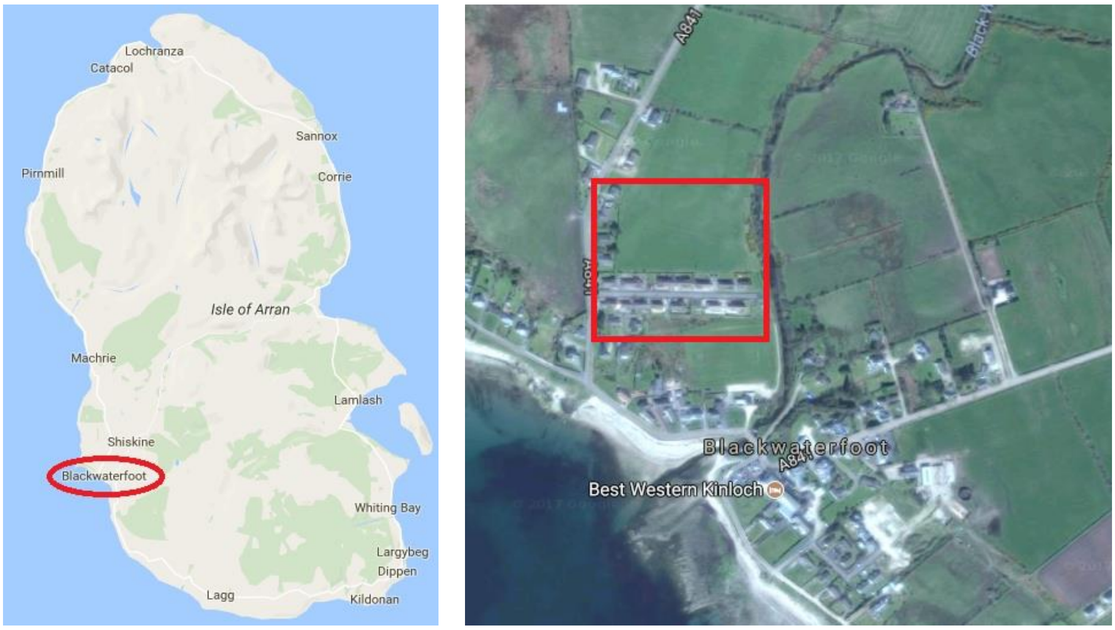


Figure 40. Site selected for the case study; Blackwaterfoot location (left) and houses selected for the analysis (right) *(Google Maps, 2017)*

6.3. Heat Map and Demand Profile

The annual heat demand of 20 selected buildings can be estimated from the Scotland's Heat Map developed by the Scottish Government. The tool does not provide only annual heat demand, but also all energy systems that are installed in the selected area. A snapshot of the island's heat demand is shown in *Figure 41*. The advantage of focusing on a small community project is that estimated heat demand can be assessed individually for each building, which would not be practically viable in the case of large-scale developments. Heat demand of each building gathered from the heat map is presented in *Table 3*.

Figure 41. Arran’s Heat Map *(Scottish Government, 2016)*

Data collected from the Heat Map should be validated by another source, which has been done through the HEM software. The main determinants necessary to model the buildings, such as building type, size and age were estimated from Google Street View followed by the site visit. It has been discovered that all buildings are detached houses with standard insulation. After applying all other parameters into the software which follows the UK and Scottish standards, average annual space heating (202.9 $\mathrm{kWh/m^2}$) and hot water demand (31.4 $\mathrm{kWh/m^2}$) were calculated. Since sizes of the assessed buildings vary significantly, they were divided into three main categories; small (estimated floor area of 75 $\mathrm{m^2}$), medium (100 $\mathrm{m^2}$) and large (125 $\mathrm{m^2}$). The results calculated in HEM are shown in *Table 2*. It can be seen that overall annual heat demand gathered from the Heat Map and HEM is 496 and 480 MWh, respectively, which means a divergence of only 3%. Therefore, annual heat demand validation can be evaluated as successful.

Table 2. Annual space heating and hot water demand calculated in HEM

Building Type	Size (m^2)	Number of buildings	Space Heating (MWh/year)	Hot Water (MWh/year)	Total Heat Demand (MWh/year)
Large	125	7	178	28	205
Medium	100	8	162	25	187
Small	75	5	76	12	88
SUM			**416**	**64**	**480**

The next step was to create a daily demand profile of each building. This was carried out in Merit that includes a daily thermal profile of a standard 3-bedroom house. The latitude was set to 55.5° N, longitude to 5.3° W, which are coordinates of the selected site. The average winter dry bulb temperature on Arran is between 5 and 7.5 °C (yr.no, 2017), and so a design day should be selected below this value to ensure reliable function of the systems during colder winter days. Therefore, a typical cold day in January was selected when temperatures ranged between -0.5 and 4.5 °C. Daily heat demand profile was then created for each individual building by inserting the annual heat demand data gathered from the Heat map. This means that 20 demand profiles have been produced and daily peaks in kW are shown in *Table 3.* The overall daily peak value will be crucial in sizing the WSHP system. The table also contains the daily heat demand of each building, which includes space heating and hot water. To demonstrate the profile curves that were created, three houses of different sizes were selected and their heat profiles are shown in *Figure 42.* It can be seen that peak load occurs at 8 p.m., which is a reasonable assumption when considering a real-world scenario.

Table 3. Annual heat demand, daily heat demand and daily peak of each building estimated from Heat Map and Merit

Building	Annual heat demand Heat Map (MWh/year)	Daily heat demand Merit (kWh/day)	Daily peak Merit (kW)
1	32	147.4	9.7
2	19	87.5	5.7
3	32	147.4	9.7
4	27	124.4	8.2
5	25	115.2	7.6
6	20	92.1	6.0
7	19	87.5	5.7
8	21	96.8	6.3
9	12	55.3	3.6
10	23	106.0	7.0

11	22	101.4	6.6
12	22	101.4	6.6
13	37	170.5	11.2
14	33	152.0	10.0
15	24	110.6	7.3
16	13	59.9	3.9
17	37	170.5	11.2
18	26	119.8	7.9
19	29	133.6	8.8
20	23	106.0	7.0
SUM	**496**	**2285**	**150**

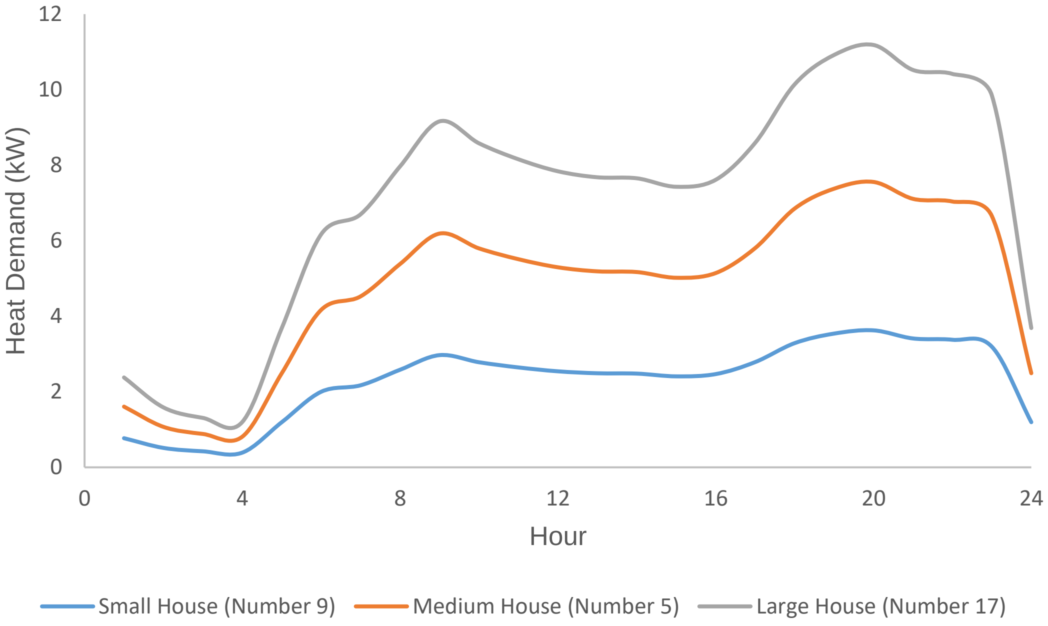


Figure 42. Daily heat demand profile in a cold winter day of three different buildings modelled in Merit

6.4. Water Source Properties

Water source properties, particularly temperature and flow velocity, are crucial aspects that have to be estimated before moving to the system design. There is only one gauging station on the island, which is located at the Monyquil Farm that monitors water level data of Machrie Water (SEPA, 2017). Therefore, CatchmentsUK was used to define an accurate water catchment area, and this data was inputted in LowFlows 2 to estimate volumetric velocity of Black Water in this specific location. Since the flow rates vary significantly throughout the year, an average rate per each month has been calculated in Low Flows 2, and results are shown in *Table 4*. The identical flow rate data can be used in the latter stage when assessing hydropower resource in the selected area. Hydro resources on the entire island with the detailed catchment area that has been used to estimate monthly flow rates is shown in *Figure 43*.

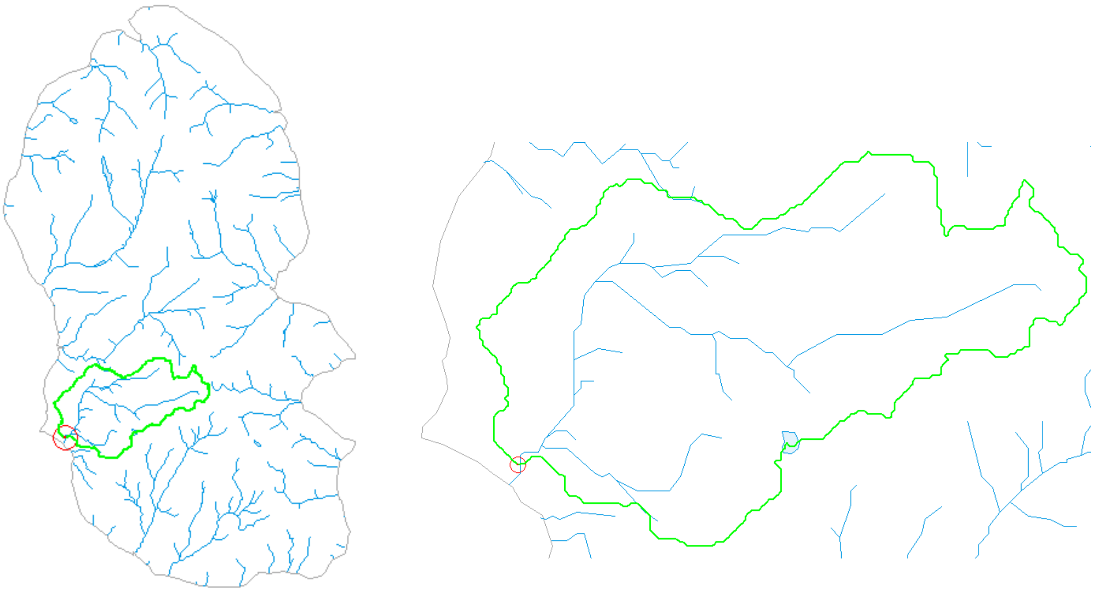


Figure 43. Hydro resources on the Isle of Arran (left) and Black Water catchment area (right) modelled in CatchmentsUK

The river temperature data is not published by SEPA, and cannot be gathered from the hydropower resource tools. Since Black Water is not a major river, it is very unlikely to find accurate water temperature data throughout the year. Therefore, it was decided to use seawater temperature data instead, which is regularly measured on the coast of Arran (World Sea Temperatures, 2017). The distance between the sea and the selected site is very short, which means that water temperature should be relatively similar. This assumption was made due to time constraints of the project, and could be significantly improved by measuring real water temperature data in the future. It can be seen in *Table 4* that water temperature slightly fluctuates throughout the year, however it is more stable compared to the outdoor dry bulb temperature.

Table 4. Flow rates and water temperature of Black Water throughout the year

Month	Flow Rate (m^3/s)	Water Temperature (°C)
January	1.585	8.5
February	1.228	7.8
March	1.112	7.7
April	0.638	8.6
May	0.434	9.9
June	0.307	11.6
July	0.351	13.4
August	0.534	14
September	0.815	13.9
October	1.382	13.2
November	1.47	12.1
December	1.608	10.2
Average	0.955	

The most important aspect regarding water properties is to ensure that the WSHP system does not reduce the water temperature below 0 °C even during maximal operating capacity. It can be seen that flow rates are the highest between October and March, which is ideal for the WSHP system, as the vast majority of heating demand occurs during the months with the highest water level. Therefore, the risk of freezing the water source is in this case negligible. A more detailed assessment of decreased river temperature throughout the entire year is shown in *Figure 49.*

Undoubtedly, water temperature is more stable at the bottom of the river compared to the water surface. This means that heat exchange between the water source and evaporator should occur as deep as possible to ensure stable performance of the system. It can be done by placing coils at the bottom of the river, if the closed-loop system is used, or ensuring that a suction pipe is placed at the lowest possible point in the case of open-loop system.

6.5. System Design

Technical design of the system is a vital aspect that comprises of many important decisions supported by various software tools. The WSHP system should not only ensure the reliable supply of space heating and hot water, but also be adequately sized to become financially viable. The heat pump capacity and thermal storage tank were designed in the Biomass System Sizing Tool that enables user to find the ideal balance between both components and estimate heat losses in the storage tank. Data calculated in the tool along with other information gathered from prior analysis were then inputted to GeoT*Sol to calculate the SPF and water temperature drop throughout the entire year. Finally, heat distribution network was sketched in Digimap to provide an adequate visualisation of the proposed development.

6.5.1. System Capacity and Thermal Storage Sizing

Although Biomass System Sizing Tool was not primarily developed to design heat pump systems, the tool has been selected to estimate the system capacity and size of the hot water storage tank by using hourly heat load profile established in previous stages. Many fields must be filled to model the desired system in the tool. The outdoor design temperature was set to 3 °C, which is an average value of the designated day in January. Glasgow is the nearest location that could have been selected from the provided options. An overall annual heat demand of 496 MWh corresponds to data gathered from the Heat Map and validated through HEM. Other requirements have been set to medium which follows the appropriate Scottish standards. The sizing results are shown in *Figure 44.*

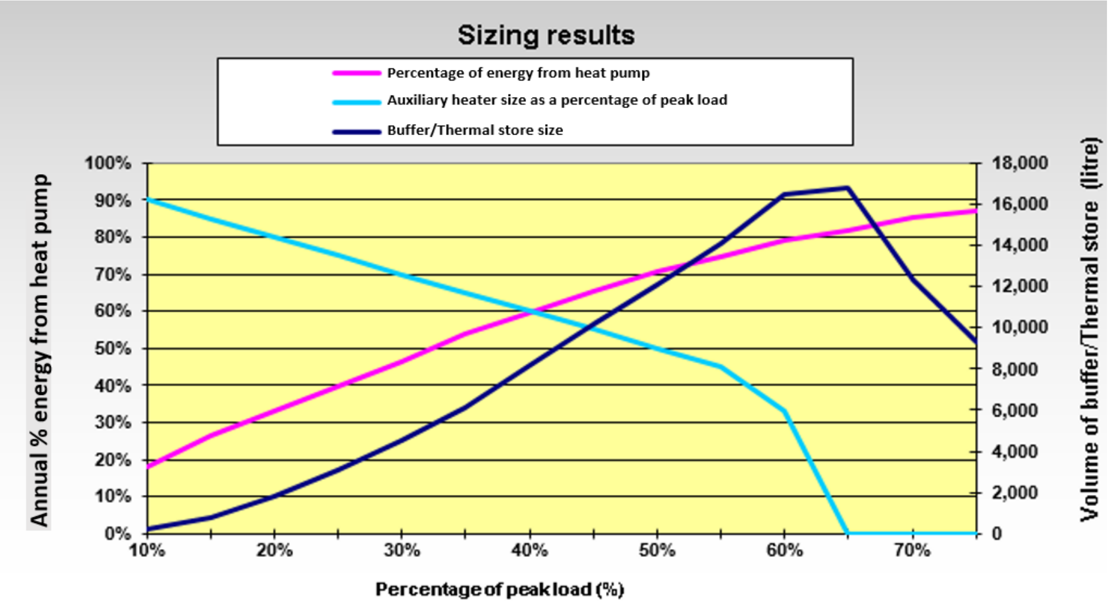


Figure 44. Relationship between WSHP capacity, thermal storage tank and potential auxiliary boiler calculated in Biomass System Sizing Tool

It can be seen in *Figure 44* that the minimum capacity of the WSHP system must be at least 65% of the peak demand to provide a reliable heating supply without any auxiliary boiler. It was decided that an auxiliary boiler will not be included in the design, as the overall size of the system is relatively small-scale, thus should not require an extra costly and usually unsustainable component. Indeed, smaller system capacity would lead to high thermal storage size requirements to meet the space heating and hot water demand. Moreover, the system capacity of 95 kW would be on the edge of supplying enough heat for the design day, and would not work reliably in colder days or when heat losses in the piping are considered. Therefore, a capacity of 105 kW (70% of peak demand) was selected, which should provide an ideal balance between space requirements for the thermal storage tank and capacity of the WSHP system. This relationship can be seen in *Table 5.*

Table 5. WSHP system and thermal storage sizing in the Biomass System Sizing Tool

	Option 1	Option 2	Option 3	Option 4
Percentage of Peak Load (%)	65	70	75	80
WSHP Capacity (kW)	98	105	112	120
Recommended Thermal Store Size (litres)	16,500	12,300	9,400	6,800

Figure 45 shows that most of the hourly heat demand could be met immediately by running WSHP without a thermal storage. The rest of the demand during peak hours can be supplied by stored energy in the thermal storage tank. In reality, generated heat is first passed through the tank, and distributed around the buildings afterwards. Subchapter 6.7 provides more details with regards to the thermal storage use, and how the tank can store generated heat when the weather or financial conditions are the most favourable. A backup system could be provided by a basic immersion heater that would be placed in the thermal storage tank. The backup heater would be switched on only during the coldest days of the year to prevent the heating system from a major failure.

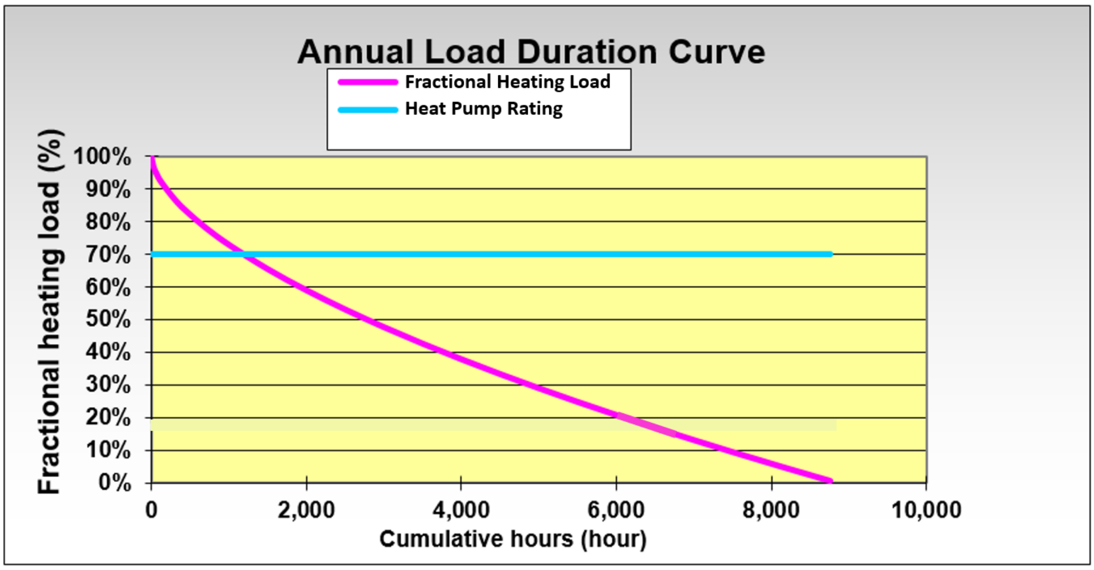
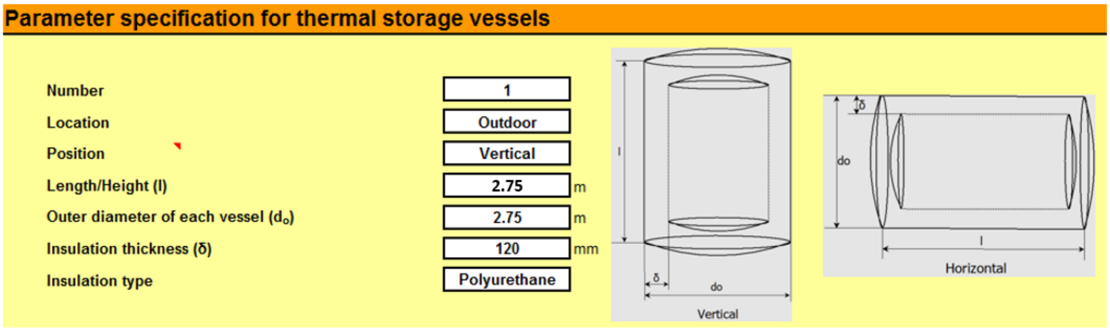


Figure 45. Annual load duration curve calculated in Biomass System Sizing Tool

The thermal storage tank can be either placed in each individual dwelling, or installed as a large community tank next to the WSHP system. Installation of individual tanks would require sufficient space in each building and disrupt residents during the construction phase. Moreover, large-scale tanks are significantly cheaper compared to individual tanks placed in each building (Lund, et al., 2016). Therefore, a single community thermal storage tank was designed in the Biomass System Sizing Tool. Both, height and diameter have been set to 2.75 m. The selected insulation type is polyurethane, which has a conductivity of 0.02 W/mK, thus results in lower thermal losses compared to other pre-defined options; rockwool or glasswool. An insulation thickness of 120 mm results in daily heat losses of only 8 kWh, which is less than 0.5% of the daily heat demand of the community, thus was evaluated as acceptable. The selected hot water storage tank specifications can be seen in *Figure 46.*


Parameter specification for thermal storage vessels

Number	1	
Location	Outdoor	
Position	Vertical	
Length/Height (l)	2.75	m
Outer diameter of each vessel (d_o)	2.75	m
Insulation thickness (δ)	120	mm
Insulation type	Polyurethane	

Figure 46. Thermal storage tank technical specifications

6.5.2. Technical System Design and Performance Evaluation

Key technical parameters gathered in all previous stages of the projects were inputted in GeoT*Sol to estimate SPF and river temperature drop throughout the year. The closest location that includes climate data in the software is Machrihanish, which is a small village relatively near to Blackwaterfoot. A ground water heat pump system with buffer tank was selected to provide space heating and hot water to the community. A basic system schematic is shown in *Figure 47*. Since the main characteristic of a heat pump technology is to use a low temperature water circuit for space heating, the supply temperature was set to 50 °C and return temperature to 35 °C. This temperature range should provide sufficient space heating to the dwellings, whilst keeping the heat losses in the distribution network as low as possible.

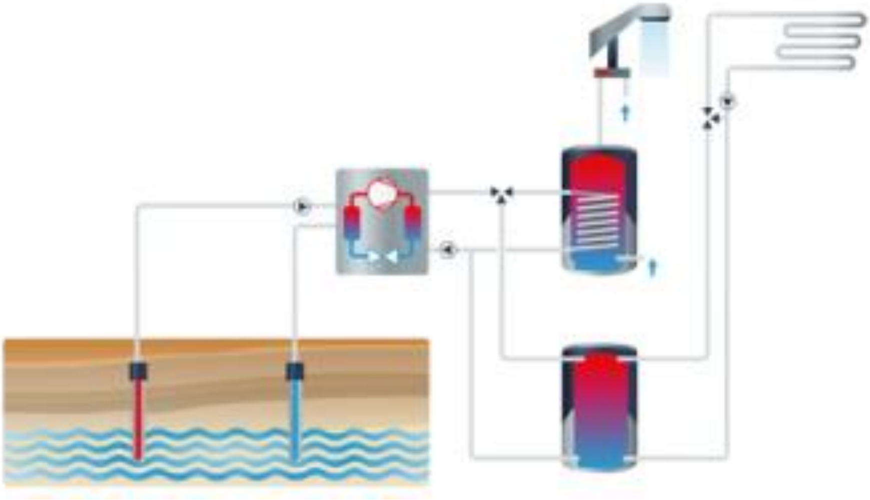


Figure 47. WSHP schematic to supply space heating and hot water including a buffer tank

Annual space heating and hot water demand was previously established from the Heat Map and HEM tool. The overall heat demand of 20 buildings corresponds to 496 MWh per year, however this includes not only space heating, but also hot water demand. Therefore, the total heat demand was divided into space heating demand of 430 MWh/year (86% of total heat demand according to HEM), and hot water demand of 66 MWh/year (13% of total heat demand estimated by HEM), which results in an average community daily usage of 3,350 litres. The indoor target temperature was set to 21 °C, and hot water temperature to 55 °C to avoid any risk of Legionella bacteria discussed in the literature review (see *Figure 15*). The cold drinking water temperature that has to be heated up to 55 °C was gathered from previously defined climate data, which the software automatically uses to create the supply water temperature curve throughout the year.

The software has a pre-defined library that includes 530 WSHP system types from a wide range of different suppliers. Each product contains all necessary technical parameters that are provided by the supplier. The largest heat pump capacity included in the list is 98.9 kW, which is lower than the capacity of the community system that is being designed. Therefore, COP values of all 530 products were exported to Excel, and the average designed COP of 5.7 was calculated. This is the highest COP that WSHP system can theoretically achieve when operating at the nominal output point. During real-time operation, COP significantly varies due to intermittent weather conditions and variable heat demand in the buildings. The relationship between input/output temperatures and COP values of the designed water source heat pump that demonstrates the performance and limitations of the system is shown in *Table 6*.

Table 6. Relationship between input/output temperatures and COP calculated in GeoT*Sol

Temperature Difference (°C)	Temperature IN (°C)	Temperature OUT (°C)	COP
25	10	35	5.7
30	15	45	5.29
35	10	45	4.54
40	15	55	4.09
45	10	55	3.64

Although a heat pump speed could be ideally higher during winter and lower during summer periods, the designed system was modelled to operate at the single speed due to lower costs of the system, and more complicated controls that would be required in the case of multi-speed heat pump system. Moreover, the multi-speed heat pump system would not be possible to model in the supply-demand matching stage.

Other variables, such as river temperature and thermal storage tank size, have already been analysed in the previous phases. However, the modelling tool requires specifications of two storage tanks, one for domestic hot water and another one which functions as a buffer tank for space heating purposes. Therefore, a total thermal storage size of 12,300 litres was divided according to the proportion gathered from HEM standards, which corresponds to 1,650 litres for domestic hot water, and 10,650 litres for the space heating buffer tank. The insulation thickness was kept at 120 mm for both tanks. Simulation results were calculated for each day of the year, and the final results are illustrated in *Figure 48.*

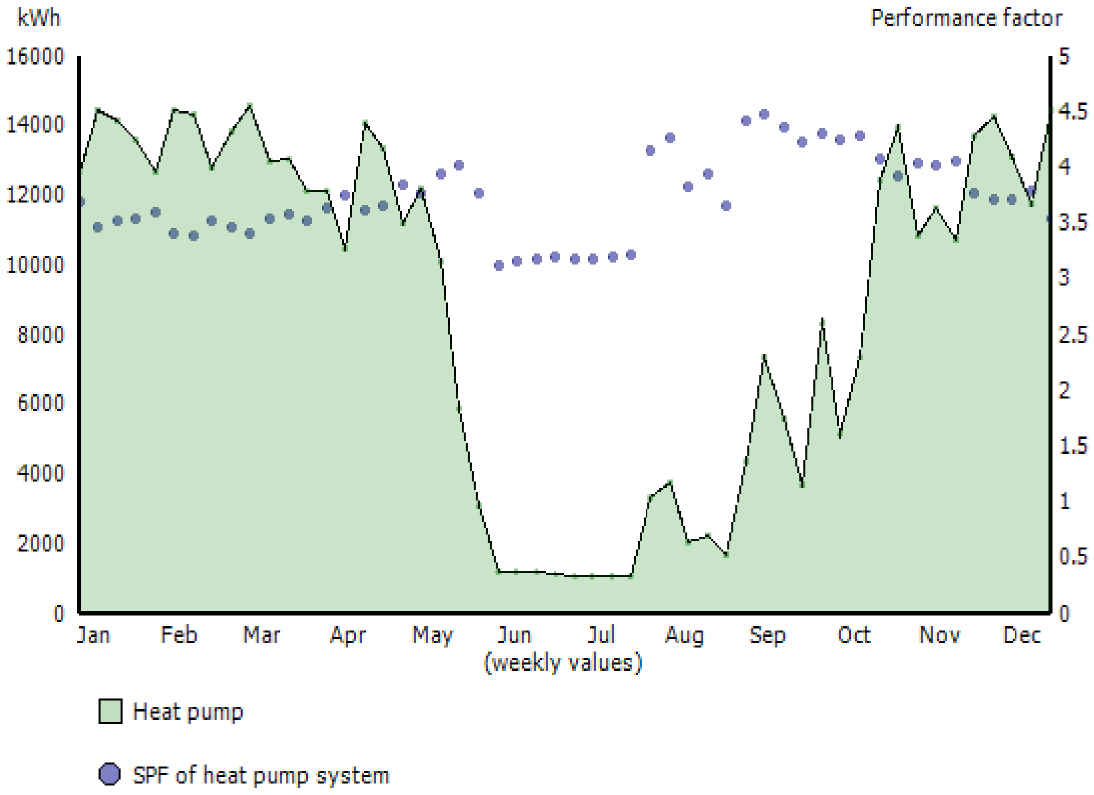


Figure 48. Seasonal Performance Factor of the designed WSHP system calculated in GeoT*Sol

The calculated SPF corresponds to 3.7, which is a reasonable outcome according to other case studies presented in the literature review. Each blue point represents weekly COP values that were calculated throughout the modelled year. It is evident that the lowest COP occurred during June and July, as there was no heating demand required during these summer months. This aligns well with expected outcomes, since the system does not operate at high capacity, and has to generate high temperature hot water, which results in lower system efficiency. On the other hand, the highest COP values are obtained when heating demand kicks in and river temperature still remains high. During these weeks, more heat can be removed from the river to evaporate the refrigerant. It can be seen that the COP remains relatively stable during winter, which proves that designed WSHP system can operate reliably even during the coldest months of the year, whilst supplying all the space heating and hot water demand to the community. The effect of designed system on river temperature values throughout the year is shown in *Figure 49.*

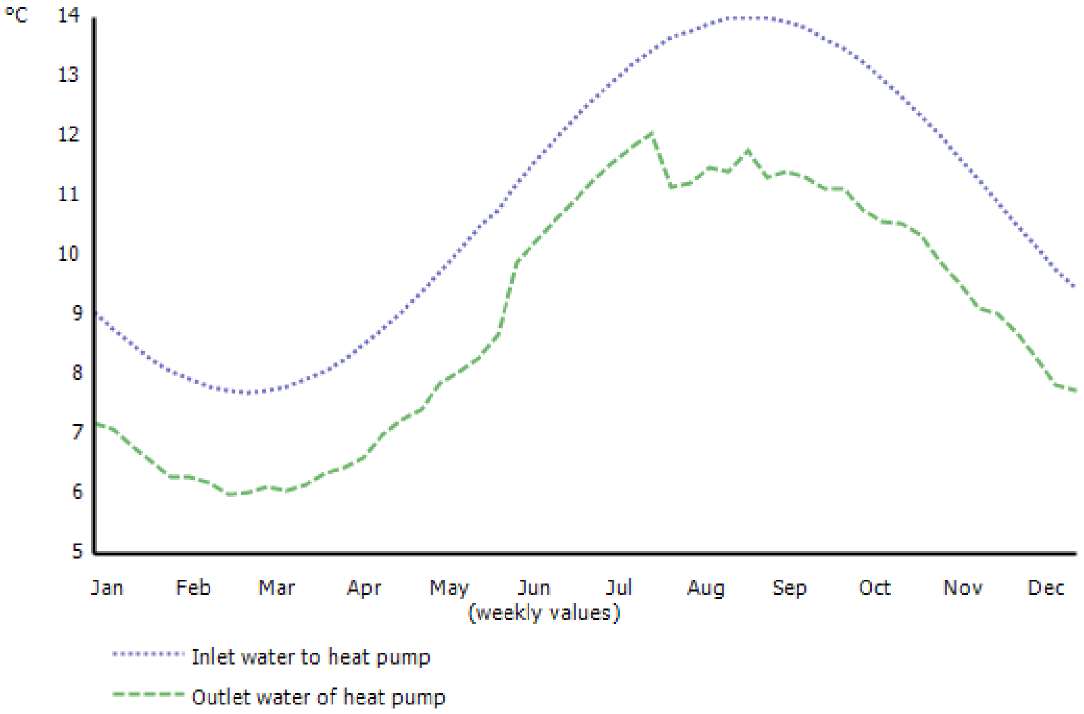


Figure 49. Estimated monthly river temperature drop before and after entering the WSHP system

The influence of implementing community WSHP system on Black Water temperature throughout the year was modelled in GeoT*Sol software. WSHP systems must always ensure that the water source never freezes at any time during the year. It was proven that outlet water temperature does not go below 6 °C even during the coldest winter months when the system operates at the highest capacity. The water temperature drop is directly related to COP of the system, as can be seen from the graph. Inlet and outlet temperatures in June and July are the closest to each other, which aligns with the lowest COP values calculated earlier. On the other hand, more heat could be removed from the river during months with the highest COP values, as can be seen from August till October. Relatively stable water temperature difference during the winter months matches with stable the COP values occurred at that time. Altogether, it was demonstrated that Black Water can be used as a sufficient heat resource for the system, and potentially could accommodate even another WSHP system in the future if required.

Although the refrigerant selection would require an extended analysis that is outside the scope of the project, only environmentally friendly working fluids should be considered to minimise the negative impacts of the system on the atmosphere. Many potential refrigerants are discussed in the literature review, which includes those approved by the EU standards. Ideally, fluid with the lowest GWP that can provide adequate COP values should be selected for the system. The potential refrigerant that would meet all the aforementioned requirements could be HFO, which is also recommended by the EU standards (see *Table 1*). However, the most suitable working fluid should be discussed directly with the WSHP supplier.

Finally, any low carbon district heating scheme that serves multiple community dwellings requires implementation of an advanced control system. Therefore, an HIU should be installed within each house of the Blackwaterfoot community to provide a user-friendly platform for the residents. The heat interface unit should be connected to both space heating and hot water systems not only to regulate the end-user requirements, but also to provide metering and billing of the involved houses. In addition, the unit can display heat consumption in real-time, which can be eventually used by the residents to keep track of their upcoming utility bills.

6.5.3. Heat Distribution Network

The heat distribution network of the proposed community heating project is an important technical feature that requires sound expertise as well as detailed technical documentation. Although the core of the project is concentrated more on the WSHP technology itself, a basic network design was sketched in AutoCAD by extracting accurate geographical data from Digimap. This sketch is captured in *Figure 50.* The approximate piping lengths of the upper and bottom branches were estimated at 305 and 195 m, respectively, which gives a total piping length of 500 m for the entire development. This value was validated by using 'measure distance' feature in Google Maps, which resulted in an identical length.

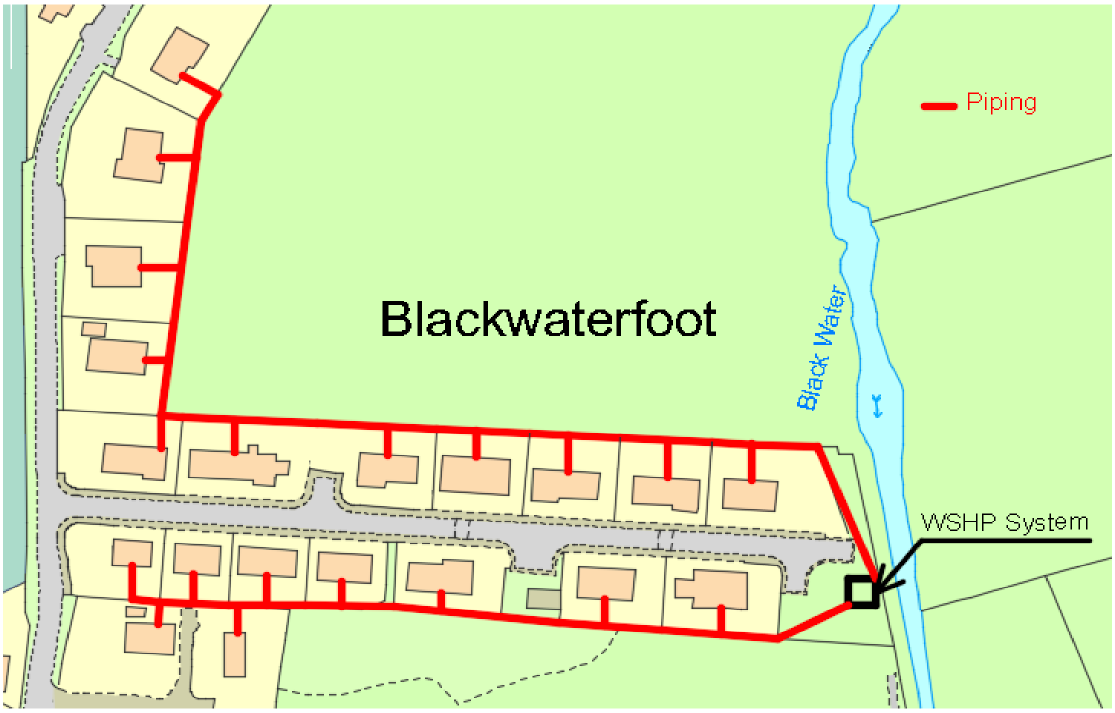


Figure 50. Heat distribution network design of the proposed development sketched in AutoCAD

Three major types of piping could be selected, which were also discussed in the literature review. Steel pipes would be more resistant to damage and could withstand higher temperatures and pressures. However, these pipes are manufactured only in straight lengths, involve high installation costs, and require more maintenance due to corrosion problems. Therefore, steel pipes are generally used rather for larger-scale projects, such as the current district heating development carried out at the University of Strathclyde shown in *Figure 51*. Bonded insulation pipes are defined by excellent thermal insulation properties, long lifespan (50 years without maintenance considering hot water temperature of 50 °C), higher flexibility and no thermal expansion characteristics, as they are self-compensating. Finally, non-bonded insulation pipes have the advantage of being extremely flexible and easy to install, however their thermal conductivity is twice as high compared to the bonded pipes. Therefore, a bonded insulation pipe with PU foam captured in *Figure 51* was selected for the heat distribution network design.

Figure 51. Steel pipes with a large diameter used for district heating scheme at the University of Strathclyde (left) and bonded pipes with PU foam (right) *(Rehau, 2017)*

The thermal loss in the heat distribution network is an important aspect of any district heating scheme that is being designed. Thermal conductivity of the selected pipes provided by the manufacturer is 0.022 W/mK. A thermal loss of 3.55 kW per hour was estimated, assuming a total piping length of 500 m and 323 K (50 °C) water distribution temperature. According to the created daily heat demand profile, heating during winter is required for approximately 18 hours a day, which means a heat loss of 64 kWh per day. Therefore, a total heat loss per designated day, including thermal storage and heat distribution network losses, has been estimated at approximately 5%. More accurate assessment of heat losses in the piping would require an extensive investigation, such as diameter selection and hot water flow rate selection, which is outside the scope of the project. The estimated thermal losses should, however, provide a sufficient accuracy considering the overall scale of the project with relatively short length of the pipes.

Finally, the main technical parameters of the system before optimising it through supply-demand matching procedure are listed in *Table 7*. The table includes specifications gathered throughout all previous phases to provide a concise technical summary that will be used in the following stages.

Table 7. Technical summary of community WSHP system parameters

Tool Used	Parameter	Magnitude
Heat Map	Annual Heat Demand	496 MWh/year
HEM	Annual Space Heating Demand	430 MWh/year
	Annual Hot Water Demand	66 MWh/year
Merit	Designated Day Peak Demand	150 kW
Biomass System Sizing Tool	Percentage of Peak Load	70%
	System Capacity	105 kW
	Thermal Storage Size	12,300 litres
	Height of the Tank	2.75 m
	Diameter of the Tank	2.75 m
	Conductivity of Polyurethane	0.02 W/mK
	Insulation Thickness	120 mm
	Thermal Storage Losses at Design Day	8 kWh
GeoT*Sol	Target Indoor Temperature	21 °C
	Target Hot Water Temperature	55 °C
	Space Heating Temperature IN	50 °C
	Space Heating Temperature OUT	35 °C
	Nominal COP	5.7
	SPF	3.7
	Minimum River Temperature	6 °C
Digimap and AutoCAD	Piping Length	500 m
	Daily Distribution Network Losses	64 kWh

6.6. Renewable Resource Evaluation

The community WSHP system requires a reliable power supply throughout the year, which would be ideally generated by a renewable power system placed near the selected site. Subchapter 6.1 already provides an extensive explanation why wind power generation is not being considered in this project. Hydropower resource data have already been evaluated at the selected location, and monthly flow rates could be theoretically sufficient for a micro hydropower scheme, however the geographical area around Blackwaterfoot does not provide appropriate head height that was estimated in Digimap. Therefore, the feasibility of a shared solar PV system to generate renewable power on the site was assessed, as many houses in Blackwaterfoot have already installed solar PV panels on their roof and successfully generate renewable electricity, which was discovered during the field survey. The system was modelled in PV*Sol, and the gained results will be further used as an input in the supply-demand matching phase.

The nearest location that includes hourly weather data necessary for solar PV modelling is Machrihanish, which has already been used for the technical design of WSHP system. The software uses average hourly solar irradiation values on horizontal surface measured in a period of 20 years, which should lead to a statistically robust model. The sum of 8,760 hourly data (one year) led to a total global radiation of 938 $\mathrm{kWh/m^2}$. The designed system is grid connected and the vast majority of roofs are orientated to the south, which is ideal for a PV panel installation. A selected inclination was set to 37°, which was considered as a compromise between summer and winter conditions to avoid any tilt adjustments throughout the year. Shading was not considered in the model, as the community is not surrounded by any large trees or other tall objects. The software contains more than 700 solar PV manufacturers, therefore a generic PV*Sol poly 200 W panel was chosen as a typical example.

The system was sized to generate an annual power equivalent to the electricity consumption of WSHP system per year. Overall community heat demand corresponds to 496 MWh, and calculated SPF was 3.7. This leads to an annual electricity consumption of 134 MWh. Heat losses were estimated at 5%, and 1% should be added to cover miscellaneous power losses as stated in PV*Sol. Therefore, a total power of

142 MWh should be generated per year to offset electricity consumption of the heat pump. This method provides initial outcomes, which will be then optimised in the supply-demand stage, as most of the heat demand occurs in winter, whereas most of the solar radiation in summer.

It was discovered that the shared solar PV system must be enormous to generate the entire annual power demand consumed by the WSHP system without even considering supply-demand matching criteria. This is mainly due to the location of the selected community, as the amount of solar radiation is relatively small compared to other countries based closer to the equator. If the PV system was sized to offset the annual power consumption of the heating system, each house in the community would require more than 8 kW of PV panels on their roof, which corresponds to more than 40 panels per house. Therefore, the following supply-demand matching stage will consider more scenarios with a variable amount of electricity generated from solar PVs. The final results, including major technical parameters of the designed PV system, modelled in PV*Sol with a step of one hour are shown in *Table 8.*

Table 8. Technical parameters of community solar PV system in Blackwaterfoot designed in PV*Sol

Gross renewable electricity (%)	Rated output (kW)	PV surface (m^2)	Annual power generation (MWh)	Nb. of panels	Rated output per house (kW)
100	162	1358	142	810	8.1
50	81	679	76	405	4.05
33.3	54	453	47	270	2.7

The total annual power output was validated by the Global Solar Atlas developed by the World Bank Group. The system size, azimuth and inclination values were inputted into the tool that used data for the exact location of the community. The annual PV power output from the Global Solar Atlas was estimated at 132 MWh, which is only 7% less than the values calculated in a more detailed model in PV*Sol.

Using solar energy to meet domestic heating demand is usually not the most favourable solution, as most of the solar radiation occurs at the time of the lowest space heating demand. On the other hand, hot water demand is relatively stable throughout the entire year, which means that designed PV panels can reliably meet power consumption of WSHP during summer months. Moreover, the relatively large hot water storage tank that was designed in previous stages can store energy that is generated during the periods with a peak solar irradiance. Different power outputs of the PV system during typical winter and summer months are shown in *Figure 52*. The basic PV design developed at this stage will be further investigated in the supply-demand matching phase.

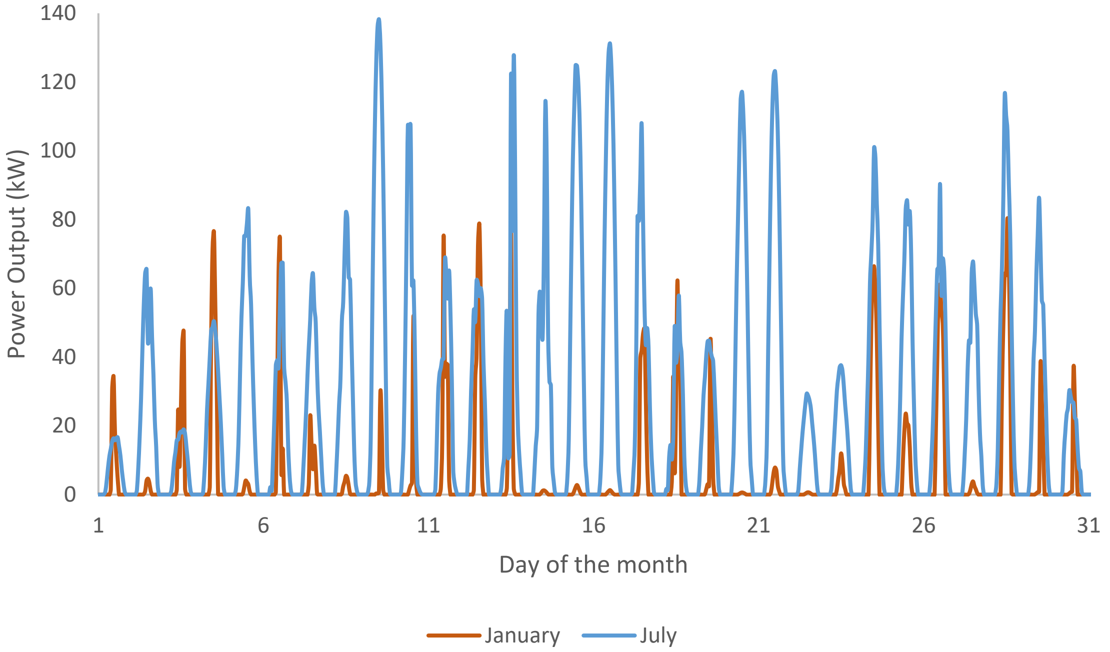


Figure 52. Renewable power generation on the site during winter and summer months modelled in PV*Sol

6.7. Supply-Demand Matching

The final stage of the technical feasibility study of the community-owned heating system was to create supply-demand matching model in energyPRO. This phase is a crucial part of the entire project to demonstrate the suitability of the system, and eventually optimise sizes of designed components. The matching procedure was modelled with hourly data over the period of one year. The relevant data used for the model were gathered either from the previous design stages, or alternatively from energyPRO that includes weather data specifically for the selected community in Blackwaterfoot. All appropriate data are from 2016, as the model is also used for the financial evaluation, which requires current electricity prices to calculate an overall net profit. Although this model is relatively complex and requires a large amount of input data with a step of one hour, the final outcomes are vital not only to demonstrate the technical suitability of the system, but also to determine its financial feasibility aiming to decrease fuel poverty in the region.

Hourly data containing weather conditions of the selected site were inputted as timeseries into the model. River temperature drop curve established in GeoT*Sol was used to establish water temperature before entering and after leaving the WSHP system. Outdoor dry bulb temperature and solar irradiance data throughout the year were extracted from energyPRO by inserting the exact location of the site. The solar irradiance occurrence, which was used when calculating renewable power generation on the site by using previously designed PV solar panels, is shown in *Figure 53*. It can be seen that most of the available solar energy occurs in summer, whereas winter solar radiation is relatively low due to the high latitude of Scotland.

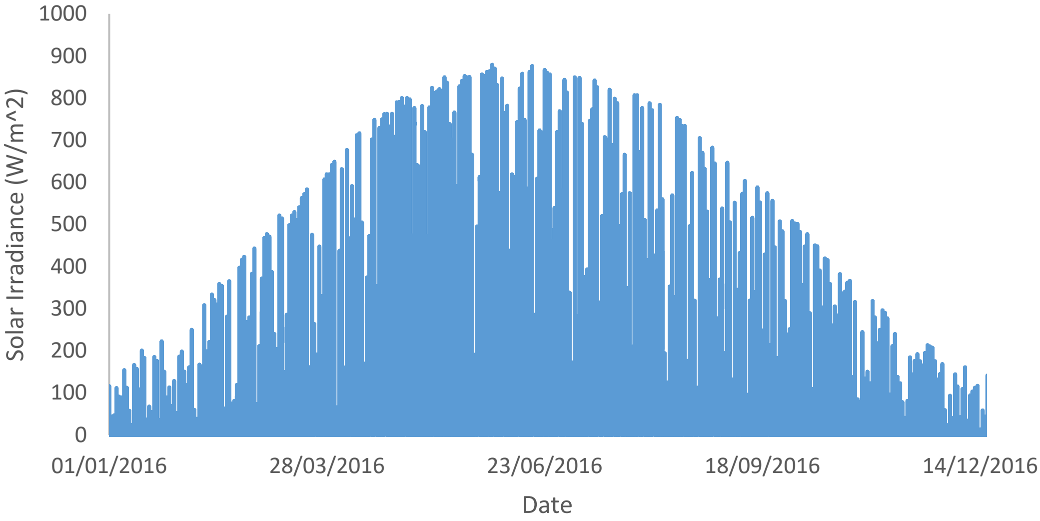


Figure 53. Hourly solar irradiance in Blackwaterfoot in 2016 gathered from energyPRO

Community heat demand over the entire year was estimated in the same way as in the technical design stage. The overall heat demand of the community gathered from Heat Map was inserted into Merit to create an hourly demand profile that can be used for the supply-demand matching stage, and is shown in *Figure 54*. It can be seen that community heat demand is never zero, as there are 20 buildings in total and so there is always going to be some heat demand even during summer to provide hot water to the community. This heat demand is, however, less than 1 kW per household which can be mostly met by heat stored in the thermal storage tank. The shape of the daily profile curve was validated by load profile from an external source (Elexon, 2017). The publicized average winter weekday profile with a step of 30 minutes corresponds to the heat demand profile shape gathered from Merit, which means that used data were successfully validated. Each value of the demand was then increased by 5% so heat distribution losses estimated in Subchapter 6.5.3 are taken into account in the supply-demand modelling stage.

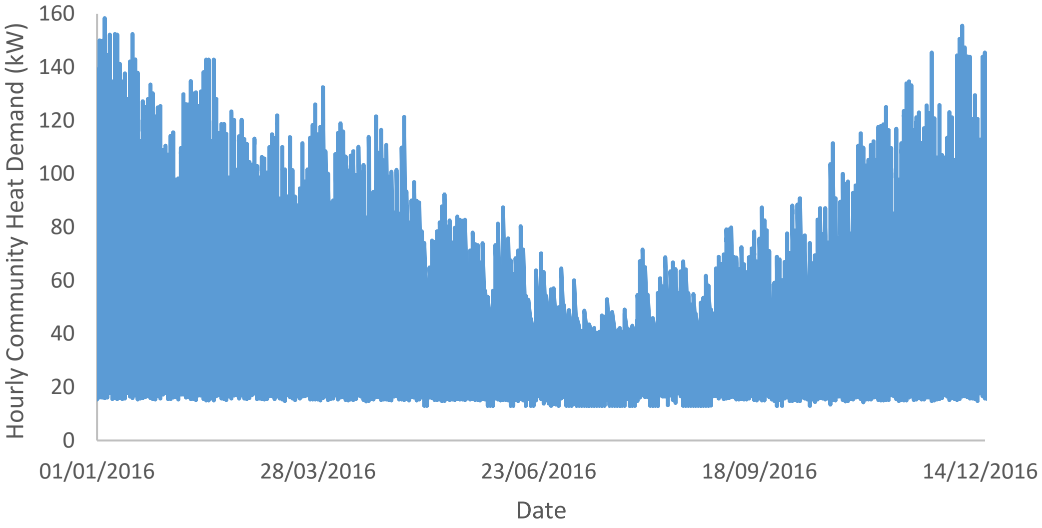


Figure 54. Community hourly heat demand data over the period of one year estimated in Merit

Technical parameters of each system component gathered during previous design phases were entered into the software. This includes technical specifications of the water source heat pump, solar PV system and hot water storage tank including size, insulation thickness and thermal conductivity value to validate heat losses that were estimated in the Biomass System Sizing Tool. A backup immersion heater was added to the system layout, and was finally sized at 15 kW of maximal heat output after running numerous simulations in energyPRO. The backup heater was designed to operate at a partial load (100 W to 15 kW) to provide the most flexibility without wasting the generated heat. A conventional immersion heater that transfers all electricity into heat should be sufficient to cover these occasional periods of the highest heat demand during the coldest days of the year.

The overall system layout is shown in *Figure 55*. The initial model was designed with a large PV system (162 kW) to provide a base for the following financial comparison. However, later stages considered a medium sized PV system (80 kW) that corresponds to 4 kW system per each house, which was evaluated as more reasonable regarding the usual practice in the UK. As shown in *Figure 55*, the system was connected to the national electricity grid to allow export and import of power. All the important revenues and operation expenditures related to produced and consumed electricity will be discussed in Subchapter 6.8.

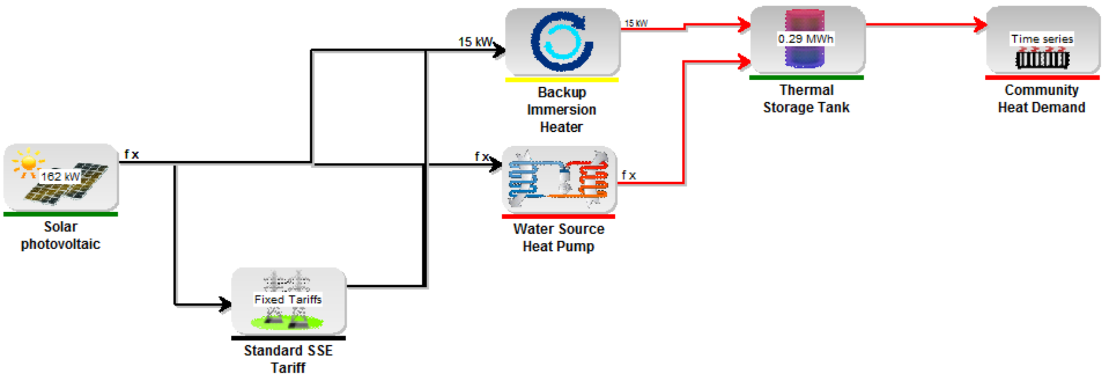


Figure 55. Overall system layout created in energyPRO to simulate one year of continuous operation

The supply-demand matching simulations generated a large amount of detailed technical and financial results, therefore only the most important outcomes were selected and further discussed. Other detailed results, containing daily, weekly and annual energy curves in a graphical interface, are presented in Appendix I. The overview of main technical results of the designed system is captured in *Table 9.*

Table 9. Main technical annual results of supply-demand matching simulation

Community Heat Demand (MWh)	496
Distribution Losses (MWh)	-24.8
Backup Immersion Heater (MWh)	4.5
Heat Storage Losses (MWh)	-1.2
Electricity Consumption of Heating System (MWh)	142
Renewable Power Generation (MWh)	77.2
WSHP Turns ON	616
Backup Heater Turns ON	45

The simulation of the designed heating system was successful in terms of meeting the entire heating demand of the community even with additional losses that occur in the thermal storage tank and heat distribution network. It can be seen that the heating system consumed 142 MWh of electricity to meet an annual community space heating and hot water demand of 496 MWh, which corresponds to the values gathered in the previous stages. The backup immersion heater provided 4.5 MWh per year which is just under 1% of the overall heat demand. The results are based on a PV size of 80 kW which generated 77 MWh of green electricity per year. The rest of the power consumption was supplied by electricity distributed from the national grid. WSHP was switched on and off 616 times per year, whereas the backup heater only 45 times during the coldest days in winter. Although the heat pump was turned on/off frequently over the operational period, the current systems are manufactured with smart controls that drag electricity from the network gradually, therefore should not cause any major problems in terms of increased strain on the local grid. An example of system operation during a very cold winter day in January is shown in *Figure 56.*

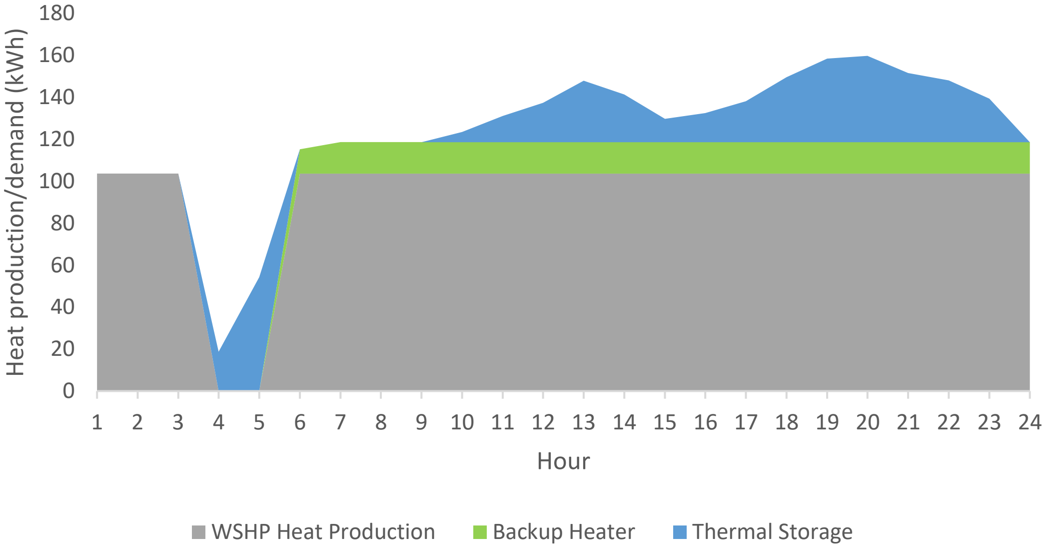


Figure 56. Community heating system operation example during a cold winter day in January simulated in energyPRO

Even during the coldest days of the year, the vast majority of heating demand is met through heat produced by WSHP. It is noticeable from *Figure 57* that the heat pump system was switched off between 3 and 6 a.m. when the heating demand is the lowest, and can be entirely met by heat stored in the thermal storage tank. In reality, the WSHP curve when turning on/off would be steeper, however this graph demonstrates the gradual start/stop progression of the current heat pump systems. Any heat demand higher than 105 kWh is met by backup immersion heater with the highest peaks covered by thermal storage tank. The blue area shows not only the thermal storage operation but also the heat demand profile including thermal losses that occur in the distribution network. The system operation during a selected week in winter is captured in *Figure 57.*

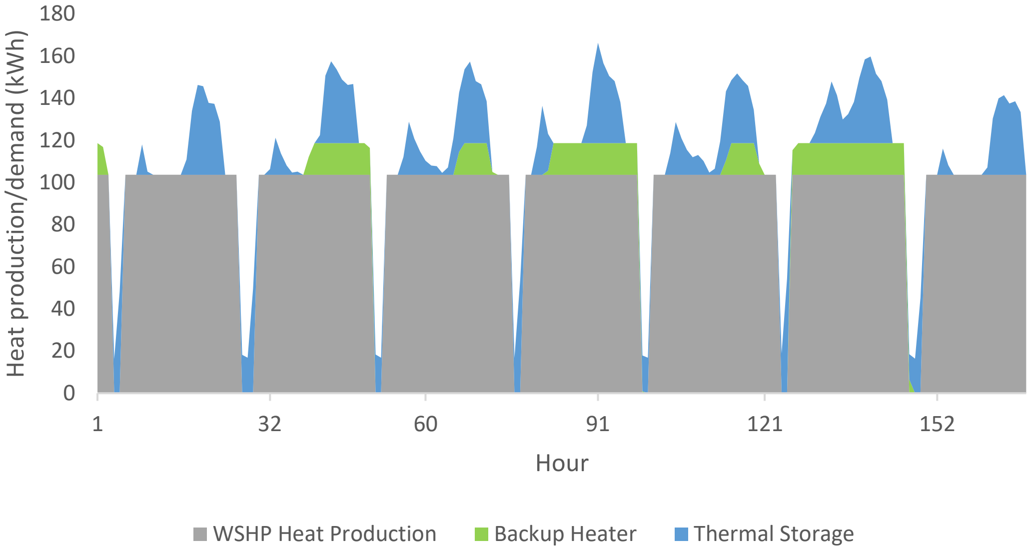


Figure 57.. Community heating system operation example during a week in January simulated in energyPRO

The graph demonstrates reliable operation during a cold winter week in Blackwaterfoot. As can be seen, some days in winter do not even require backup heater operation, as the peak demand can be met by heat accumulated and supplied from the thermal storage tank. Detailed hourly capacity of the implemented thermal storage tank over the same period is shown in *Figure 58*.

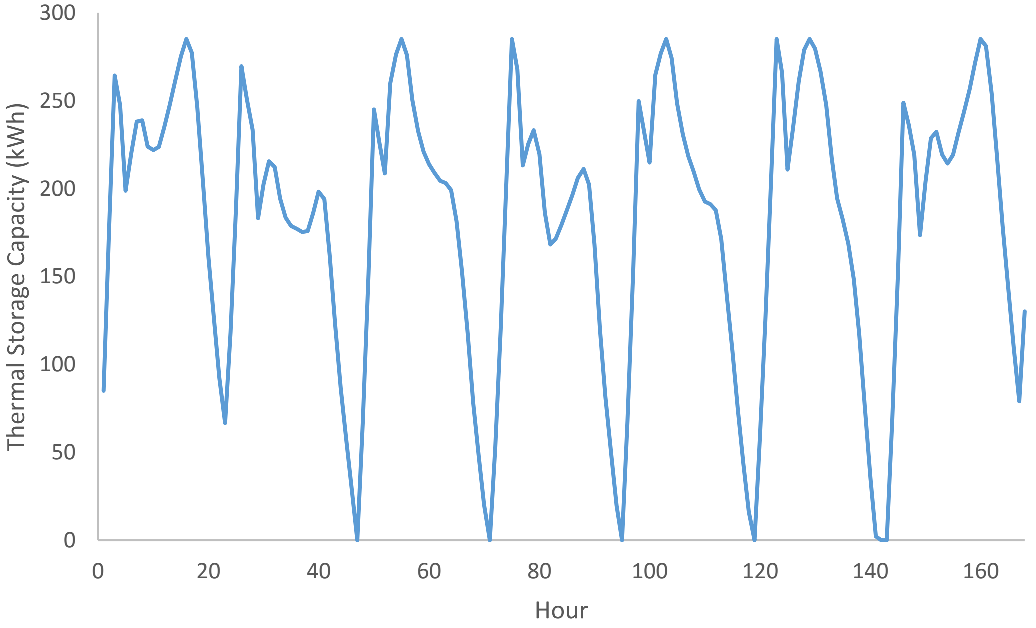


Figure 58. Thermal storage capacity continuance over a period of one week

The thermal storage plays a very important role in the community heating system function as can be seen in *Figure 58*. The system generates and stores heat when the demand is low to provide space heating and hot water during the peak times, as the WSHP system is not sized to meet immediate demand over 105 kW. The graph verifies that the tank was sized in Biomass Systems Sizing Tool fairly accurately, as the capacity goes down to zero during the coldest days in January. The system is, however, refilled fast again after the peak demand passes. This is the reason why the backup heater is used very rarely throughout the year, as the heat stored in the hot water tank covers most of daily peak demands. The annual heat load duration curve highlighting the occurrence of peak demands and rare backup heater operation is shown in *Figure 59.*

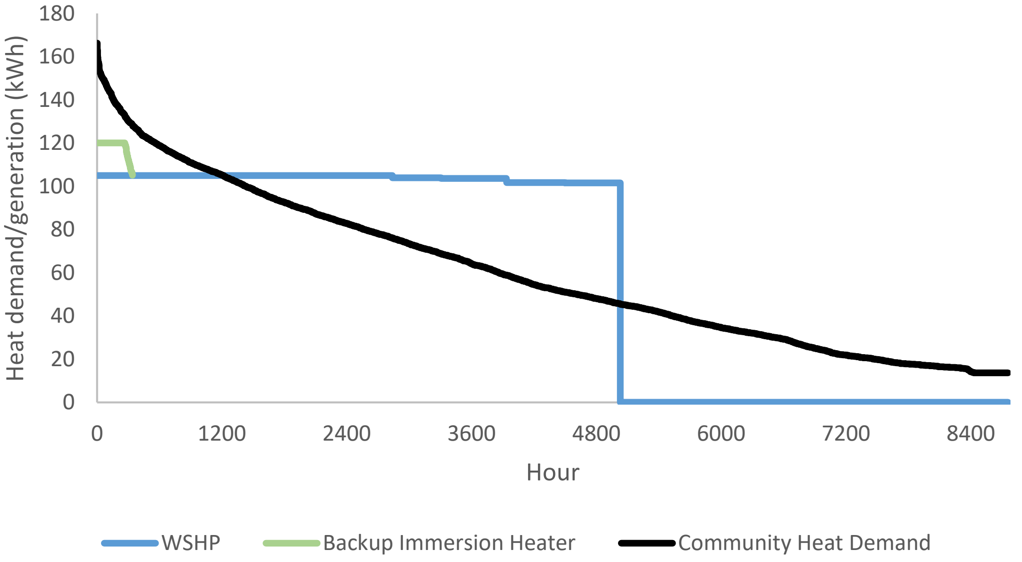


Figure 59. Annual heat load duration curve calculated in energyPRO

It can be seen that the WSHP system was running for more than 50% of the time over the simulated period of one year. The vast majority of community heat demand was met by the WSHP system with a small number of hours covered by the backup immersion heater that is highly inefficient compared to the heat pump technology. The top left corner of the graph represents the number of hours when heat demand was met entirely by thermal storage operation, as the combined capacity of WSHP and backup heater together was still lower than the community space heating and hot water demand at that time. The duration curve is similar to the one generated in Biomass Systems Sizing Tool (see *Figure 45*) with minor differences that are related to system heat losses that were estimated at latter stages. The final step of technical supply-demand matching evaluation was focused on studying the suitability of using solar PVs to meet power consumption of the heating system. Typical winter and summer weeks were selected and results are shown in *Figures 60* and *61*.

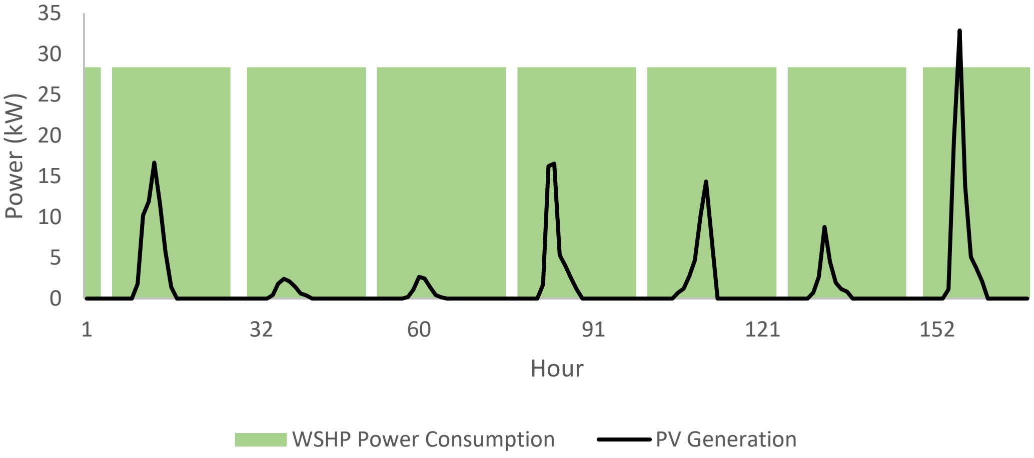


Figure 60. Supply-demand match between WSHP power consumption and solar PV power generation during a typical winter week

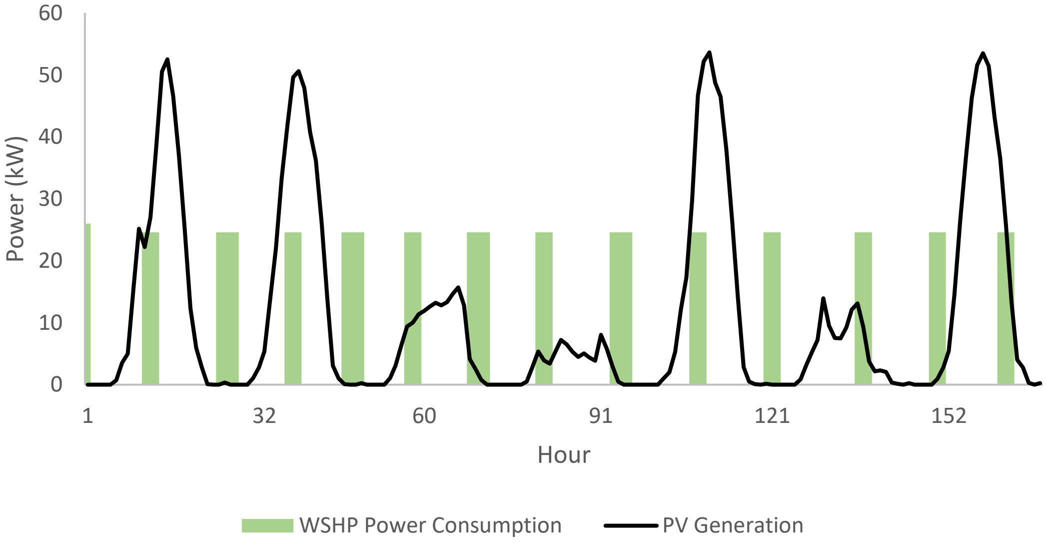


Figure 61. Supply-demand match between WSHP power consumption and solar PV power generation during a typical summer week

Solar PV power generation and heat pump power consumption frequently do not match in winter, neither in summer. In winter, the community heating system is mainly running at a full rate, when the solar radiation is often extremely low and very rarely reaches the WSHP power consumption at any given time of the day. On the other hand, the WSHP system does not operate frequently over the summer, whereas green electricity generated by solar PV panels is the highest, and often produces more than double than is required by the heat pump system. This means that most of the electricity must be exported in summer, and imported in winter which is highly undesirable not only due to financial reasons, but also in terms of distribution losses that occur when the power is transmitted in the national grid. Both figures demonstrate that the supply-demand match between solar PV and WSHP systems is not ideal, and micro hydro would be more favourable to use as most generated power would be used locally, thus reduce stress on the electricity distribution network, whilst saving money from reduced electricity import. Although Blackwaterfoot community does not lie within a geographical location with sufficient hydropower resources, a potential site with a more favourable hydropower resource is discussed in Subchapter 6.10. Although the supply-demand match between power generation and consumption on the site could be higher, the presence of PV panels offsets the majority of greenhouse gases that would be otherwise released to the atmosphere by conventional power generation systems, which would be used to supply power to the heating system.

Finally, the designed system was proven to provide a reliable source of sustainable heating for the selected community based on most up-to-date data gathered from numerous sources and tools. A robust model was run by using hourly data over the entire year, and the simulation confirmed the capacity of meeting the annual heat demand of the community successfully. More detailed results over the entire simulation period are presented in Appendix I. The selected software was found to be very suitable for this kind of simulation, especially due to the strong focus on the thermal side, which tends to be sometimes overlooked by other supply-demand matching tools.

6.8. Financial Evaluation

The financial evaluation of any community based project is a crucial aspect that requires thorough market research to ensure that the selected community can benefit from the development. This subchapter is mainly focused on finding the ideal operating conditions with regards to the current electricity tariffs and government incentives to decrease fuel poverty in the selected area. The capital cost estimation of each individual component of the system is outside the scope of the project, as such projects are often tailored individually by companies, which leads to highly varying prices and common confidentiality of exact components costs. That said, a rough estimation of what the system would have to cost at most to become financially viable was estimated by using a simple loan repayment formula presented in this section.

The system model created in energyPRO was designed to not only simulate technical performance, but also provide a financial assessment of the project over the same period of one year. This required input of current electricity prices and government incentives that are used to support small-scale projects across the UK. Precise annual net profit estimation of the system required most up-to-date electricity prices, FIT tariffs and RHI tariffs.

Arran is primarily supplied by electricity from SSE, therefore a standard SSE tariff was used to create a base model for a financial comparison. This tariff enables the user to buy electricity for the same price at any time of the day. Most electricity providers offer a wide range of other tariffs that allow their customers to use electricity at cheaper rates during off-peak times. Two common tariffs often used in Scotland are Economy 7 and 10, which were selected for financial evaluation of the model. Economy 7 gives customers seven hours of cheaper electricity every night, which is highly beneficial when most of the electricity demand is shifted to this period. This tariff is widely used especially in households with electric storage heaters that are charged over the night and provide heat during the day. Economy 10 works on a similar principle, however off-peak times are five hours at night, three hours in the afternoon and two in the evening. *Table 10* shows exact rates of each tariff offered by SSE to houses situated in Blackwaterfoot.

Table 10. Electricity prices offered by SSE to houses situated in Blackwaterfoot *(SSE, 2017)*

	Standard(p/kWh)	Off-Peak (p/kWh)	Standing charge (p/day)
Standard	17.59	17.59	14.8
Economy 10	20.45	13.55	14.8
Economy 7	20.5	10.99	14.8

Revenues generated through the system consist of three main parts with exact amounts collected from the official OFGEM website (OFGEM, 2017). Surplus power generated by solar PVs that cannot be used on the site can be sold to the grid at a fixed rate of 5 p/kWh. Heat generated by water source heat pump systems in the UK is generously supported by the government at the moment at a rate of 19.5 p/kWh, which generates the main profit of the system. The highest FIT tariff from power generated by solar PVs is currently targeted on systems between 10 and 50 kW of rated output. As the size of the PV system was designed at 80 kW in this case, the community could either consider decreasing the size of PV to 50 kW, or split the PV installation into two individual parts, where each part would be rated at 40 kW and maintained and operated separately. This would generate 4.3 p/kWh from the FIT scheme. The final outcomes calculated in energyPRO are shown in *Table 11*.

Table 11. Comparison of the annual net profit (£) of the system regarding different electricity tariffs calculated in energyPRO

	162 kW PV Standard SSE Tariff	80 kW PV Standard SSE Tariff	80 kW PV Economy 7	80 kW PV Economy 10
Revenues				
FIT PV	6,726	3,321	3,321	3,321
RHI WSHP	102,015	102,015	102,015	102,015
Total Revenues	108,740	105,336	105,336	105,336
Operating Expenditures				
Imported Electricity	-17,407	-19,036	-19,744	-17,344
Standing Fee	-1,080	-1,080	-1,080	-1,080
Exported Electricity	5,719	2,223	2,223	2,223
Total Operating Expenditures	-12,769	-17,893	-18,601	-16,202
Annual Net Profit	**95,971**	**87,443**	**86,735**	**89,134**

Financial assessment of various electricity tariffs indicated that the most profitable tariff that suits the WSHP operation is Economy 10 (highlighted in *Table 11*), which would generate slightly higher profit than other tariffs. The highest potential net profit was clearly the case with a large number of solar PV panels, however the technical barriers of such a large system outweighs the small profit difference considering the size of the community and available roof area.

The reason why Economy 10 leads to the highest profit of the system is noticeable from *Figure 62*. The graph demonstrates the relationship between heat demand during a cold winter day and electricity price variation of the tariff. The lowest demand occurs between midnight and 4 a.m. when the electricity price is high. Although the daily peak demands appear during expensive periods, these are mostly met by using stored heat in the thermal storage that has been charged during the off-peak times (4.30 a.m. to 7.30

a.m. and 1 p.m. to 4 p.m.). The system is therefore the most profitable with the Economy 10 tariff compared to any other tariffs commercially offered by SSE.

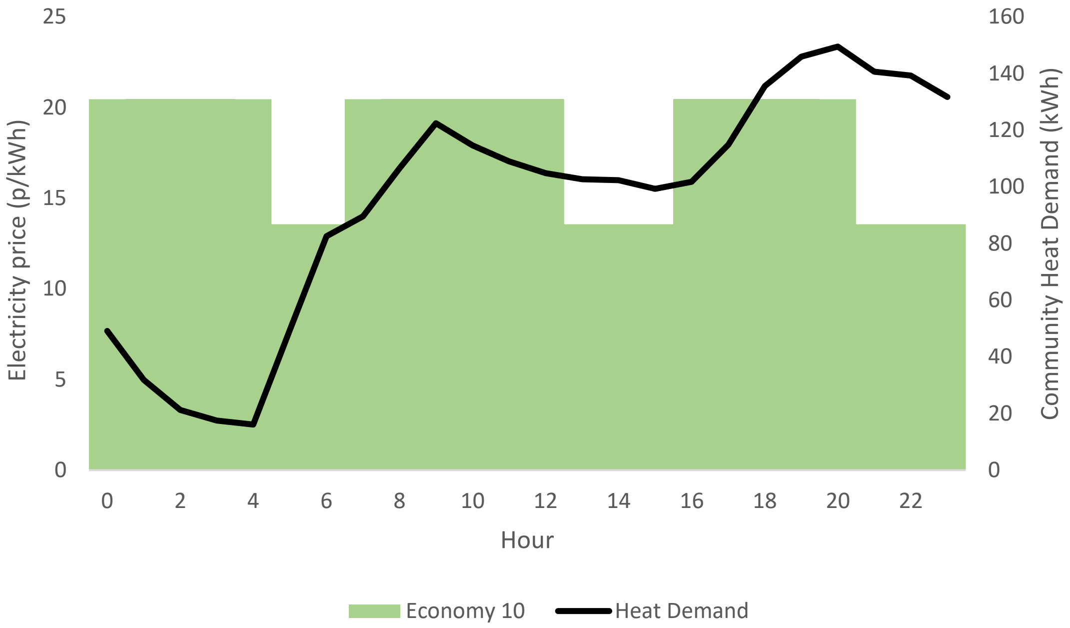


Figure 62. Community heat demand and Economy 10 tariff over a period of 24 hours

One of the main objectives of the project was to design a system that would prevent a risk of fuel poverty in the selected community. Considering that all houses use electric storage heaters, although some dwellings might even use basic immersion heaters, this would mean a price of 10.99 p/kWh of heat (assuming no losses in the electric heaters). The Standard SSE tariff would lead to even higher prices per one heating unit. Therefore, it was decided that the proposed WSHP system would sell heat at a fixed rate of 5 p/kWh, which should immensely help the community to have access to affordable heating, possibly even cheaper than households situated within the national gas network on the mainland. This would at least halve the current space heating and hot water bills, whilst generating a total of £24,800 annually on top of net profit presented in *Table 11*.

The maximum capital cost that the system would have to be built for when considering all aforementioned operating expenditures and revenues was estimated by using a basic loan repayment formula shown in *Equation 3* (Clarke, 2016);

$$R_{\mathrm{Annual}} = \frac{C.r(1+r)^{n}}{(1+r)^{n}-1} \qquad \textit{Equation 3}$$

Where R_{Annual} is a total annual net profit including revenues generated from the sold heat, r consists of an annual inflation rate of 5% and maintenance and operation expenditures of 10% and n stands for the repayment period of 15 years (assuming a system lifespan of at least 25 years). This leads to a capital loan value of £1.2 million. This value was then compared to other similar projects that were more thoroughly concentrated on financial assessment of community based WSHP systems, such as a feasibility study of Kinlochleven project (ESRU, 2017). The comparison strongly indicates that the actual overall capital cost of Blackwaterfoot heating system would be significantly lower than the calculated value of £1.2M. This would lead to a shorter repayment period than was primarily assumed, which would give the community more money to invest into other development projects, such as retrofitting of houses to decrease annual energy consumption or building an outdoor/indoor leisure centre to attract more young people to live in the area. To demonstrate this in an example, if the actual capital cost of the system would be a third of the calculated capital loan value (£400k), this would shorten the payback period from 15 to 5 years, and the rest of the system lifespan would generate significant profit to the community. More accurate capital cost of the system should be discussed directly with the selected company that would be in charge of the construction and operation phases.

The calculated capital loan value does not take into account any other grants or government incentives that could fund the proposed development. The Scottish Government currently runs a wide range of schemes that are designed to support community based projects, and especially those concentrated on implementing low carbon heating systems. Apart from RHI and FIT schemes that have already been considered in the simulation modelling stage, District Heating Loan from Energy Saving Trust could be used to receive an affordable loan with favourable conditions. Another possible source of support could be the Climate Challenge Funding (CCF) as a part of Scottish Government’s Keep Scotland Beautiful scheme with headquarters in Stirling. This incentive programme was fundamentally established to support community projects across Scotland, which could help to build the designed system in Blackwaterfoot.

6.9. Environmental Considerations

Environmental considerations related to the community development project are mainly positive with some negative aspects that should be mitigated. An undesirable distraction during the construction process could be moderated by allowing work only during normal working hours, when most of the residents might be away from their homes. Increased traffic in the area should not cause major problems due to the relatively small size of the system, when most of the components could be brought to the site in large bulks instead of delivering them individually. Since the selected site is based in the heart of Blackwaterfoot, piping installation should not distract many wild animals that occupy areas further from the village. Moreover, the system layout shown in *Figure 63* indicates that piping should take a relatively short amount of time, as none of the pipes cross a man-made road, which would not only increase the capital cost of the installation phase, but also negatively influence the required building time.

The construction phase is expected to cause more distraction than the operation, however some impacts are expected even at the latter stage. According to the computer simulation in GeoT*Sol, the Black Water temperature drop is at most 3 °C, and never goes below the freezing point of the river, which would be fatal for most living creatures that live in the river. Even if open-loop system was to be used, the amount of water taken from the source would be relatively small compared to the estimated flow rates throughout the year. Noise of the operating pump could be mitigated by using sound proof materials when building then engine room. Regardless, despite the relatively small size of the project, all phases should be carefully discussed and be approved by SEPA and SNH to ensure that professional assessment is provided and supervision is presented on the site to mitigate any major impacts caused by the development.

Due to the presence of solar PV panels, more than 50% of annual electricity consumption of the heating system is guaranteed to come from a renewable source. This assumption is based on supply-demand matching simulation which estimated an annual PV power output of 77 MWh that offsets an equivalent of 55% of overall WSHP and backup heater power consumption. Moreover, the imported electricity from the national grid is often sourced from renewables with even higher percentage expected in the near future due to ambitious targets set by the Scottish Government. This means that the vast majority of heat generated on the site would be renewable, and therefore decrease pollutants released by conventional heating sources often used in areas out with the national gas network, such as kerosene or coal. These pollutants include not only CO_2, but also NOx, SOx, particulate matter, and heavy metals that significantly worsen local air quality.

More detailed assessment of any potential environmental impacts should be undertaken before going ahead with the project. Nevertheless, it is expected that the advantages of the small-scale low carbon heating system outweigh the negative impacts that would mainly occur throughout the construction phase, which should be relatively short compared to the operational stage. The potential site layout accompanied by detailed photographs taken during a site visit in June 2017 are shown in *Figure 63*. The bottom right photograph captures the potential location where the WSHP system could be situated, and bottom left the Black Water delta.

Figure 63. Potential site layout including photographs gathered during a site visit on June 23, 2016

6.10. Social Impacts

The majority of social impacts linked to the project are expected to be positive without any known major obstacles that could arise from the proposed development. The project anticipates fuel poverty reduction, local job creation and showcase for other communities. The only social drawback that has been discovered could arise from natural envy, as some residents of Blackwaterfoot would pay significantly less for heating compared to the rest of the village. This issue could be, however, mitigated by investing gained profit from the scheme to start new community projects that would increase well-being of the entire area well beyond the zone of involved buildings.

One of the key advantages of the low carbon heating project is the significant reduction of fuel poverty in the community, as the current rate on the island is alarming. Moreover, the possibility of low prices for heating could attract more young families to the area, since the ageing population on Arran is a long-term issue that has not been resolved yet. The attractiveness of the community could be even enhanced by the potential job opportunities that are expected to emerge. Local jobs would be created not only during the construction process, but also operation would most likely lead to at least one full or part-time job to maintain the WSHP system and solar PVs installed on the roofs, which should be given to a local resident that has a sound knowledge of the area and is known to the locals.

The community should ensure that the selected development company has previous experience with community based projects, and they should be in charge of the project from the planning stage all the way to the operational phase to avoid the risk of ’built and run away’ tactic. Ideally, the company that will be in charge should either be located on the island, or alternatively from the mainland but cooperate with heating engineers from Arran. This would guarantee that the community project would be beneficial mainly to the residents of the island with only necessary specialised input that may be required from the mainland.

An appropriate demonstration of the system performance is another crucial aspect that should be implemented. A smart control system should include advanced sensors that would upload the system performance data directly on the community website, where everyone could see generated heat and power from WSHP and solar PVs, respectively.

This would help to prove the successful operation of the system to local residents, including young pupils as a part of their education about renewables, and increase awareness of this innovative system even beyond Blackwaterfoot. Such monitoring system used as a part of the Harlaw Hydro project was discussed in the literature review, and is considered to be a great success especially amongst the young generation at a local school.

Notably, the project could act as a showcase for other communities, as it would be a relatively unique system that incorporates community owned WSHP system combined with solar PVs which is entirely owned by the community. Such project is expected not only to decrease the heating bills of the residents, but also provide a significant profit to the community when the repayment period is over. Moreover, the generated profit could be used to build new leisure centres in the area that would greatly increase health and well-being of the residents. Finally, the Blackwaterfoot system could function as a pioneer project which demonstrates the WSHP system feasibility even at a smaller scale, whilst harnessing renewable power coming from the sun that is generated on site by the integrated solar PV panels, all entirely owned by the community.

6.11. Applicability of Methodology to Future Off-Grid Site

Developed methodology that was prepared for an existing site in Blackwaterfoot could be eventually applied to any other community within and out with Scotland that is relatively close to a water source, which is suitable for the water source heat pump system. To demonstrate the applicability and flexibility of the established methodology, the system’s feasibility as a part of a potential future off-grid site on the island was examined. This opportunity arose from the field trip that was an important part of the project research methodology. Although at the time of writing this thesis the off-grid site has not been given consent, the following analysis could be beneficial for the decision makers that are involved in the feasibility study process. Nonetheless, this analysis should primarily demonstrate the flexibility of WSHP technology and the effectiveness of the created methodology regardless of the final outcome whether the off-grid site will be built in the future or not.

The location highlighted in *Figure 64* is situated on the west coast of Arran, relatively close to Brodick. The off-grid site would be placed at the spot where Merkland Burn discharges into the sea, on the other side of the main road. This area was selected due to possible suitability of harnessing hydropower from the burn as a part of a high head run-of-river scheme. More detailed layout of the site is shown in *Figure 69*.

Figure 64. Off-grid site location next to Merkland Burn *(Digimap, 2017)*

The next stage of the methodology was to create a heat demand profile of the community. The size of the available area would be suitable for approximately 5 large houses, which was estimated during the field visit. Although new houses are likely to be more energy efficient compared to the ones in Blackwaterfoot, the annual heat demand was estimated to be similar, as the buildings would be designed to function not only as family homes but also as educational or medical centres that generally require more demand. Therefore, the overall heat demand of the off-grid site composed of 5 houses was estimated to be proportionate as a quarter of the community heat demand in Blackwaterfoot with a total of 20 houses.

Although domestic electricity demand was not part of the created methodology, it was decided to add this parameter to the Merkland model due to the fact that the site would not be part of the electricity grid, therefore would have to be completely self-sufficient.

The hourly data for electricity demand was extracted from Merit by following the same procedure as with heat demand, and altered proportionally according to the heat demand of 5 studied buildings. Both demand profiles during the year are shown in *Figure 65*. It is noticeable that the electrical demand profile is more stable throughout the year compared to the heat demand, which aligns with the expectations.

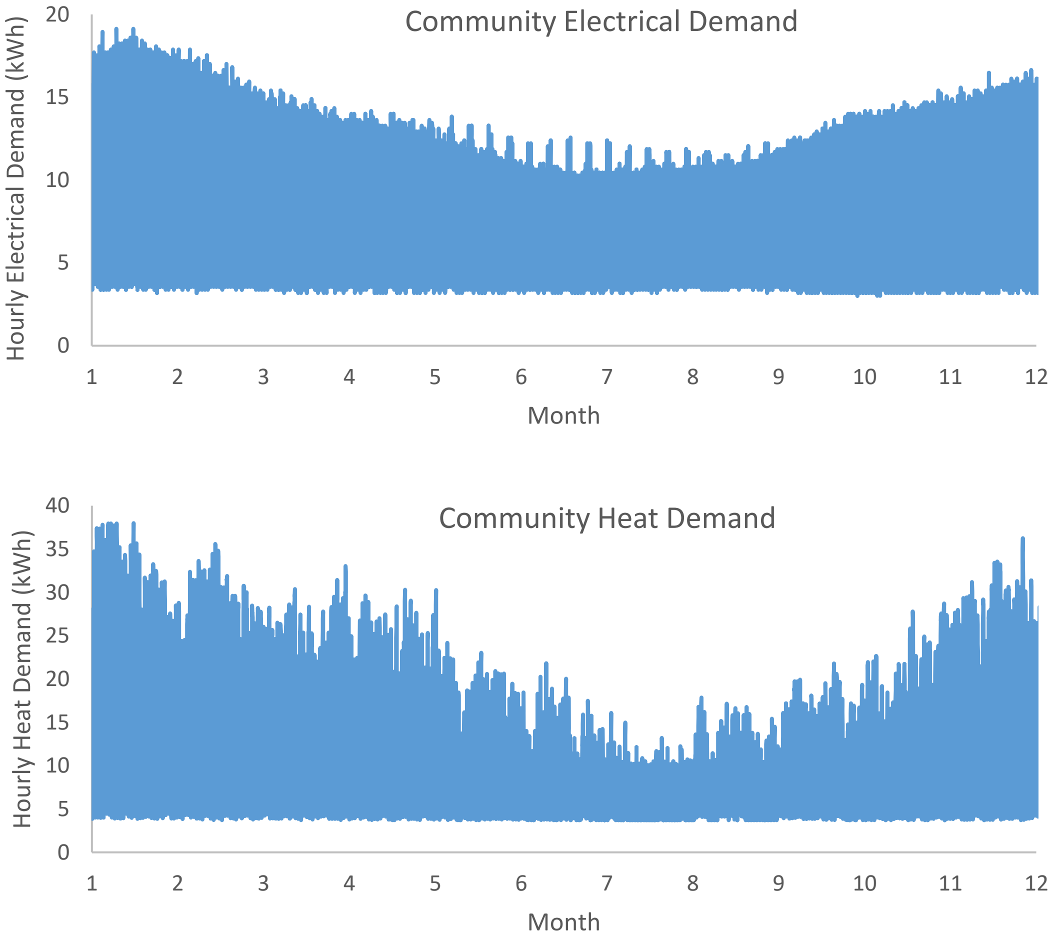


Figure 65. Estimated community electrical and heat demand based on hourly data throughout the year gathered from Merit

Water source properties of Merkland Burn was the next phase of analytical evaluation according to the methodology. For modelling purposes, the water temperature was assumed to be identical to the figures used for Black Water in Blackwaterfoot. The establishment of the flow rate was even more critical in this case, as these values would not be used only to model the WSHP system, but also to calculate power output of the micro hydropower scheme. The flow rate assessment was once more calculated in CatchmentsUK and LowFlows 2 by selecting the catchment area of Merkland Burn. Gathered results are summarised in *Table 12*.

Table 12. Estimated flow rates and water temperature of Merkland Burn throughout the year

Month	Flow Rate (m^3/s)	Water Temperature (°C)
January	0.2220	8.5
February	0.1460	7.8
March	0.1180	7.7
April	0.0806	8.6
May	0.0545	9.9
June	0.0803	11.6
July	0.0547	13.4
August	0.0691	14
September	0.128	13.9
October	0.1760	13.2
November	0.205	12.1
December	0.191	10.2
Average	0.127	

Heating system design for the off-grid site was left with identical specifications as the previous recommendations, but scaled down proportionately according to the size of the new site. It is notable that the off-grid system should be ideally designed with larger thermal storage and integrated electrical storage that would ensure the reliability of the system, whilst avoiding any power cuts. Such a complex model could be created in the future, as this process is focused on testing already created methodology, and so a rough projection of the system design should be sufficient.

The main modification of the off-grid site consists in renewable resource evaluation. A wind power assessment was excluded from the analysis for the identical reasons as mentioned in the Subchapter 6.1, and solar PVs were disregarded after the practical research on the site, as the steep cliffs would block the vast majority of sun rays. Moreover, solar PVs have already been analysed in the previous model. The field study revealed that the most adequate renewable power system would be a micro hydropower system that would generate enough electricity to meet the entire electrical demand of the community, including WSHP system power consumption.

The rated output of the micro hydro scheme should not exceed 100 kW to be eligible for the highest FIT rate which is currently 7.8 p/kWh (OFGEM, 2017). The available head was estimated from Digimap at 130 m in total, which would require only one forestry road crossing of the penstock. It was decided that a maximum of 50% of flow rate could be harnessed throughout the year to leave enough water in the stream to avoid negative environmental impacts. After analysing the available flow rates, head and running initial simulations in energyPRO, the maximal possible rated power output was estimated at 80 kW, assuming standard turbine efficiency of 85%. The appropriate turbine type should be selected from *Figure 21* that is part of the literature review. For this specific case of high-head low-flow conditions the most suitable could be Pelton, Turgo or PAT turbine. There is no need for a pumped storage technology, thus impulse turbines can be considered. Pelton is an established turbine type that can harness even small streams in the mountains, whereas Turgo and PAT are defined by low capital and maintenance costs. The final selection should be discussed with hydropower professionals that would be assigned to build the site. However, the most recommended type could be Turgo wheel due to its low cost and the fact that it only has one manufacturing site in the world, which is located in the UK. The system layout in energyPRO is captured in *Figure 66.*

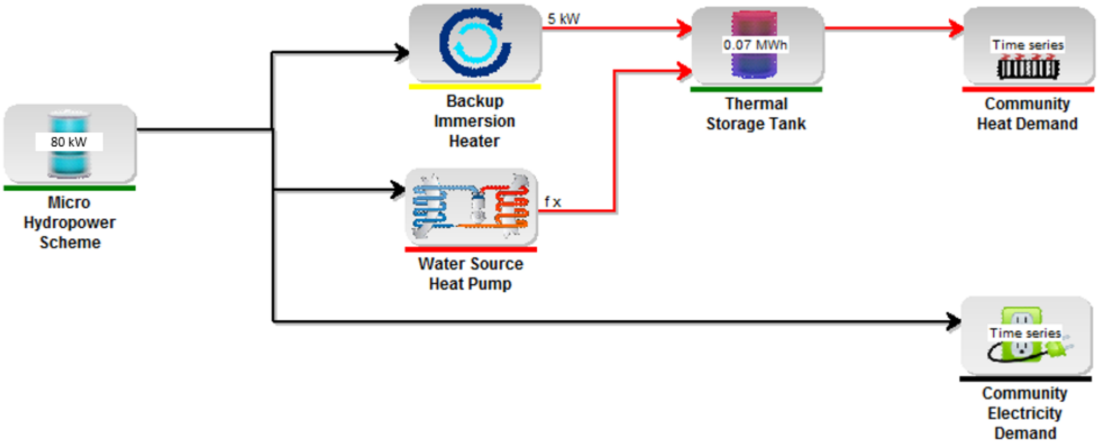


Figure 66. System layout of Merkland off-grid site modelled in energyPRO

Energy simulations revealed that micro hydro system is largely oversized for the assumed size of the community. A total annual power demand of the community, including heating system power consumption, is 110 MWh, whereas 80 kW micro hydro system could generate 504 MWh per year. This means that a vast majority of the generated electricity would either have to be used for other purposes, or the site would need to be extended. This is due to the fact that the hydro system was sized in a way to make most of the available hydropower. The supply-demand matching results after running multiple simulations in energyPRO revealed that the 80 kW hydro system could successfully meet a total electricity demand, including WSHP power consumption, of 12 large houses. However, this solution would be realistically problematic to implement due to restricted building area availability that was discovered during the field trip. Theoretically, the selected site of 5 houses with 80 kW system could be connected to the grid, however this analysis aims to study completely off-grid conditions, and so the hydro system size was optimised to provide more suitable supply-demand match of only five community buildings.

The system was designed to meet thermal and electrical demand by using only thermal storage that was already in place rather than making the most of the available hydropower. The hourly electrical demand was established by adding heating system power consumption and electrical demand, which resulted in an annual peak demand of 30 kW with many occasions over 25 kW. Therefore, it was decided to design the system with the same head and rated power output of 30 kW. The monthly power outputs of larger and smaller micro hydro systems are shown in *Figure 67*. This is a very approximate estimation due to average flow rate values per month, whereas real power output curves would fluctuate significantly every day.

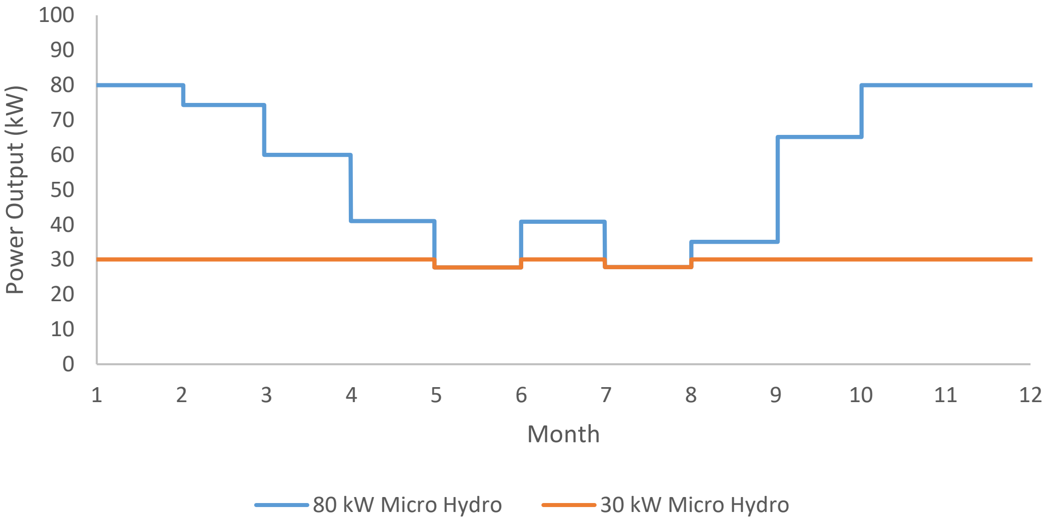


Figure 67. Potential micro hydro power output at Merkland Burn modelled in energyPRO

The graph shows that the power output curve from the hydro system is relatively similar to the heat demand curve over the year. Moreover, the lowest heat and electricity demand occurs in July, when the flow rates are the lowest, and therefore generates the least power. On the other hand, heating and electricity demand is the highest during winter months when the power generation is maximal. This gives micro hydropower systems a large advantage over other renewable power systems when it comes to supply-demand matching, especially in terms of power use on site and energy storage size. This is extremely important especially in off-grid areas, where both electricity and heating systems completely rely on renewable power generation on site. This model proves that hydropower technology is significantly more suitable to supply electricity to heat pumps compared to solar PVs due to similar generation and electricity demand curves.

Both 80 kW and 30 kW systems operate at relatively high capacity factors throughout the year. The former system makes most of the hydropower resource in winter and runs at approximately half capacity during summer months, whereas the latter system provides very stable power output during the entire year with a capacity factor of more than 0.9. This means that 30 kW system generates nearly half of the 80 kW system's power output per year. Moreover, the size of hydropower scheme could be further decreased by increasing thermal storage size and/or implementing electrical storage. Nevertheless, the optimum design would have to be financially assessed to find the best possible solution. Hourly operation of the system during a typical cold winter day is shown in *Figure 68.*

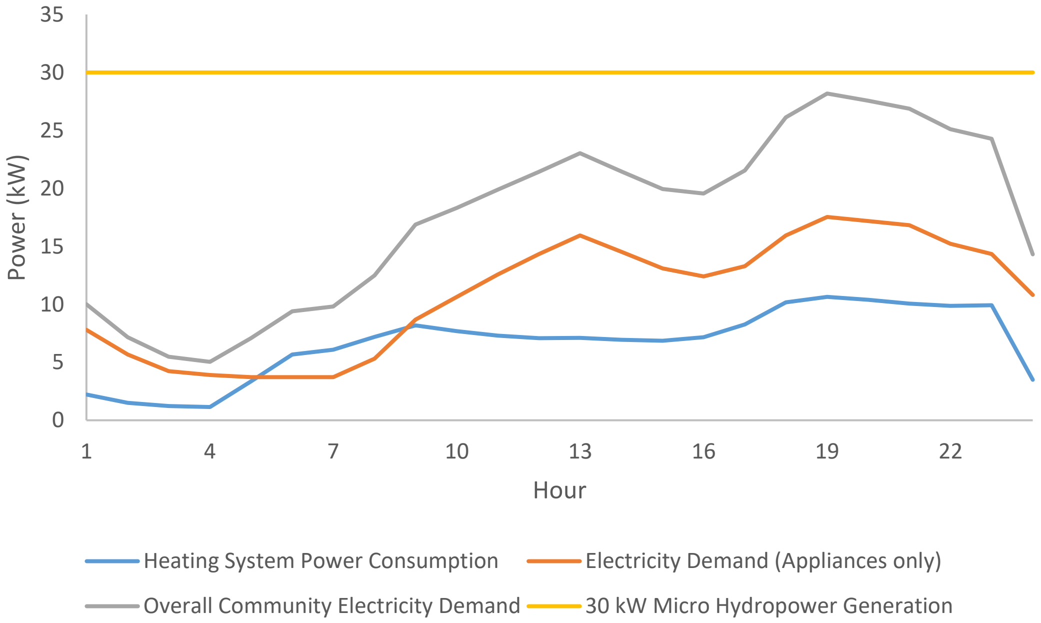


Figure 68. Supply-demand match between micro hydro system and overall community demand

The graph clearly demonstrates that the total electricity consumption of the site can be entirely met through generated power even during the coldest winter days. It can be seen that the heating system power consumption curve is fairly fluent without sudden peaks, which is due to the integration of thermal storage that provides heat during the peak demand. Another interesting fact is that heating system power consumption is in most cases lower than electricity demand of appliances. This is due to the COP of

WSHP system, which corresponds to a seasonal average of 3.7. In fact, daily heating demand would be clearly much higher than electricity demand. Finally, the supply-demand simulations confirmed that 30 kW micro hydropower system can provide enough power even during the coldest days of the year without any additional electrical storage. This outcome is, however, based on the assumption of constant monthly hydro power output estimated in LowFlows2. The technical results summary is shown in the *Table 13.*

Table 13. Main technical specifications of the Merkland off-grid system

Community Annual Heat Demand (MWh)	124
Water Source Heat Pump System Capacity (kW)	26
Water Source Heat Pump SPF	3.7
Thermal Storage Size (litres)	3,075
WSHP Turns ON	2,016
Backup Heater Turns ON	86
Community Annual Electrical Appliances Demand (MWh)	75
Total Annual Electricity Demand (MWh)	110
Micro Hydro Turbine Type	Turgo
Rated Micro Hydro Power Output (kW)	30
Annual Renewable Power Generation (MWh)	260
Annual Surplus Electricity for EVs or Hydrogen Production (MWh)	150

Financial assessment of the system was included in the energyPRO model that included revenues from RHI (19.5 p/kWh) and FIT (7.8 p/kWh), which leads to an expected annual net profit of £20,000 from RHI and £26,000 from FIT that results in a total of £46,000 per year. The generated surplus electricity of 150 MWh per year could be theoretically sold to the national grid at a rate of 5 p/kWh, however this option would mean expensive grid connection set up, and additionally the potential site would lose its uniqueness.

A more highly recommended solution would be to use the surplus for other innovative projects, such as electric vehicle charger installation. According to the interviews made during the field trip, some residents would be willing to purchase an electric vehicle, however there is not any electric charging point situated on Arran, and so Merkland off-grid site could be the first of its kind. To demonstrate this in an approximate example, the surplus power produced by the 30 kW micro hydro system could potentially charge six new Tesla Model 3 cars from empty to full per day on average (GTM, 2017). Alternatively, the surplus electricity could be used to pass water through an electrolyser to generate and store hydrogen that could be used by residents and visitors on the island to charge their hydrogen fuel cell vehicles. This solution is ideal for off-grid sites, as the system can take advantage of the stochastic electricity at any time of the day, especially if the hydrogen is stored in bottles and sold to customers afterwards. Nonetheless, either of these solutions would meet all three major demands; electricity, heating and transport; with 100% renewable power. It is expected that such a distinctive complex system would be eligible to receive government grants to demonstrate the potential renewable future of Scottish islands. Detailed site layout of the considered site is shown in *Figure 69*.

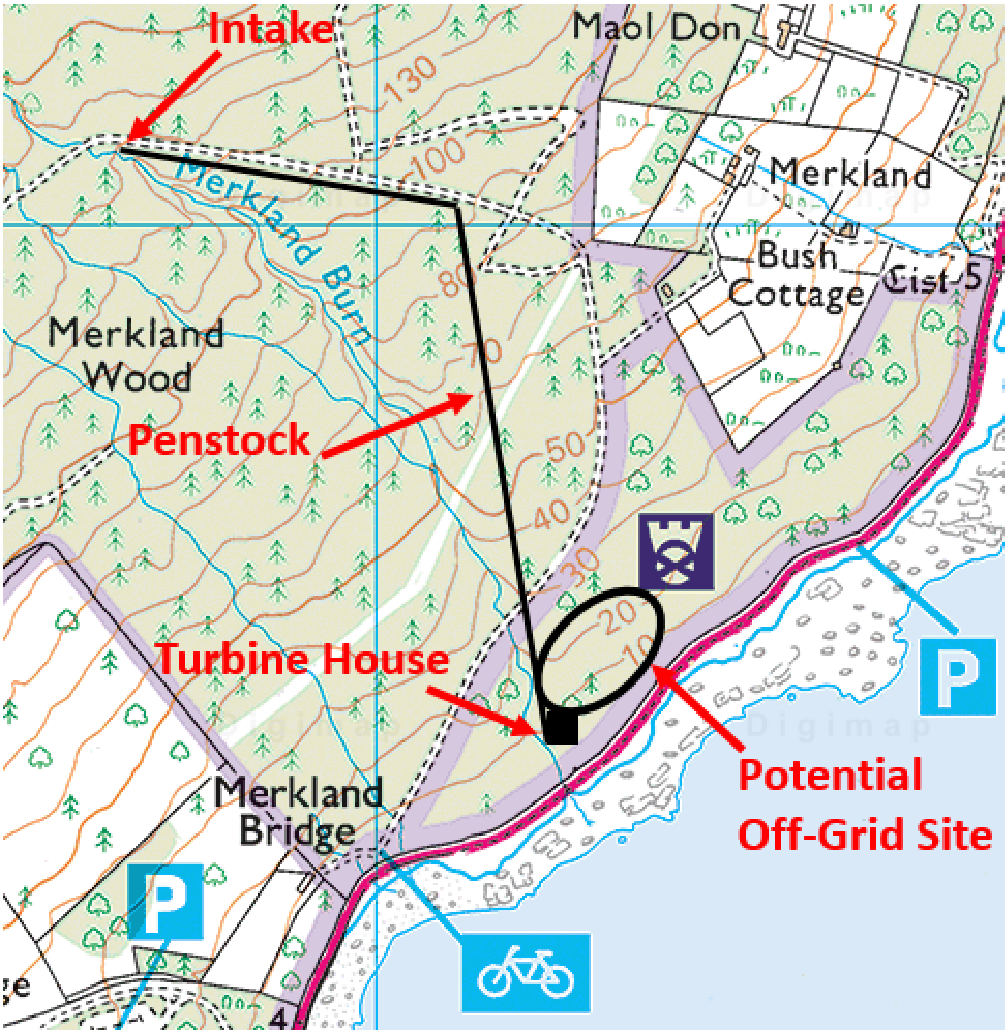


Figure 69. Merkland off-grid site layout with highlighted main parts of the system *(Digimap, 2017)*

The largest obstacle that would need to be overcome is the fact that the piping layout and the site itself are situated within the areas owned by SNH and the Forestry Commission, who would need to give official consent to approve the project. Environmental impacts are expected to be relatively minor due to the size of the system, and current policies set by SEPA ensure adequate sustainability of any new rural renewable energy projects. Moreover, results of supply-demand simulation showed that 30 kW run-of-river system would utilise only 27% of Merkland Burn flow rate every year, which would mean that nearly ¾ of water would be bypassed. In terms of social aspects, these are expected to be vastly positive since this site would contain educational and medical centres, whilst providing comfortable accommodation for residents working in these sectors.

7. Final Discussion

The analytical section of the project revealed that a community based WSHP system supplied by renewable power generation is capable of meeting overall annual heat demand, if the system is designed correctly. The main outcomes, limitations and recommendations are further discussed in this chapter.

The field trip turned out to be an essential part of the project, as some data and other valuable information were simply not possible to gather online, especially when it comes to small remote communities. Numerous interviews with the residents living on the Isle of Arran gave the project a real-world insight, and confirmed that the vast majority of islanders would be willing to use alternative sources of heat and power generation, which are expected to have mostly positive financial, environmental and social impacts on the community.

All the selected tools used throughout the modelling process were found to be immensely helpful to model the system and simulate its performance. The heat demand data gathered from Heat Map were found to be very accurate, which was validated by the HEM tool. The hourly heat demand profile, which corresponded to the annual community heat demand, was exported from Merit. The combination of Biomass System Sizing Tool and GeoT*Sol was found to be extremely powerful, as both tools are designed to concentrate on different technical specifications. The former was used to size the WSHP and thermal storage tank, whereas the latter to find SPF and river temperature drop throughout the entire year on a weekly basis. The power generation results of the solar PV system designed in PV*Sol was validated by Global Solar Atlas, which ensured the robustness of the calculated outcomes. The energyPRO software used all the inputs from previous stages, including renewable power generation, and proved that the designed system can successfully meet the entire heat demand in any given hour throughout the whole year. The hourly steps ensured robust results with regards to all the important outcomes of the energy simulation. The main drawback of the used computer-based modelling tools was the fact that the LowFlows2 tool only estimates river flow rates on a monthly basis, which does not correlate accurately with reality, and could be improved in the future. Apart from that, all other data varied with every hour.

One of the most imprecise assumptions made in the design process was the use of seawater temperatures to model the system. In reality, the river temperatures might even go near to zero in a very cold winter. Although winters have tended to be milder in the past years, an emergency backup could be provided by increasing the immersion heater capacity that would generate heat during these extremely cold periods, as the WSHP system could not be used. The risk of freezing the river needs to be minimised, which means that the heat pump system would not be turned on during these extremely rare situations. Instead, the large backup immersion heater, in a combination with the thermal storage tank, would have to meet the entire heat demand of the community.

Both Blackwaterfoot and Merkland sites were found to be suitable locations for the proposed community-owned district heating schemes. The energy modelling process revealed that the entire heat demand of the selected communities, including thermal storage and heat distribution network losses, can be predominantly met by a water source heat pump system, with the rest supplied by an additional backup immersion heater. The energy simulations input data also considered the fact that buildings located at the end of the distribution network would receive hot water at slightly lower temperatures. Nevertheless, the expected temperature difference is expected to be fairly low due to the relatively short distances between the location of the engine room and the farthest building of the site. Finally, the risk of Legionella appearance in the thermal storage tank and the heat distribution network was found to be minimal due to a distributed hot water temperature of 55 °C (see *Figure 15*). Moreover, the potential increase of heat distribution temperatures would lead to a lower COP of the heat pump, which was demonstrated in the energy modelling phase.

Although a detailed control system design was outside the scope of the project, all the involved dwellings were recommended to be equipped with HIUs to regulate required indoor temperatures as well as to provide precise metering and billing of the buildings. These units were found to be extremely helpful to the residents, as they could follow their energy consumption in real-time, thus manage their spending more efficiently. Moreover, the collected data from the control units could be used to prove the successful operation of the community low carbon heating system that was already demonstrated in the supply-demand model.

The supply-demand phase revealed that the power generation profiles from hydropower schemes are generally more favourable than using solar PVs, due to the substantial stochasticity of solar irradiation throughout the year. This significant technological advantage is, however, eliminated by a larger capital cost related to hydropower systems, especially considering the recent price drop of solar PV panels. Nevertheless, both renewable power generation technologies proved to be successful in terms of supplying electricity to run the low carbon heating system based within or out with the national electricity grid network.

In the case of Blackwaterfoot, solar PVs were found to be an ideal solution to generate the majority of WSHP annual electricity consumption, whilst generating an additional profit from the FIT scheme. The combination of WSHP and solar PVs could eventually become a competitor to solar thermal collectors that have been widely installed in many parts of Scotland, which are often not able to meet the entire heat demand especially during the dark winter periods. Finally, the established Black Water properties, in terms of estimated temperatures and flow rates, could eventually accommodate even another WSHP system, if new buildings that are starting to be built in Blackwaterfoot would decide to follow this low carbon heating project in the future.

The analysis stage revealed that communities with sufficient hydropower resources could also consider the combination of WSHP and micro hydro systems, especially those based out with the national electricity grid network. This was discovered during energy simulations of the potential Merkland site that could meet all the major energy demands by using the nearby burn. The water source was found to be suitable not only to meet the electricity and heat demands of the entire community, but the surplus power could be used to charge electric or hydrogen fuel cell vehicles. The larger capital cost of a hydropower system would be justified by providing an additional source of income, whilst requiring considerably smaller energy storage compared to other renewable technologies, such as solar PVs. Moreover, such an innovative off-grid project could become a showcase for other communities within and out with Scotland due to its uniqueness of meeting all the main energy demands that are essential in the current society.

The financial assessment of the proposed developments differed for the grid connected, and off-grid sites, respectively. The Blackwaterfoot community based within the national electricity network was recommended to select Economy 10 tariff that provided the most financially feasible solution. Although the vast majority of the income would come from the RHI scheme for the generated low carbon heat, an additional profit would be received from the solar PV power generation used either on site or exported to the grid. It was discovered that the recommended price of 5 p/kWh for space heating and hot water would halve the current utility bills in dwellings that use electric storage heaters, and so significantly decrease the alarming fuel poverty rate on the island. In the case of the future Merkland off-grid site, the electricity surplus generated through the micro hydro scheme was recommended to be used for alternative forms of transport, such as electric vehicle charging points or hydrogen production to sell the fuel to the potential hydrogen fuel cell vehicle owners. These solutions of harnessing surplus electricity were suggested to overcome the drawback that the site will not be connected to the national electricity grid, thus cannot export the excess power generated on site.

Finally, the recommended schemes are expected to have vastly positive environmental and social impacts in the selected locations. Although some distractions are anticipated to occur during the construction phases, the environmental impacts during the system lifetime were evaluated to be minimal. Moreover, new job positions and empowerment of the involved communities are highly positive social aspects that could arise from the recommended renewable energy projects.

8. Conclusion

The overall aim of the project was to analyse the technical, financial and environmental feasibility of using water source heat pumps that could provide affordable space heating and hot water for rural communities living on the Isle of Arran. The study was executed to increase the independence and resilience of those communities, while decreasing fuel poverty rate in the area, which was found to be one of the highest in Scotland.

The function of both conventional and cutting-edge water source heat pumps was thoroughly described in the thesis, which also included an overview of selected small-scale renewable power generation systems that were used in the modelling phase to meet the heating system's power consumption. The established methodology that describes all the major steps of the project was prepared to function as a guideline for other communities situated within or out with Scotland.

The Blackwaterfoot community with an annual heat demand of 496 MWh was selected to demonstrate the viability of the designed system. The recommended heating system consisted of a WSHP system with a capacity of 105 kW and an overall seasonal performance factor of 3.7 that was calculated with a step of one hour. The heating system was also designed with an implemented 12,300 l thermal storage tank, and a backup 15 kW immersion heater. The majority of the annual heating system electricity consumption was met through power generated on site through a solar PV system with a rated output of 80 kW.

The flexibility of the established methodology was verified on a potential off-grid community site that is expected to be built close to Merkland Burn on the east coast of Arran. This site was designed with a WSHP system capacity of 26 kW and a 30 kW micro hydro system that was sized to generate enough electricity to meet both heat and power demands of the community all-year-round. Since the system was modelled outside the national electricity network, the surplus power was recommended to be used for other purposes, such as charging electric vehicles or producing hydrogen to fill hydrogen fuel cell vehicles.

All in all, the executed analysis proved that water source heat pumps are capable of providing a reliable source of space heating and hot water even for small rural communities based within a short distance from a running water source. Moreover, the combination of the WSHP system with renewable power generation technologies, such as solar PVs or micro hydro systems, were discovered to be highly suitable not only to meet the majority of the heat pump’s required power consumption, but also to generate additional profit to the involved community, whilst having mainly positive environmental and social impacts.

9. Further Work

The project could be followed by further research to address some concerns that were only roughly assumed, or outside the scope of the thesis. The main points that could be investigated in the future are; precise measurement of river properties and control system design. Further work could include cost estimation of system components and detailed assessment of current heating bills.

River temperatures and flow rates

The technical design of the system was based on seawater temperatures on Arran, however river temperatures are expected to vary more significantly due to the lower mass of water compared to the sea. Flow rates were estimated only on monthly basis, but realistically they would fluctuate within days, or even hours. Both aspects would require long-term physical measurements that could be done in the future.

Control system design

A control system could be designed as a further work to ensure that the most advanced controls are installed, which would ensure smooth operation of the system.

Accurate prices of system components

The capital cost estimation of each component could be a part of further financial assessment that should then be compared to the offer presented by a company that would be selected to build and operate the site.

Detailed assessment of current heating bills

Precise heat demand measurement and site survey should be executed to establish current heating bills that involved residents pay per kWh. Moreover, heat demand data gathered from the Heat Map might not be up-to-date, as houses often undergo building upgrades that lower their annual heat demand.

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Appendices

Appendix I.

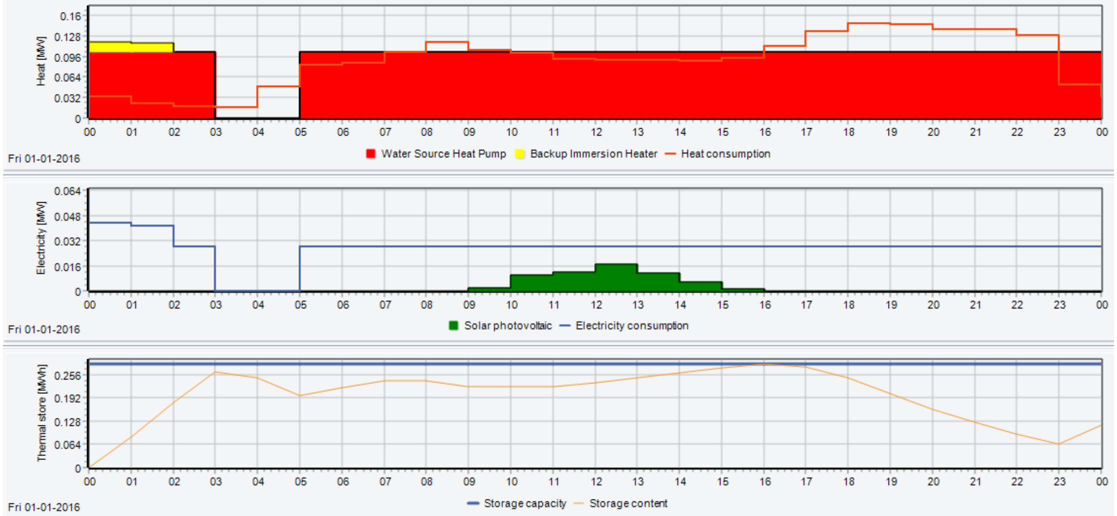

Figure i. Snapshot of a daily supply-demand profile in Blackwaterfoot simulated in energyPRO

Figure ii. Snapshot of a weekly supply-demand profile in Blackwaterfoot simulated in energyPRO

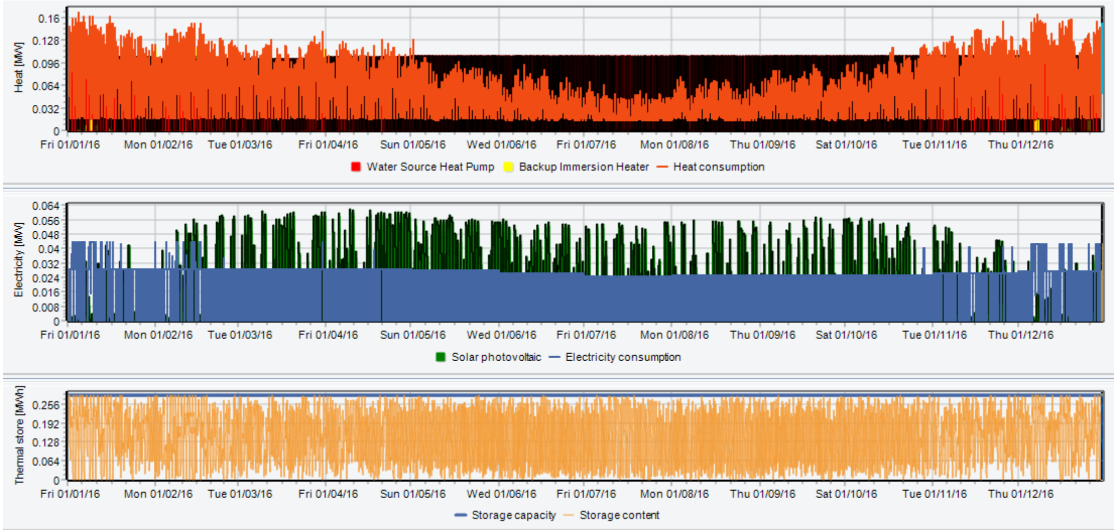

Figure iii. Snapshot of an annual supply-demand profile in Blackwaterfoot simulated in energyPRO