Department of Mechanical and Aerospace Engineering

Renewable Energy Supplied District Heating for a Scottish Community Utilising Heat Pumps: Isle of Barra Future Heating Case Study

Author: Markus Auer

Supervisor: Graeme Flett

A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2019

Copyright Declaration

Signed: Markus Auer Date: 23/8/2019

Abstract

Decarbonisation of heat is a crucial step in the process of mitigating climate change. Buildings amount for 29% of global energy demand, in temperate climates mainly for heating. Ambitious targets have been set to decarbonise heat in the UK but currently it lags all other European countries with a renewable heat share of only 5.5%.

Heat pumps are a viable low carbon heating system, either installed for individual properties or in district heating (and cooling) schemes. While being established in some European countries, these technologies are not widely adopted in the UK and are currently gaining uptake due to public subsidies.

To proof viability and benefits of future heating solutions on a community energy approach, this thesis analyses a specific case study: Castlebay on the Isle of Barra. The investigated Horve area consists of residential, public and commercial properties and was subject of a two-step future heating assessment. Firstly, individual heating solutions were evaluated and compared to a low-temperature district heating system. Secondly, the identified future district heating system was designed in more technical detail. The comparison includes cost (levelized cost of heat in p/kWh), emission savings (tCO2-eq/y) and efficiency (seasonal performance factors of heat pumps).

Air source heat pumps are the most economical solution for large commercial or public buildings (6.1p/kWh). They are moderately efficient (SPF 3.0), reduce CO2 emissions significantly (up to 491t-CO2-eq/y), but face some issues. The proposed district heating scheme includes 119 properties with 2.1GWh/y heat demand, resulting in a distribution grid length of 2270m. A seawater source heat pump was identified as most suitable, with an average SPF of 3.81. Equipment was sized using a 1h timestep simulation model: heat pump 500kW, thermal store 70m^3, electric heater 100kW, backup boiler 600kW. Investment cost is high (£2.7million), resulting in moderate cost of delivered heat (8.7p/kWh). The integration of 200kW wind turbines was simulated, reducing cost and emissions. CO2 reduction with integrated wind energy is ideal (634tCO2-eq).

On its own, district heating for Castlebay is not an ideal solution due to high cost (low heat density), but it brings various benefits. Development of a long-term community energy roadmap is recommended. This could justify district heating as part of a holistic transition towards implementation of renewable energy as a local revenue stream.

Acknowledgements

I want to express my gratitude to everybody who supported me during my studies and while writing my thesis including family, friends and colleagues. It was a pleasure doing this MSc course. I want to especially thank:

Graeme Flett for supervising my thesis. Thanks for all the continuous support, the helpful discussions and the useful data and tools.

Harris Bokhari from LittlEnergy for all the meetings providing in-depth information about the developments on Barra. Thanks also for sharing so many creative ideas and all the best for realising them.

Euan Scott from Coimhearsachd Bharraigh agus Bhatarsaigh for the huge support and all the information about Barra. I hope this contributes to Barra’s way of using even more local energy to empower community. All the best for your next projects.

Toben Lewis from Iona Renewables for the nice meeting on Iona and background information on Iona district heating. Best of luck for implementing this big vision.

Table of Contents

Abbreviations

ASHP	Air Source Heat Pump
CAPEX	Capital Expenditures
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
GHG	Green House Gases
GSHP	Ground Source Heat Pump
HDD	Heating Degree Day
HP	Heat Pump
LCOH	Levelized Cost of Heat
LPG	Liquified Petroleum Gas
OPEX	Operating Expenses
RHI	Renewable Heat Incentive
SPF	Seasonal Performance Factor
WSHP	Water Source Heat Pump

List of Figures

List of Tables

1. Introduction

1.1. Problem

Heat for buildings is a significant energy demand with a high amount of fossil fuel boilers worldwide (BP Global, 2019). In Scotland only 5.4% of heating comes from renewable sources (Scottish Government, 2018a). Building standards are relatively low, making heating even more energy intensive.

Renewable heat is necessary for climate change mitigation but is commencing only slowly. If climate change mitigation targets should be reached, energy demands need to be minimised and heating needs to be decarbonised.

On the Isle of Barra several issues persist regarding energy. Regarding heat, low building standards together with inefficient heating raises cost for energy for residents. Heating is mainly electric and fuel oil, which is expensive and emission intensive (Voluntary Action Barra & Vatersay et al., 2018). This situation is representative for similar communities in Scotland.

Alternative options for property-owners are limited. They can either upgrade housing fabric or upgrade their heating systems. Both measures are initially expensive, as a high funding amount is necessary. Therefore, they are only commencing slowly, and alternative approaches should be evaluated to bring down cost and emissions.

1.2. Aim

This thesis aims on providing solutions for future heating on a community ownership model, from which residents on Barra can benefit. Both individual and district heating system solutions shall be investigated, and a recommendation shall be made by comparing results for cost, efficiency and emission reduction. The most suitable solution for the investigated area shall be provided in more technical detail. A connection to a proposed wind turbine development shall be made and possible synergies identified.

1.3. Methodology

The following approach has been chosen:

1. Define system boundary where district heating is feasible on Barra
2. Identify future low-carbon and low-cost heating systems for Barra
3. Design high-level specifications for individual and district heating system
4. Compare individual to district heating system in terms of:
    a. Heat decarbonisation efficiency: tCO_2-eq savings per year
    b. Energy efficiency: seasonal performance factors of heat pumps
    c. Cost efficiency: p/kWh for generated heat over lifespan
    d. Renewable integration ability: energy demand and supply matching
5. Refine chosen system and present refined results
6. Give recommendation if the new heating system should be developed and if yes, which important parameters should be considered

2. Literature Review

2.1. Renewable Heat Transition Challenges

This section puts energy use for heating residential and commercial buildings into perspective by relating it to global energy demands. Decarbonising heat is currently not sufficiently pursued in the UK (OFGEM, 2016), but it is an important step in order to mitigate climate change.

2.1.1. Energy Demand

Global energy demand can be separated into three main sectors of end-use: transport, industry and buildings. Figure 1 shows that global demand is mainly accountable to industry (50%), followed by buildings (29%) and transport (21%) (BP Global, 2019). Non-combusted parts are included in industry and account for usage of oil, gas and coal for petrochemicals, lubricants, etc.

Considering demand-growth in Figure 1, industry and transport reduce due to higher efficiency standards. Buildings do not increase significantly in energy efficiency and are predicted to have a steady energy demand rise. This means they account for almost the same demand as industry by 2040.

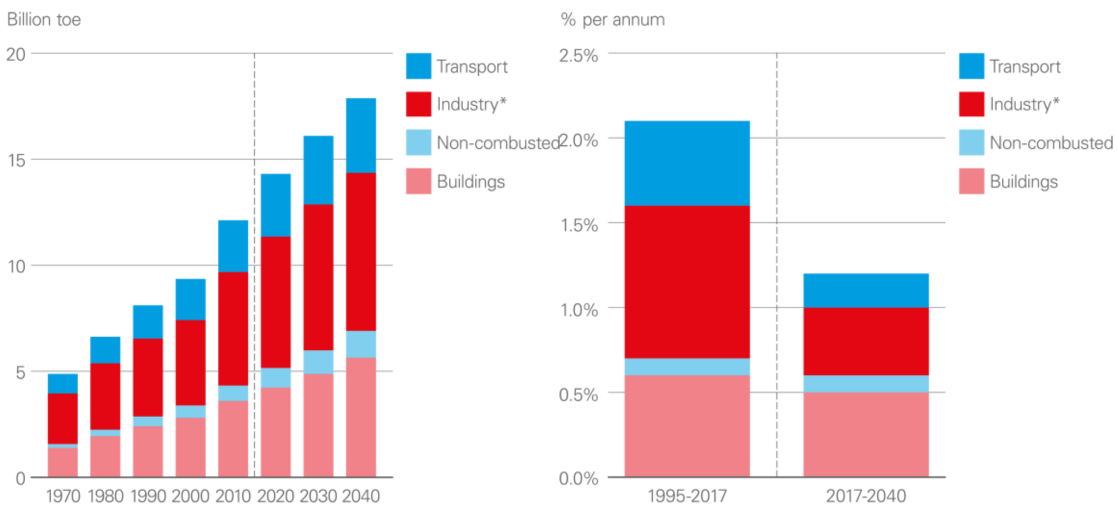

Figure 1 Global Primary Energy Use (Left) and Annual Demand Growth (Right) by Sector of End-Use (BP Global, 2019)

2.1.2. Energy Sources

Energy systems are primarily based on fossil fuels. Currently, a transition towards renewable energy generation is ongoing. Looking into the global share of renewable energy in Figure 2, the amount of renewable energy generation is still outweighed by an 80% share of fossil fuel generation (Zervos, 2018, p. 31). A transition of traditional energy systems towards "modern renewables" (wind, solar, biomass, geothermal, ocean power) is therefore happening at a very modest rate in global context.

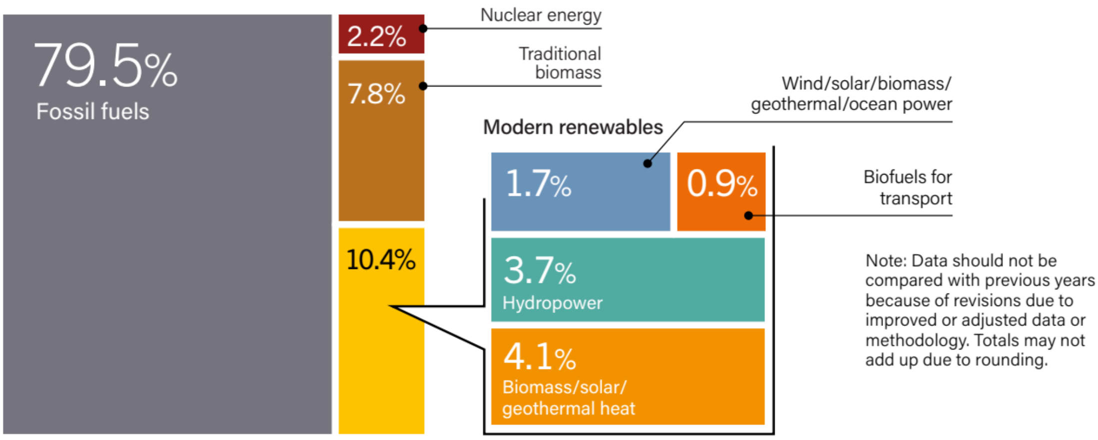

Figure 2 Estimated Renewable Energy Generation Share of Total Final Energy Consumption (Zervos, 2018, p. 31)

2.1.3. Fossil Fuels and Climate Change

The use of fossil fuels contributes towards climate change as they are emitting GHG emissions (Green House Gases) (IPCC, 2014, p. 167). The prolonging use of fossil fuel sources has shifted levels of atmospheric CO_2 towards unusual high concentrations of over 400ppm (CO2.Earth, 2018). This leads to severe climate issues including warmer atmosphere temperatures and rising sea levels (Field et al., 2014). Furthermore, combustion processes emit particles that contribute towards air pollution, causing lower life expectation (European Commission, 2018). Imminent action is required in order to shift energy systems towards more sustainability, using renewable and low emission sources (United Nations, 2018). Action plans to achieve these goals are widely integrated by national (Scottish Government, 2017) and international policy (European Climate Foundation, 2012) and are commonly referred as decarbonisation of energy.

2.1.4. Heating Energy Demand

The end-use for energy in colder climates is primarily heating, electrification and transport purposes. Figure 3 depicts how these demands are distributed in Scotland (Scottish Government, 2018a, p. 31). The Scottish energy demand is dominated by heat demand, accounting for 51% of total final energy consumption. Electricity and transport equally amount for the rest. Excluding transport, domestic and industrial uses are the main energy demand in Scotland. This highlights the importance that an energy transition must include the decarbonisation of domestic and commercial heat.

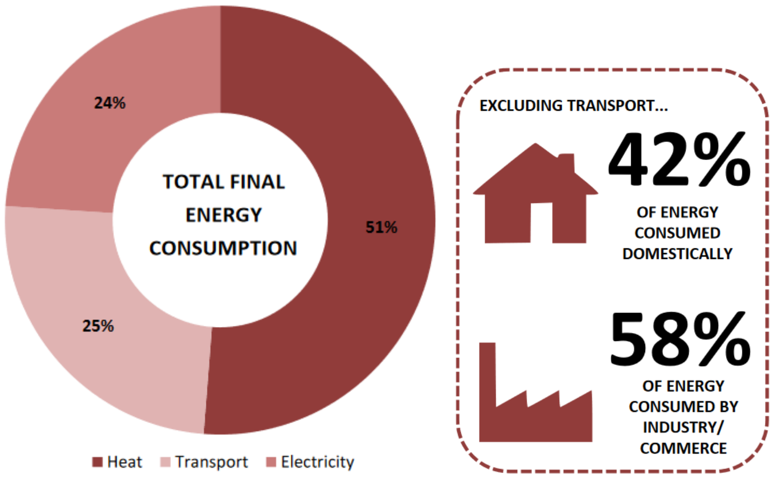

Figure 3 Scotland 2015 Total Final Energy Consumption (Left) and Distribution between Domestic and Industrial (Right) (Scottish Government, 2018a, p. 31)

2.1.5. Decarbonisation of Electricity

The electricity system is globally shifting from centralised, large-scale, fossil fuel based power plants towards smaller scaled, renewable energy systems. CO2 and other greenhouse gas emissions are reduced by increased use of renewable energy. As Figure 4 shows, this so called decarbonisation of energy generation can be observed over the last decade (Bruce, 2019; IEA, 2018, p. 93) and is predicted to continue falling substantially (BEIS, 2019; OFGEM, 2016). This is happening in different pace, depending on the amount of available renewable resource, the electrical power infrastructure, as well as political support. Comparing specific CO2 emissions of different countries, very different results can be observed (Bruce, 2019; Tomorrow, 2019).

In Scotland 54% of the gross electricity consumption was covered by renewables in 2016 (Scottish Government, 2018a, p. 47) and is since increasing (UK Government, 2018).

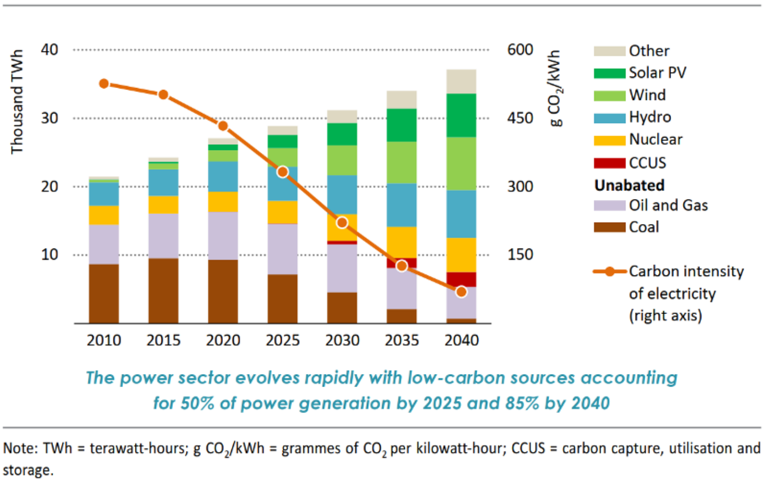

Figure 4 Electrical Energy Generation and Carbon Intensity of Electricity for an Estimated Sustainable Development Scenario (IEA, 2018, p. 93)

2.1.6. Decarbonisation of Heat

While renewable electricity generation share is more than 50% in some European countries, the overall energy use is often significantly lower, as shown in Figure 5. 17.8% of Scotland's energy use is covered by renewable energy. This can be explained by high fossil fuel shares for transport and heating.

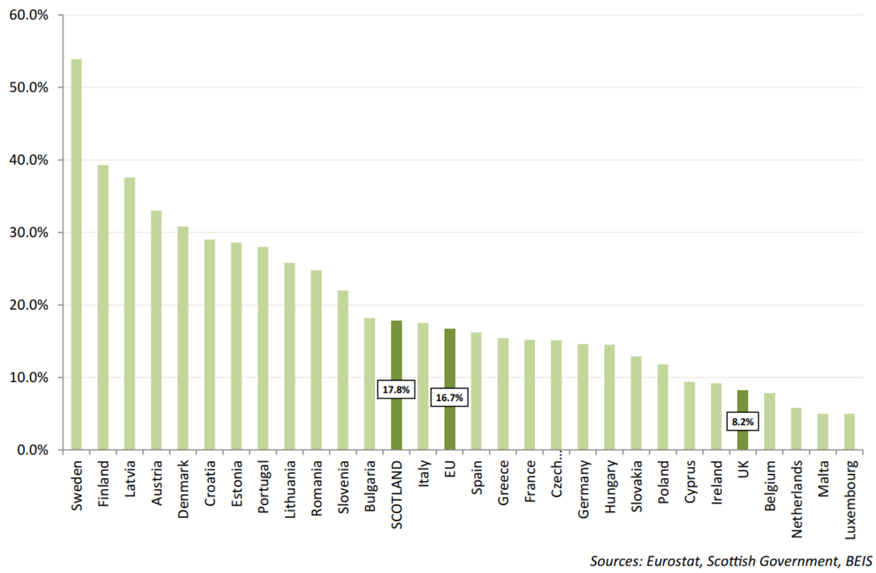

Figure 5 Renewable Energy Generation Share in Gross Final Energy Consumption in the European Union, 2015 (Scottish Government, 2018a, p. 9)

Figure 6 shows that an energy transition towards renewable heat is in a very early stage in Scotland (Scottish Government, 2018a, p. 78). The renewable heat share is only at 4.8% in 2016, being the lowest in the EU. The "renewable heat target" Scotland set for non-electrical heat demand by 2020 is only at 11% (Scottish Government, 2018a, p. 12) and seems hardly reachable. Still 95% of heating systems in Scotland are based on fossil fuel, having a large potential for getting substituted by low-carbon technologies.

The plans for the future are ambitious, as the Scottish climate change plan (Scottish Government, 2018b, pp. 87–88) sets out for decarbonising 35% of domestic and 70% of non-domestic buildings by 2032.

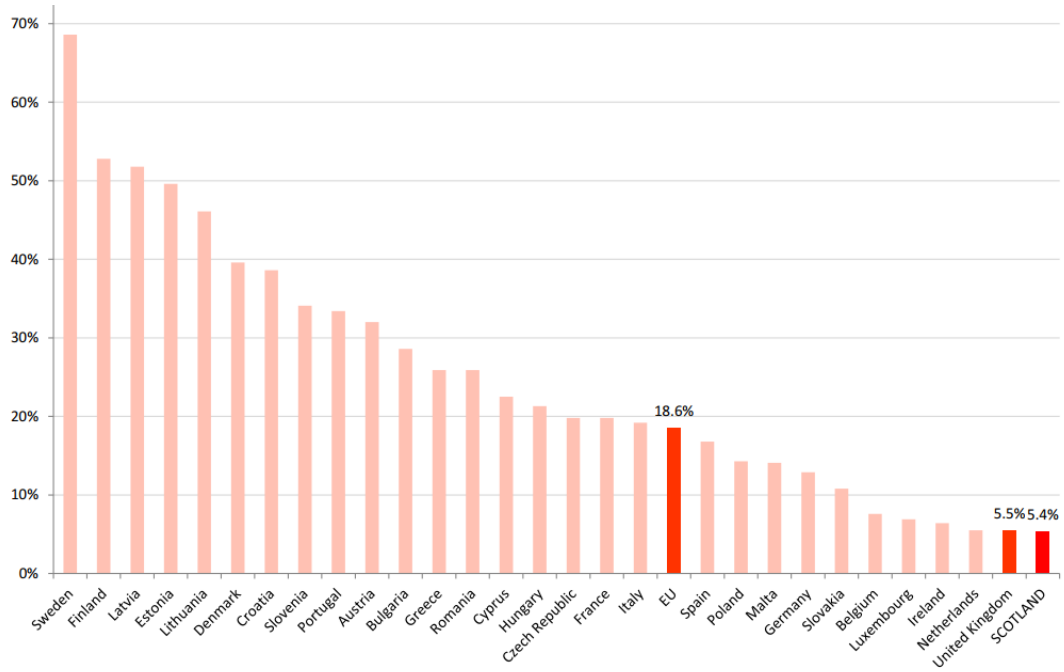

Figure 6 Share of Renewable Heat of all Heating and Cooling Demand Consumption in the European Union, 2015 (Scottish Government, 2018a, p. 78)

2.1.7. Low-Emission Heating

There are numerous technological solutions for shifting traditional buildings with fossil fuel based heating towards highly efficient, low carbon and renewable sources. All these solutions currently have a low uptake as they face some issues such as cost competitiveness. Ofgem (2016) states that decarbonising heat is the biggest challenge in current UK energy policy.

The UK heat supply is mainly (70%) based on burning natural gas across domestic, industry and service sectors. Suggested policy pathways for future heat are considering the following measures (OFGEM, 2016):

- Improving energy efficiency (building fabric and conventional heating systems)
- Electrification of heat with heat pumps
- Heat networks
- Natural gas with low carbon gas and/or hydrogen networks

Figure 8 shows how these measures should be adapted to different building types. For off gas grid locations such as the Scottish Western Isles heat pumps and low carbon heat networks are favoured along with improving efficiency improvements.

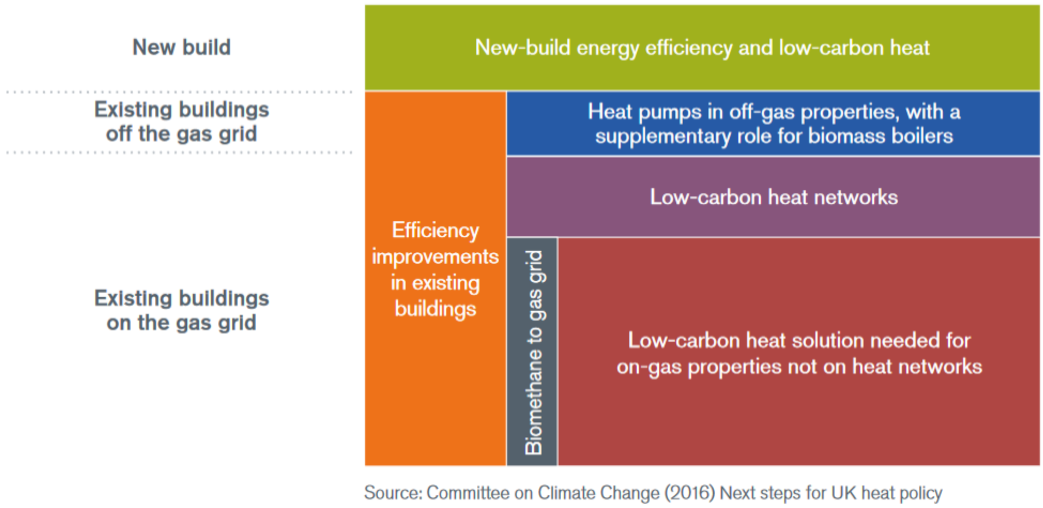

Figure 7 Decarbonisation Strategies for New Build and Existing Off and On-Grid Buildings in the UK (OFGEM, 2016)

Different heat sources and their lifecycle-equivalent CO_2 emissions are shown in Figure 8. Wood based biomass and ground-source (GSHP) or air-source (ASHP) heat pumps are clearly in favor of gas, oil and coal. Emission factors for electricity based heat pumps or direct electric heating depend on the electrical energy generation mix. Renewable energy generation is relatively high in Scotland, so grid carbon intensity is low (Bruce, 2019). Heat-pump based heating is a viable path for future low-carbon heat.

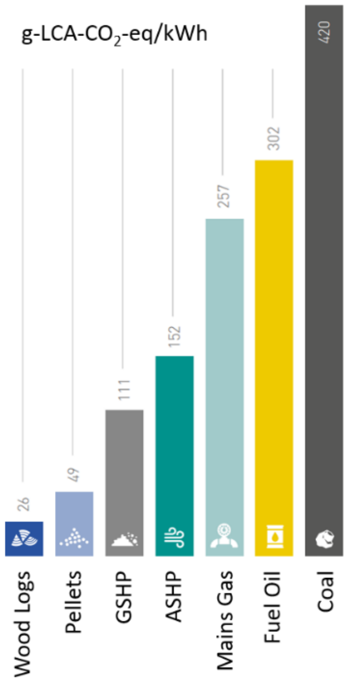

Figure 8 Specific CO_2 Emissions for Different Heating Systems, Using Life Cycle Analysis (LCA) CO2-Equivalents (Klima- und Energiefonds, 2017, modified)

Low-carbon heat technologies including biomass boilers, solar thermal panels and heat pumps are currently supported by UK subsidies, called renewable heat incentive (RHI). This subsidy compensates high initial cost (Trnka, 2018) for these technologies. Heat pumps for average domestic homes are priced around 5,000-10,000 pounds (OFGEM, 2016) and therefore significantly more expensive than gas, oil or direct electric systems. Despite this subsidy, the uptake is relatively low (OFGEM, 2016). Possible issues are a lack of awareness of renewable heat solutions and too high initial costs for private owners as well as a lack of benefit for landlords renting their properties.

This indicates that targeting single properties will not gain enough momentum to create significant change. Ofgem (2016) states that area-based retrofit and district heating measures can lead to a more efficient heat system transition. Successful district heating schemes developed by housing associations, local communities or similar bodies such as the Wyndford Estate in Glasgow (SSE Utilities, 2015) or the West Whitlawburn Housing Association in Cambuslang (npower, 2014) support this theory.

2.2. Community Energy Approach

This section explains how renewable energy generation can be utilised by communities creating numerous benefits. Projects in Scotland are highlighted and the energy situation on the Scottish Western Isles is explained.

2.2.1. Decentralised Energy Generation

Electrical energy systems are historically grown in centralised schemes (Murty, 2017). Traditionally, large-scale power stations fuelled by coal, oil, gas or nuclear fuels as well as hydropower generate energy with capacities of Megawatts up to Gigawatts. This requires an extensive energy transmission and distribution grid in the form of high-voltage and low-voltage power lines and companies that operate these systems.

These systems currently undergo change, as renewable energy generation enable not only further implementation of large-scale renewable generation, but also low-capacity generation for households or communities using solar, wind and biomass resources. This is commonly referred to as decentralised energy generation (Andrews Tipper, 2013). The potential ability of decentralised energy contributing to a low-carbon energy system transition is widely recognised. Multiple benefits are being pointed out by Carson et al. (2008):

- Increased conversion efficiency (less transmission losses)
- Renewable and low-carbon sources can be adopted
- Energy security given by control over own energy generation
- Awareness of energy issues through community-based energy generation, driving change in social attitude including more efficient use of energy

This points out that local renewable energy generation, led by businesses and communities rather than centralised corporations, can contribute towards a low-carbon energy transition.

2.2.2. Community Energy Idea and Examples

The principle benefits of communities investing into renewable energy projects is shown in Figure 9.

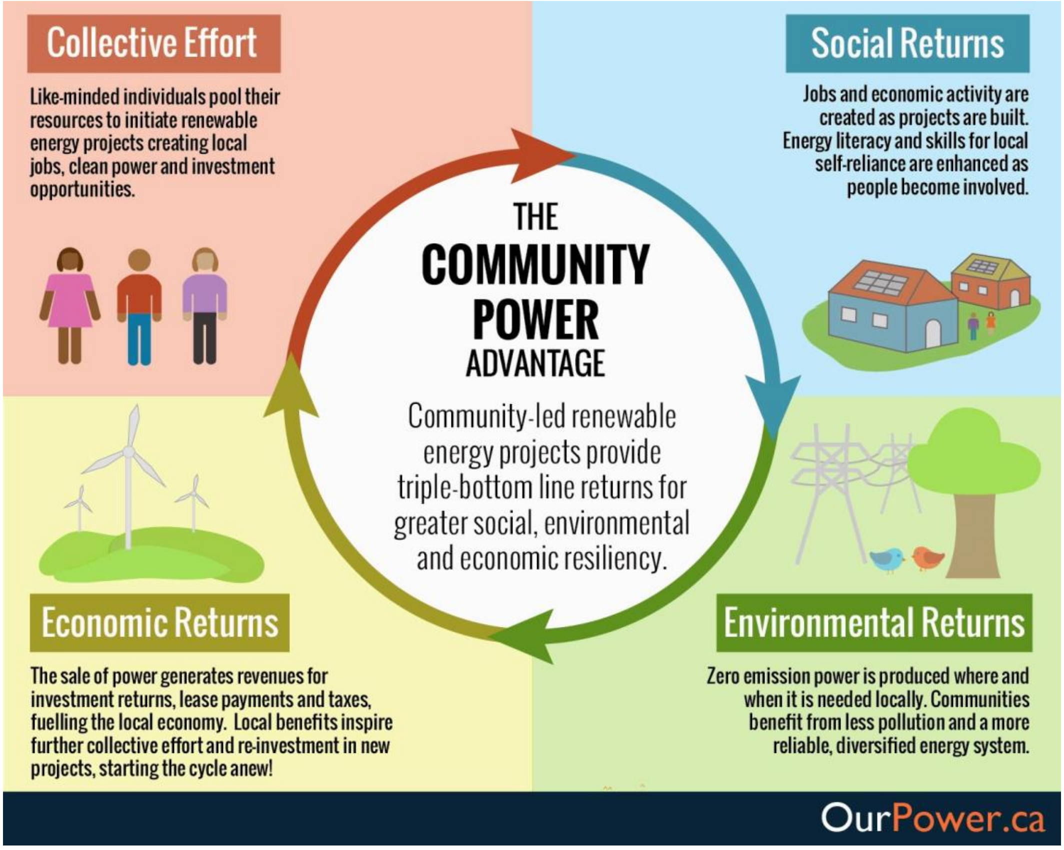

Figure 9 Community Energy Advantages for Social, Environmental and Economic Sectors (Options Group of Companies, 2015)

Rural and remote areas often face an "Energy Dilemma": high prices are paid for heating fuel and electricity, whilst low infrastructure (gas and electricity grid) is provided, and a high dependency is created towards suppliers of energy. This issue is amplified by often low efficiency building standards.

Renewable energy systems have seen positive change in the last few decades. The technologies were subsidised, leading towards economically competitive prices for wind and solar generation units (Kost et al., 2018). This enabled households as well as communities to invest into clean energy supply for their homes.

Several communities in Scotland have developed renewable energy projects over the last years (Edmunds et al., 2018). For example, in Fintry biomass district heating and

PV panels were installed, as well as retrofit programmes were conducted, upgrading heating and building fabric for residents homes (Fintry Development Trust, 2019).

The benefits of community energy were also comprehended Scottish authorities, resulting in governmental support in the form of subsidies and information platforms (UK Government, 2015). Numerous successful projects led to creation of several non-profit organisations such as Community Energy Scotland and Local Energy Scotland. These organisations support interested communities by providing knowledge and funding (Community Energy Scotland, 2019; Local Energy Scotland, 2019).

2.2.3. Community Energy on the Scottish Western Isles

The Scottish Western Isles are a remote area, benefitting from abundant wind resources which can be used for locally generated renewable energy in a cost-effective way. Several renewable energy projects were implemented by both companies developing multi-Megawatt wind farms (Smeed et al., 2014) as well as communities installing single-Megawatt turbines generating revenue they can reinvest locally (Coimhearsnachd Bharraidh agus Bhatarsaidh Ltd, 2012).

Extensive export of short-term renewable peak-generation and seasonal over-production to the mainland is currently curtailed by grid operators, due to lacking grid infrastructure. This is mainly caused by a missing high-capacity interconnector (600MW are proposed) between the Western Isles and the mainland. The current grid infrastructure and regarding voltage levels are shown in Figure 10. This is unlikely to change in the next years, as a possible interconnector is being discussed since 2001 and still no agreements have been achieved between grid regulators and grid operators (SSEN, 2019).

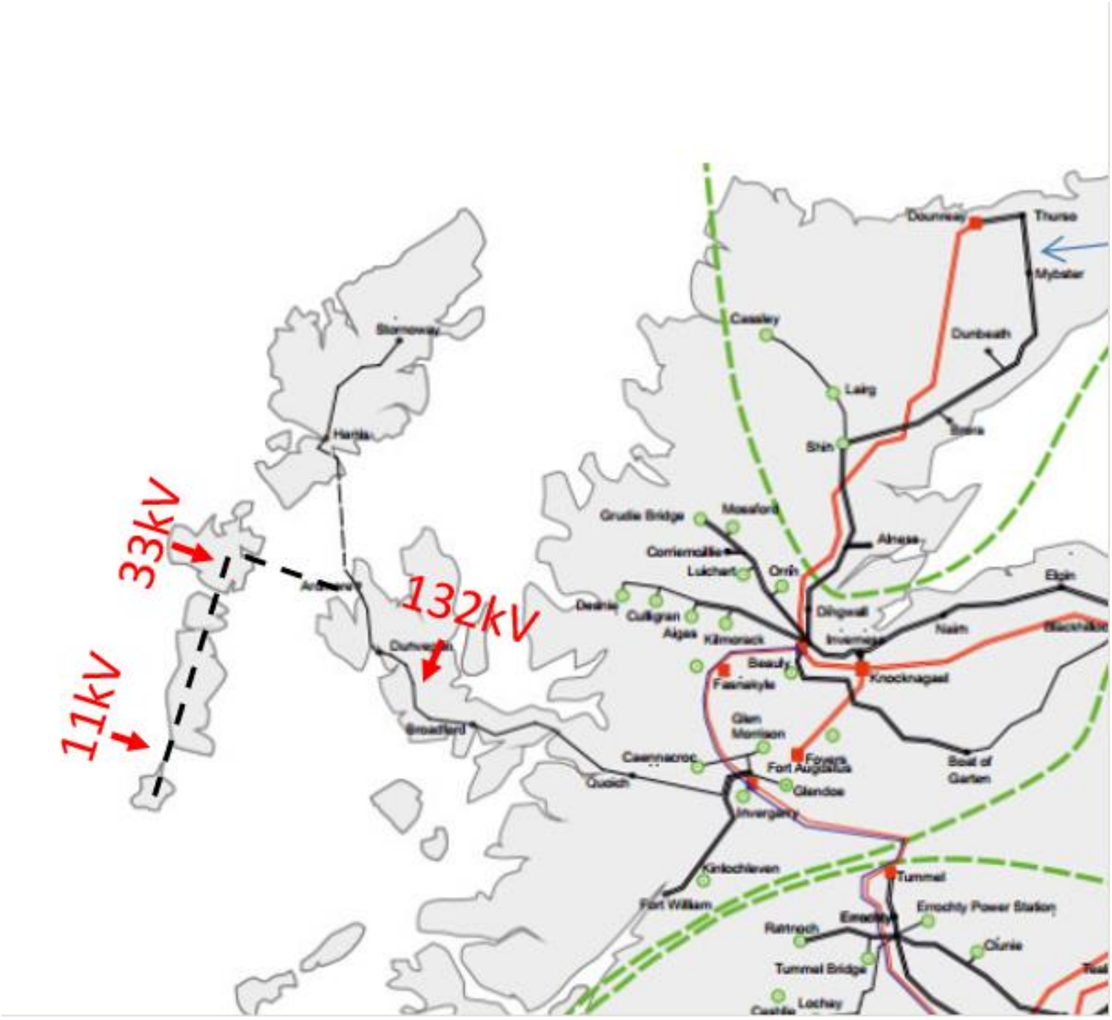

Figure 10 Transmission Grid Infrastructure in Scotland (Kelly, 2018, modified)

Future renewable energy projects on the Western Isles are currently limited to small-scale projects in a several kW range or must be installed off-grid. Alternative solutions need to be found in order to install further larger scaled renewable energy generation.

This issue of renewable energy generation challenging electrical grids is not only limited to islands or rural areas but can be observed elsewhere. Distribution grids with high integration of renewables can be affected by voltage rises in peak generation times. This was the case with photovoltaic generation in Germany and led to load management mechanism for photovoltaic inverters (Stetz et al., 2013). Further renewable energy implementation will rely on curtailed peak generation capacities, reinforced grid infrastructure as well as dispatchable loads coupled with local decentralised renewable energy generation. District heat networks with thermal storage have potential for the latter.

A possible solution for the Western Isles is the implementation of own grid infrastructure, connection generation with local consumers in a so-called private wire scheme. Private-wire schemes are challenging but not technically or economically unfeasible.

Another solution are virtual connections between generation and consumers relying on smart metering technology. This way existing grid infrastructure can be used. Overloading is prevented by matching flexible generation with flexible demands. Several projects in Scotland investigated the potential by looking into specific case studies. For example, projects are or were based on Mull (Community Energy Scotland, 2015), Orkney (EMEC, 2019) and in Fintry (Fintry Development Trust, 2018).

All two options require electrical loads were generation can be delivered to. Electrification of transport and heat seem promising future loads with limited flexibility for coupling demand with renewable generation. Large scale heat pumps with thermal storage such as in district heating systems bear potential for shifting large scale renewable electrical power to heat. Simulation results for Finnish district heating systems show that Power to Heat can decrease renewable energy surplus to the grid up to 80% using the right control algorithms (Salpakari et al., 2016).

2.3. District Heating Schemes

2.3.1. Definition and History

District heating systems transport thermal energy, either for heating or cooling, from centralised generation to distributed consumers in proximity, relying on a high density of heat demand per area. They originate from the basic principle of using geothermal heat or waste-heat from power generation including waste incineration or industrial processes for space heating and domestic hot water supply (Werner, 2017).

District heating systems range from kW to MW schemes in rural areas utilising for example biomass in Austria (Pfemeter, 2016), up to GW schemes in cities utilising for example rejected heat from power plants in Russia (World Nuclear News, 2016). Figure 11 displays the main components of a district heating scheme in a simplified schematic: an energy centre where heat is generated, supply and return pipes (shown as picture in Figure 11) which distribute heat to different loads such as residential and commercial buildings (Wiltshire et al., 2014).

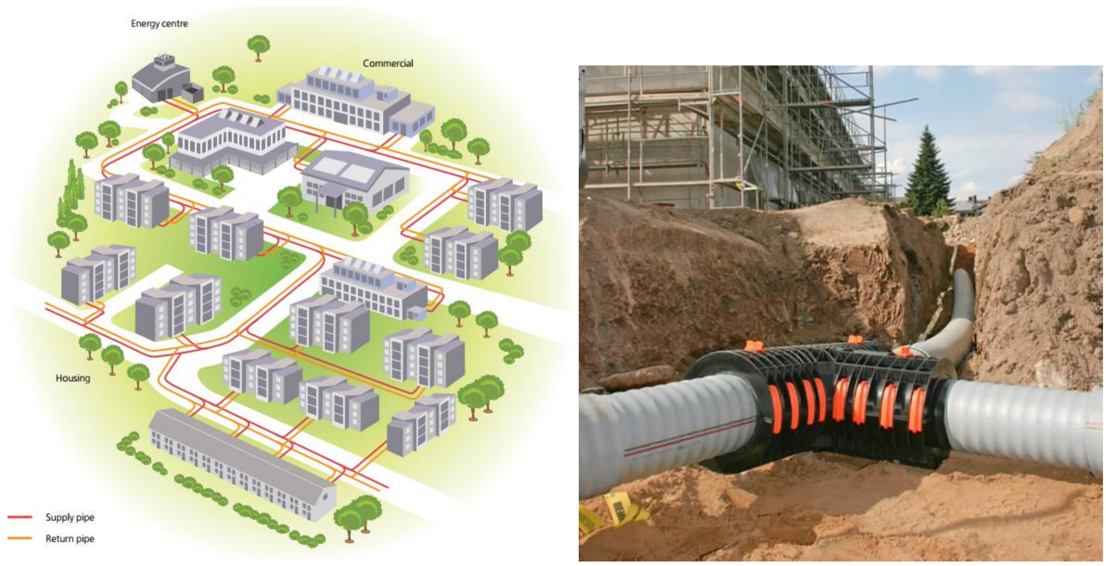

Figure 11 Left: Simplified Schematic of a District Heating Scheme (Wiltshire et al., 2014) Right: Polyethylene (PE-X) Pipe with Fitting in a Trench (Trecco Ltd, 2019)

District heating networks are taking advantage of economy of scale. They aim at generating and transmitting energy in a more efficient and convenient way than decentralised heating systems, such as oil or wood boilers. Despite their existence since the late 19th century, they still are considered a niche technology (Frederiksen and Werner, 2013, p. 13).

Figure 12 shows the historic evolution of district heating systems for the system constellation, temperature and efficiency levels. A trend can be seen towards low temperature grids that profit from a higher efficiency due to lower thermal losses. Lund (2014) identified the biggest challenge for the current 4th generation of district heating systems:

- Prepare grids to accommodate renewable energy generation, in order to eliminate fossil fuel generated heat in the long term
- Integrate buildings of both of low-efficiency (stock) and high-efficiency (new built) standard
- Couple district heating with electricity and gas grids in order to allow higher renewable energy utilisation with power & gas two heat technologies

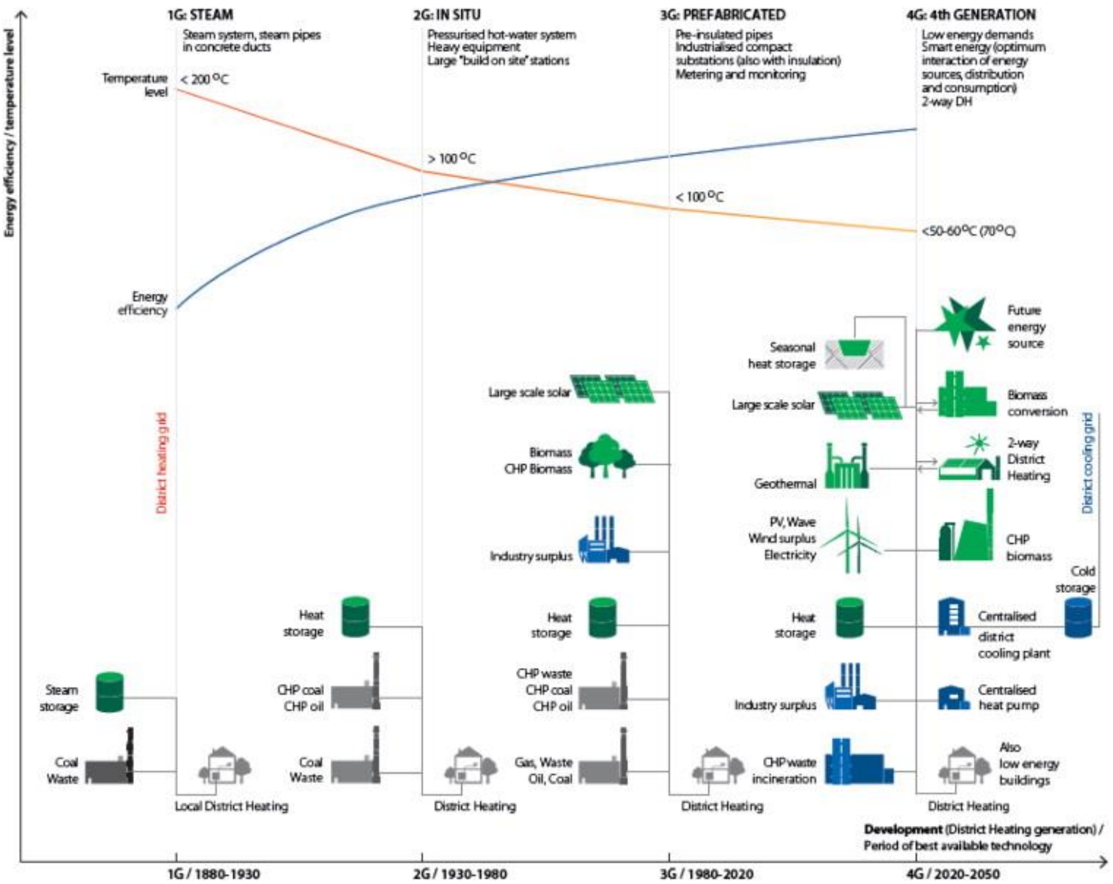

Figure 12 Evolution of District Heating Systems towards 4th Generation Concept (Lund et al., 2014)

2.3.2. Distribution and Market Share

Figure 13 highlights that most district heating schemes are in Europe, Russia and China. District heating accounts for less than 15% of global heat supplies in residential and service sector buildings. In Europe countries which have well-established district heating grids are Iceland, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania and Poland.

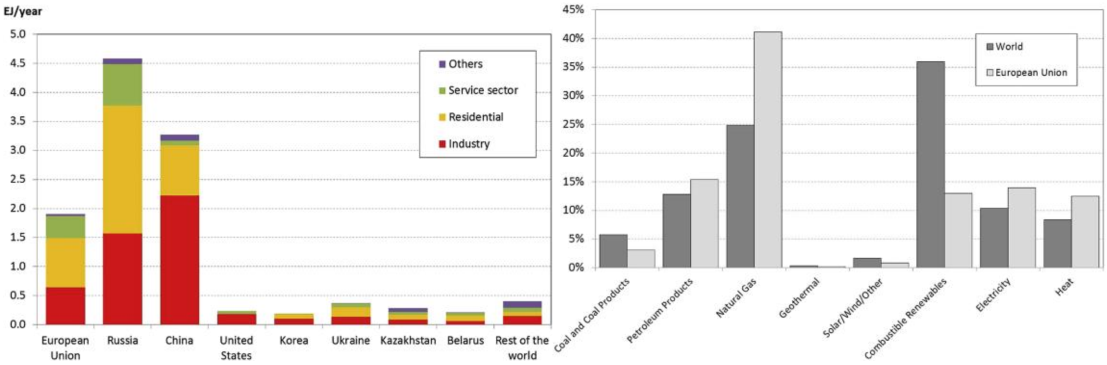

Figure 13 Heat Delivery Split into Client Sector in Various Regions (left) Estimated Global Proportion of all Heat Use for Residential and Service Sector Buildings. Heat Denotes District Heating Share. (Werner, 2017)

In the UK district heating only account for around 2% of total supplied heat to the building stock and is therefore not yet well established (DECC, 2016, p. 17), mainly due to availability of low-cost natural gas and well established infrastructure (Wiltshire, 2015, p. 6). District heating is likely to increase in the next decade, as the UK government identified electrification of heat along with renewable energy generation as an important element in their plans to decarbonise heat by 2050 (DECC, 2016, p. 6).

2.3.3. Benefits, Disadvantages and Constraints

District heating can supply areas of high heat density with efficient heating if an adequate heat source is available. These large systems benefit from economy of size, high flexibility, higher security of supply as well as eliminating local emissions (Frederiksen and Werner, 2013).

From a customer viewpoint district heating offers several benefits (Frederiksen and Werner, 2013):

- Comfortable and reliable heat delivery with no major maintenance requirements
- Less capital investment and space needed for heating equipment (boiler, fuel store, chimney, etc.)
- Lower risk of fuel supply safety (boiler faults, gas or fuel explosion)
- Lower emissions as heat source is most commonly low-emission and high-efficiency

These benefits are accompanied with several disadvantages:

- Heat supplier monopoly allows disproportionate pricing
- Once connected, switching to other sources is expensive and binds customer to heat supplier
- If the district heating system fails, every connected building is affected with limited possibility to switch to backup systems
- Knowledge about heating system is replaced from property tenants to the district heating system operator

District heating is constrained to areas of high heat density, as otherwise pipe and pumping cost exceeds levels of reasonable initial investment and operation cost. This means remote areas of low heat density cannot be supplied and must rely on other individual heating systems.

2.3.4. District Heating with Heat Pumps

Heat Pump District Heating System Design

Heat pumps can either be integrated into existing district heating schemes or as new schemes with heat pumps as main heat generation. If heat pumps are used as main heat generation, peak boilers of other heat sources are commonly integrated in order to optimize economics as well as security of supply (except for ambient temperature grids).

Heat pump district heating systems can be classified by the following parameters:

- Purpose
  - Heating and cooling
  - Heating only
  - Cooling only (referred to as refrigeration unit rather than heat pump)
- Heat source (most common according to David et al. (2017))

- Sewage water
- Ambient water (sea, river, lake)
- Industrial waste heat
- Geothermal heat
- Flue gas
- District cooling rejected heat
- Solar heat

- Heat pump location
  - Central heat pump
  - Central heat pump with decentralised “booster” heat pumps
  - Decentralised heat pumps
- Distribution temperature network (according to Ommen et al. (2017))
  - High temperature >80°C
  - Low temperature >50°C
  - Ultra-low temperature >35°C
  - Ambient temperature >5°C

Distribution and Market Share

Heat pumps have been used for several decades by few European countries in district heating grids. Figure 14 shows European countries with the largest capacities of district heating up to 2016 according to David et al. (2017). Sweden stands out with an installed heat pump capacity of 1.2GW beginning in 1981 in order to manage nuclear power surplus generation (Averfalk et al., 2017). They utilise sewage, ambient water and industrial heat sources.

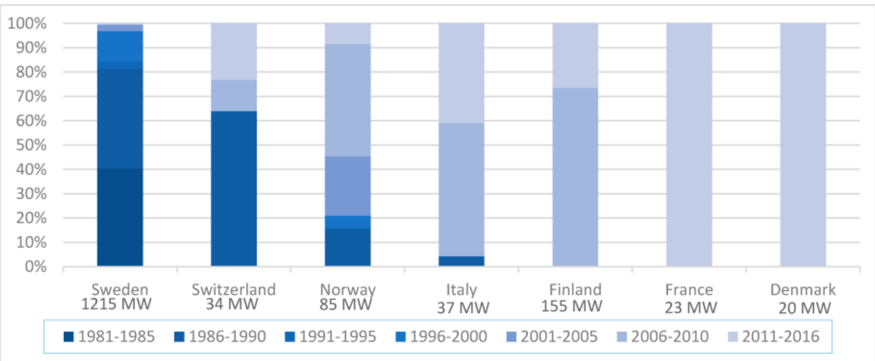

Figure 14 Largest Heat Pump District Heating Capacities in European Countries Split into Installation Year (David et al., 2017)

Heat pumps are not yet widely adopted in district heating grids in Europe. Other heat sources often are significantly cheaper in terms of capital expenditure (CAPEX) and operating expenses (OPEX). The main competitor is gas-fired combined heat and power (CHP) power plants.

Efficiency

The performance of district heating schemes is determined by conversion efficiency of heat generation, distribution losses and auxiliary energy needs, mainly for pumping.

The conversion efficiency of heat pumps is measured as coefficient of performance (COP) for a current state of electricity to heating power ratio, or seasonal performance factor for electric energy to heating energy ratios over a year. Auxiliary energy consumption of pumps, fans or control are not considered in this notation. They are defined as follows in equation 1 and 2 (Zottl et al., 2012):

$$COP = \frac{\dot{Q}_{heat}}{P_{electric}} = \frac{\dot{Q}_{environment} + P_{electric}}{P_{electric}} \quad (1)$$

$\dot{Q}_{heat}$ … provided heating power in Watt

$\dot{Q}_{environment}$ … provided environmental heat power in Watt

$P_{electric}$ … provided electrical power in Watt

$$SPF = \frac{Q_{heat}}{W_{electric}} = \frac{Q_{environment} + W_{electric}}{W_{electric}} \quad (2)$$

Q_{heat} … provided heating energy in Joule

$Q_{environment}$ … provided environmental heat energy in Joule

$W_{electric}$ … provided electrical energy in Joule

Figure 15 shows performance and temperature level of various heat pumps in European district schemes. Source temperature vary from near zero to over 50°C. Sink temperature from 40 to 90°C. Average annual COP’s (basically SPF) for high temperature gaps are between 3 and 4. For low temperature gaps performance goes up to 6.5

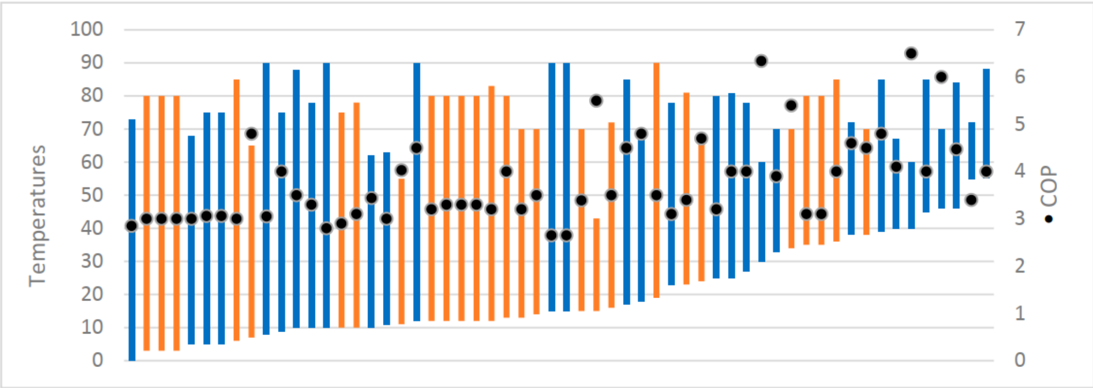

Figure 15 Heat Pump District Heating Temperature Levels and Performance in European Countries (David et al., 2017)

This can be related to the basic efficiency principle of Carnot, as shown in equation 3:

$$COP_{Carnot} = \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{3}$$

COP_{Carnot}	… Carnot coefficient of performance
T_{hot}	… Sink temperature in Kelvin
T_{cold}	… Source temperature in Kelvin

As a simple rule, the higher the temperature gap between sink and source, or condenser and evaporator temperature in the case of heat pump, the lower the efficiency. Figure 16 shows the relation between COP and the condensation or sink temperature for realistic efficiencies of different heat pump systems. These efficiencies are divided into different categories, whereas ε_{carnot} is the COP reached in reality COP_{real} divided by COP_{Carnot} .

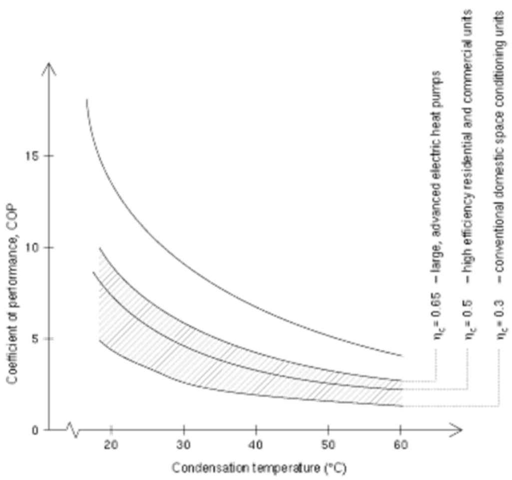

Figure 16 Coefficient of Performance Related to Condensation Temperatures for Typicial Heat Pump Types (Zottl et al., 2012)

Future Development

As emission reduction strategies are widely adopted from European frameworks and transferred towards national plans, governments are seeking find appropriate future heating solutions.

Heat pumps provide low-emission heat, as described in chapter 2.1.6. Furthermore, they are also a viable method of shifting electricity into heating grids (Wiltshire, 2015). This power to heat approach is currently evaluated by research (Marczinkowski and Østergaard, 2019; Østergaard et al., 2019) and several projects were realised. Case studies with different heat sources and plant sizes are introduced in chapter 2.4.

A study published by the UK government (DECC, 2016, p. 11) indicates that significant CO2 emission savings achieved by heat pumps in district heating grids face significantly higher cost (-84% CO2 but +74% LCOH for LT with central +decentralised HP's). This was explained as follows:

- Higher capital cost for heat pumps
- Higher operating cost due to higher electricity price than gas price
- Building integrated HP's result in higher total installed capacity
- Higher network cost for low temperature grids due to higher mass flow

2.4. Heat Pump District Heating Schemes

This section gives an overview of recent and established heat pump district heating schemes. It is separated into different heat sources. Further case studies are provided by: DECC (2016), Schmidt (2018) and Lit et al. (2017).

2.4.1. Waste Heat Source Schemes

Wien Energie Heat Pump Integration, Vienna. 2019. (Horak, 2019).

Rejected heat from a CHP Power plant and an adjacent river is utilised and integrated in existing high temperature district heating grid. A large-scale heat pump uses waste heat with a temperature level of 6 up to 27°C and feeds into the city-wide district heating network at 95°C.

A schematic of the overall district hating integration into is shown in Figure 17.

Capacity: 40MW
Source temperature: up to 27°C for rejected heat / down to 6°C for river
Sink temperature: up to 95°C
Seasonal Performance Factor: 3 (estimated)
HP Manufacturer: Friotherm

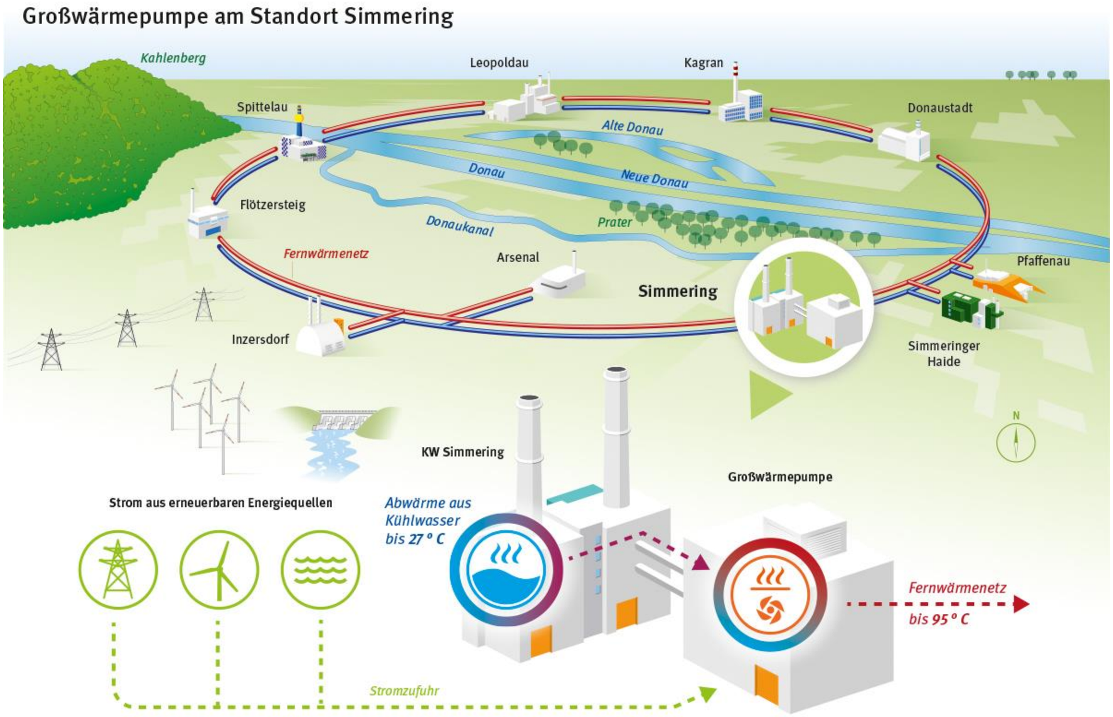

Figure 17 Wien Energy Schematic of Large Scale Heat Pump Integration (Horak, 2019, modified)

2.4.2. Seawater Source Schemes

Large Scale Heat Pumps in Sweden, 1982. (Averfalk et al., 2017).

Sweden started in 1982 to use heat pumps instead of only electric boilers to transfer excess electrical power from nuclear power stations towards their well-established district heating grid. The principle is the same as for the Vienna heat pump system. Currently (last data from 2013), most of the capacity is still used. Heat pumps with capacities of up to 50MW result in a total capacity of 1.2GW. The annually generated heat by source is shown in Figure 18.

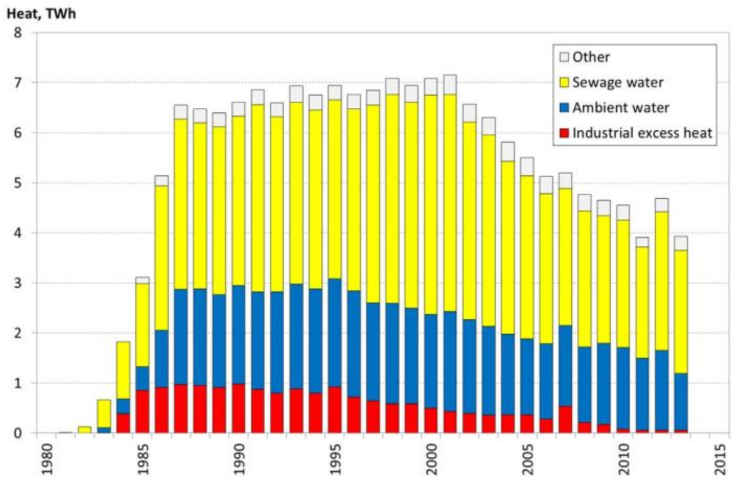

Figure 18 Annual Heat Generated by Large Scale Heat Pumps in Sweden by Heat Source (Averfalk et al., 2017)

District Heating Drammen, Norway. 2013. (Pearson and Stajic, 2015; Warners Group Publications, 2014).

A sea-water source heat pump together with biomass boilers and a gas and oil peak boiler heats a district of 225 buildings in Drammen. The water is taken out of a fjord with relatively stable temperatures. An overview of the scheme is shown in Figure 19.

Capacity: 13.2MW
Source temperature: 8-9°C (varies annually)
Sink temperature: up to 90°C
Seasonal Performance Factor: 2.85 (estimated), 3.15 (first heating period)
HP Manufacturer: Star Renewable Energy

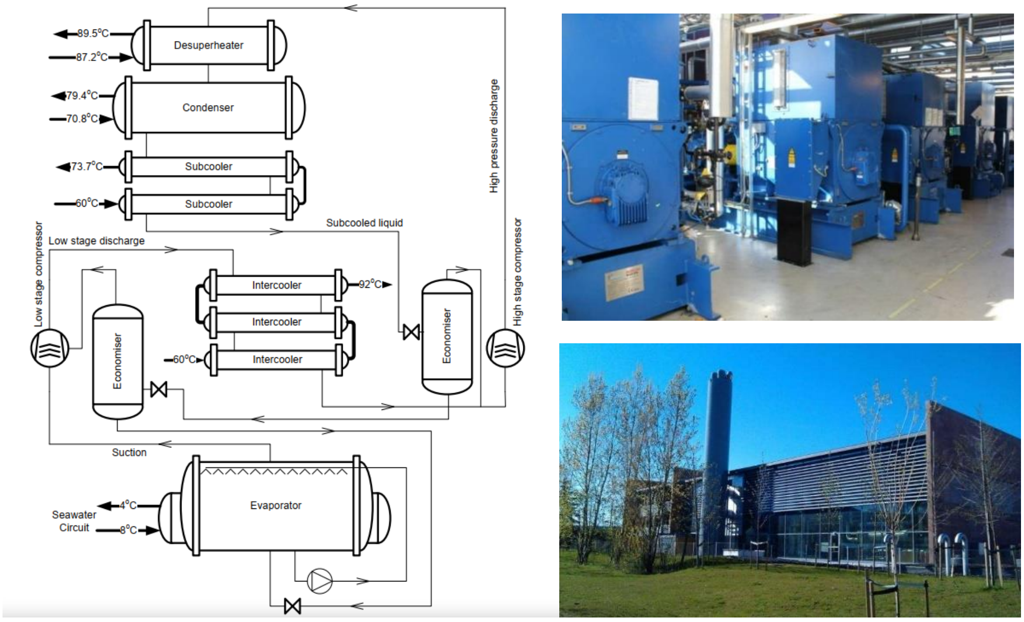

Figure 19 Drammen Heat Pump System. Left: Ammonia-Cycle Schematic. Top Right: System Installation. Bottom Right: Energy Centre

Clydebank Queens Quay Development District Heating. 2019. (Ryden and Dawn Developments, 2019; Star Renewable Energy, 2019).

A new site development of residential, educational and healthcare buildings with an investment of about £250m in Clydebank includes a district heating system with large scale water-source heat pumps. An overview scheme is shown in Figure 20. The renewable heat incentive (RHI) subsidy for heat pumps is applied on this scheme.

Capacity: 2x2.6MW
Source temperature: 6-10°C (varies annually)
Sink temperature: up to 75°C
Seasonal Performance Factor: 3 (estimated)
HP Manufacturer: Star Renewable Energy

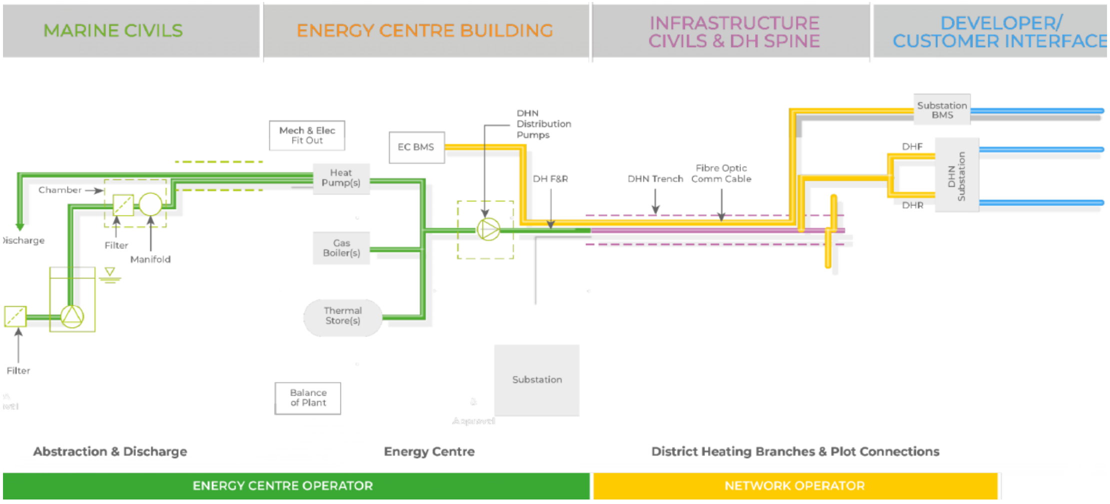

Figure 20 Queens Quay District Heating Schematic (Gosling, 2019)

Duindorp Low Temperature Grid with Central and Decentral Heat Pumps. 2009. (CLUE - Climate Neutral Urban Districts in Europe, 2009; DECC, 2016)

This district heating system in the Netherlands uses seawater and if its temperatures are low, a central heat pump, in order to distribute heat at low temperatures between 11-18°C to connected apartments. This kind of heat distribution is referred to as ambient temperature or sometimes “anergy” grid. Decentralised heat pumps in every property are used to provide either 65°C for hot water or 55°C for space heating.

Capacity: 2.4MW (central HP), 6kW (decentral HP)
Source temperature: 3-20°C (varies annually)
Sink temperature: up to 75°C
Seasonal Performance Factor: 11 (central), 3 (decentral)
HP Manufacturer: York, IVT

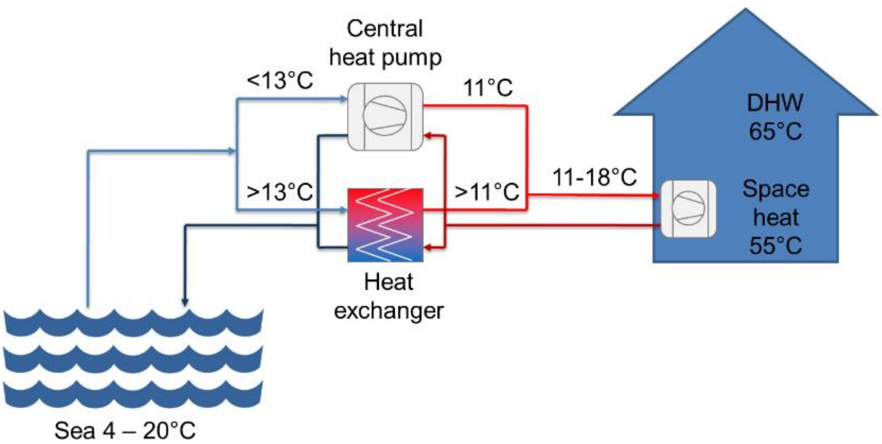

Figure 21 Duindorp Seawater Source Heat Pump Schematic (DECC, 2016)

2.4.3. Ground Source Schemes

ETH Zürich Heating and Cooling "Anergy-Network". 2012. (ETH Zurich, 2019; International Energy Agency, 2015)

The ETH Zürich campus in Hönggerberg uses a so-called soil storage system consisting of several hundred earth probes. Water is pumped in a low-temperature "Anergy-Network". This enables heat pumps and refrigeration systems to do both heating and cooling on the campus. This arrangement has the benefit that the soil is regenerated, being warmed up after the summer period and cooled down after the winter period. Furthermore, when heating and cooling demands occur at the same time, it can be shifted in between buildings, enabling free cooling and heating. This system required a high initial investment but benefits from high efficiencies resulting in low operating cost. A schematic of the scheme is shown in Figure 22.

Capacity: 5.5MW (heating), 4.5MW (cooling
Warm feed/distribution pipe temperature: 8-22°C (varies annually)
Cold return/distribution pipe temperature: 4-18°C (varies annually)
Seasonal Performance Factor: 5.8 (heating), 7.2 (cooling)
HP Manufacturer: not published

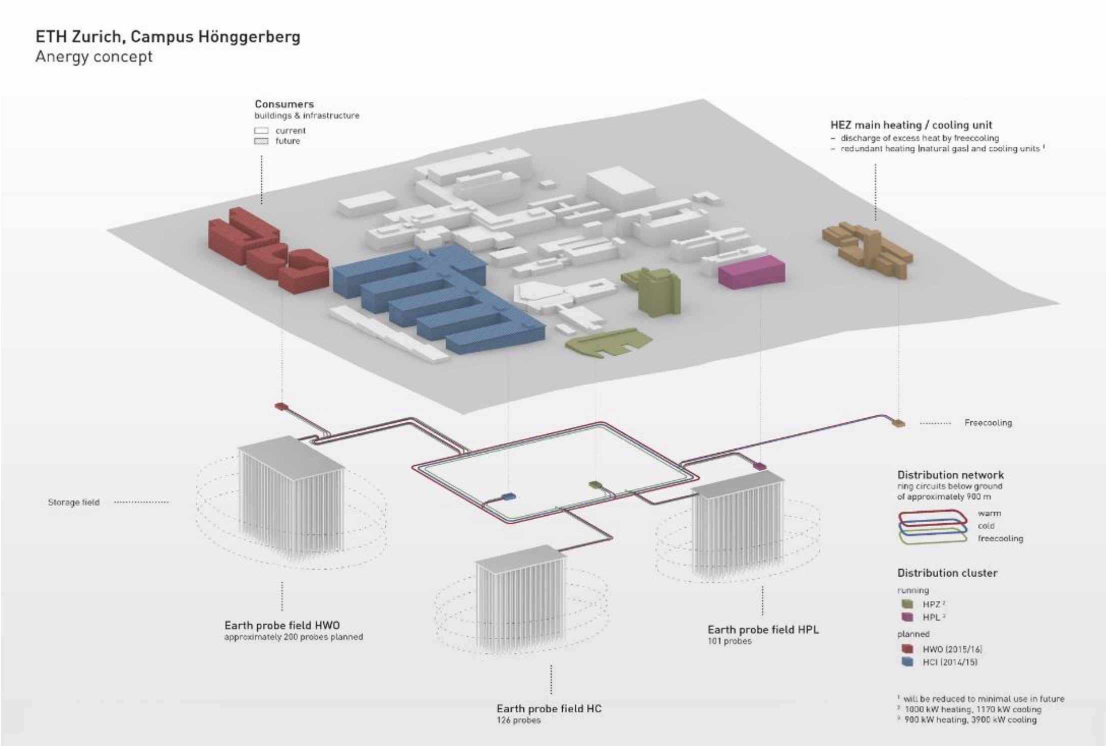

Figure 22 ETH Zurich Anergy-Network Schematic (ETH Zurich, 2019)

Iona Village District Heating Scheme. 2019. (Iona Renewables, 2019).

Community owned medium scale district heating scheme with a proposed ambient temperature grid, distributed boreholes and decentralised heat pumps.

This scheme is currently being developed and info was gathered from the Iona Renewable homepage and a meeting with a member of the charity. The groundwater source heat pump scheme incorporates the village including the Iona Abbey. The annual heat demand is about 2GWh/y (Scottish Government, 2018c). An ambient temperature grid with boreholes as heat source and decentralised heat pumps is proposed, which is novel for a Scottish Isle. No specific data for system size and temperature levels could be acquired at this point.

Summary

Heat pumps are a highly efficient heat conversion technology with lower emissions than fossil fuel based technologies. The presented schemes have mainly been built with synergetic benefits, such as power to heat, in mind. Recent developments show that climate change mitigation benefits can outweigh economic constraints, even if subsidies are required (Queens Quay) but can provide heating and cooling at highest system efficiency (ETH Zürich).

3. Case Study: Isle of Barra

3.1. Introduction

This section introduces the case study area in Castlebay on the Isle of Barra. The local energy system is explained and an overview of issues focussing on heat is provided. Future solutions for heating are evaluated and the viability of district heating is discussed.

3.1.1. Location

The Isle of Barra and Vatersay are two causeway-connected islands with a population of about 1300 people in the southernmost part of the Outer Hebrides or Western Isles, highlighted in the map in Figure 23. Though being two different islands, they are referred to as Barra in this work. Barra is connected via ferry to the mainland in Oban.

Figure 23 Map of Scotland. Isle of Barra Highlighted (Gaba, 2008, modified) License: CC BY-SA4.0

This remoteness is accompanied by limited access to infrastructure. There is no mains gas network. The electricity grid is constraining current and future renewable energy generation due to capacity and availability issues (Local Energy Scotland, 2019, p. 4; West Coast Energy Ltd, 2006). This situation reflects the general situation on the Western Isles as described in chapter 2.2.3.

3.1.2. Climate

The climate on Barra is characterised by its location in the Atlantic Ocean, resulting in a temperate but wet climate (Peel et al., 2007) with high exposition to wind and rain, especially in winter. Figure 24 (left) shows a low annual amplitude of monthly mean temperatures with averages not being below 6°C in winter and not above 14°C in summer. Looking at observed maximum and minimum temperatures in a more detailed climate diagram in Appendix A shows that hourly temperatures exceed 20°C in summertime, and fall below -2°C in wintertime regularly.

Wind data in Figure 24 (right) shows that wind speeds are generally high and seldomly below 19km/h. In winter average wind speeds are higher than in summer with velocities greater than 61km/h occurring regularly.

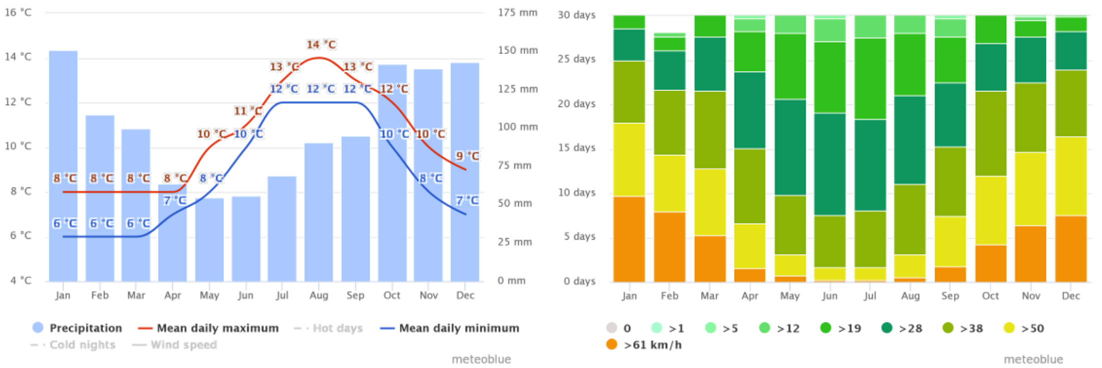

Figure 24 Castlebay Historical Climate Data for Temperature, Precipitation and Wind Speed (Meteoblue AG, 2019)

Regarding heating demand, Heating Degree Days (HDD) were calculated with a base temperature of 15.5°C. HDD are a simplified way of comparing different climates (BizEE Software Limited, 2019). Castlebay had 2165 HDD averaged over the last three years. This is slightly lower than Glasgow (2300) but higher than London (1690).

There is no significant cooling demand on Barra, as cooling degree days are as low as 1.2 (base temperature 22°C) (BizEE Software Limited, 2019). Though cooling demands have significantly risen over the past decades (European Environment Agency, 2019), it is unlikely that significant cooling demand arises for buildings on Barra if solar gains are limited efficiently by architectural design.

In summary, though the absence of harsh winters with temperatures well below zero, there is a long winter period with low temperatures and high humidity which requires significant amounts of heat. High wind speeds not only are a potent source for renewable energy generation, but also increase air infiltration into buildings, resulting in even higher heating demands if buildings are not airtight.

3.1.3. Energy Demand

A total energy demand of 43.3GWH/y was estimated for transport, industry and heating. Electricity, fuel oil, petrol and diesel are imported, except for the electricity generated by a community wind turbine (3.3GWH/y) and several small-scale wind turbines or photovoltaic panels. Tariffs for electricity and fuel oil are above mainland levels due to the higher effort of transport and transmission.

A local energy plan, involving numerous stakeholders on the island (Voluntary Action Barra & Vatersay et al., 2018), addressed various possibilities for renewable energy generation and energy conservation for building, industrial and transport sectors. These measures could increase environmental, financial and social sustainability on the island. Heating demands were identified as a major energy consumption as Figure 25 shows. Electricity demand includes electric heaters which are used in almost half of properties on Barra. 75% of energy demand can be accounted to residential use.

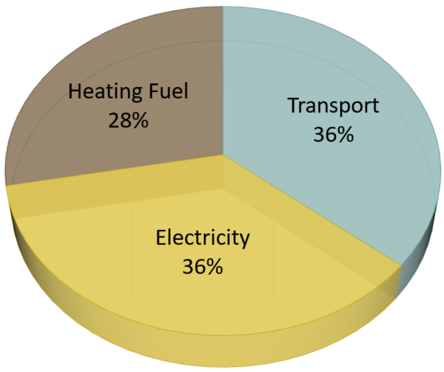

Figure 25 Energy Demand by Sector on Barra. Data Source: Local Energy Plan (Voluntary Action Barra & Vatersay et al., 2018)

3.1.4. Heat Demand

Estimated energy demand for heating fuel is 12GWh or 28% of total energy use. Domestic properties account for the major heating demand of 90% and non-domestic for the remaining (Voluntary Action Barra & Vatersay et al., 2018, p. 26).

However, there is no specific data on how much energy is used for electrical heating. According to a UK household study by Brown (2012), 70.5% of total electricity demand is spent on heating by residential properties using electrical space heating (storage/panel heaters) and hot water boilers. This is the case for 46% of properties on Barra. Using these figures, the total share of energy spent on heating is assumed to be 50% or 21.7GWh. This aligns with data from the Scottish heat map which is 21GWh for Barra (Scottish Government, 2018c).

Figure 26 gives an overview of building standards and heating systems on Barra. Housing is at relatively low efficiency standard, as 56% of all properties have an EPC rating between E to G. A heat source distribution per energy demand shows that they are mainly heated by electricity and fuel oil.

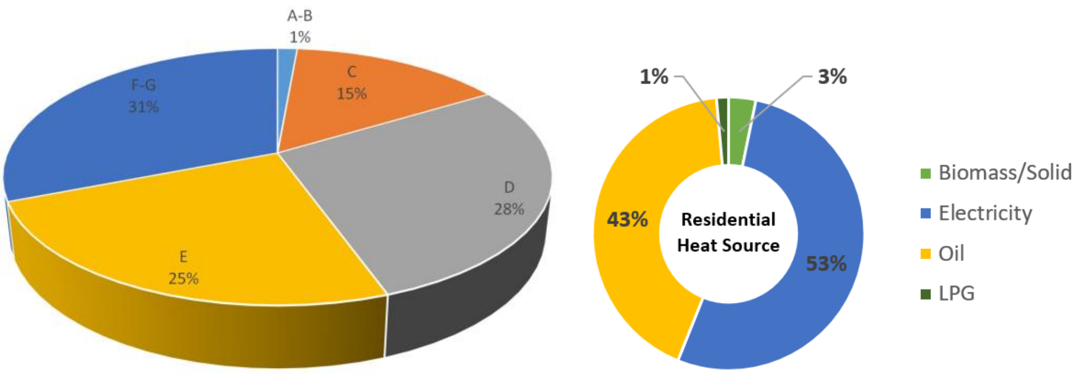

Figure 26 Left: EPC Rating of Properties (Voluntary Action Barra & Vatersay et al., 2018, p. 49). Right: Heat Source of Residential Properties by Energy Demand.

Table 1 relates energy demands to EPC ratings as defined in the standard assessment procedure for acquiring energy demands of buildings (Building Research Establishment, 2012). Average energy demands of over 100kWh/m²/y are very common on Barra and represent a very low building efficiency.

Table 1 Energy Demand in kWh/m²/y According to Energy Rating Band

Energy Rating Band	***A***	***B***	***C***	***D***	***E***	***F***	***G***
Energy Demand in kwh/m²/y	*32*	*33-65*	*66-100*	*101-135*	*136-170*	*171-200*	*>200*

3.1.5. Energy Issues

The Isle of Barra faces several issues relating energy. They were identified in a local energy plan (Voluntary Action Barra & Vatersay et al., 2018), as well as in student projects (Auer et al., 2019; Boie and Klein, 2009). The main issue is the remoteness of the island which causes relatively expensive energy infrastructure and fuel transport, resulting in high prices for heating oil, coal, biomass, liquified petroleum gas (LPG), diesel, petrol and electricity. High energy demand for electricity, transport and foremost heating raises living costs for residents. The average fuel poverty rate was estimated to 56%, as defined by the UK Government (2019), according to Voluntary Action Barra & Vatersay et al. (2018). Furthermore, energy sources are mainly fossil fuel based contributing towards local emissions and global climate change.

Heating is the highest energy demand on Barra, resulting in high cost for people, bearing substantial potential for a shift towards more efficient heating systems which are cheaper to operate and emit less GHG.

3.1.6. Current and Future Heating Systems

The current heating systems in residential properties on Barra are summarised in Table 2. Key figures for investment and operational cost, heat transfer and thermal comfort are stated, and systems are sorted according to their distribution on Barra. Prices for fuel cost are only indicative as for a realistic comparison, lifecycle costs must be calculated for every system in order to find the most cost-efficient solution.

Table 2 Current Heating System Distribution on Barr., Thermal Comfort Estimation and Estimated Cost for Initial Installation (Capital Expenditure CAPEX), Fuel (excluding lifecycle cost like maintenance) and CO2 intensity. Data from: [1] (Voluntary Action Barra & Vatersay et al., 2018), [2] Own price and tariff study 5/2019 and inflation adjusted SAP data (Building Research Establishment, 2012)

Heating Type	System	CAPEX +Installation £/KW	Fuel Cost p/kWh	CO2 Intensity g/kWh	Thermal Comfort	Share
Electric	**Panel heater**	Very low 200[2]	Very high 15.5[2]	205	Intermediate (Radiator)	<53%[1]
	Storage heater	Intermediate 400[2]	High 10.7h[2]	205	Low (Convector)	<53%[1]
	Heat pump (SPF 3)	High ASHP1000[2] GSHP1500[2]	Intermediate 5.2[2]	68	High (UFH) Intermediate (LT-Rad.)	<<53%[1]
Boiler	**Fuel oil**	Low 250[2]	Intermediate 6.3[2]	30	Intermediate (Radiator)	43%[1]
	Coal (Anthracite)	Low 300[2]	Intermediate 5[2]	420	Intermediate (Radiator)	<3%[1]
	Biomass (Pellets)	Intermediate 500[2]	Intermediate 7[3]	50	Intermediate (Radiator)	<3%[1]
	LPG (bottled)	Low 200[2]	High 12[3]	260	Intermediate (Radiator)	1%[1]

The predominant electric panel and storage heaters share similar characteristics of a low capital, high operational cost systems with low thermal comfort. The second widely used heating system are fuel oil boilers. They are higher in investment cost, but lower in operation cost due to lower fuel prices.

Both predominant systems have issues, making them not the best choice for heating. Electric heaters are expensive to operate and often lead to fuel poverty or colder homes as they are used sparsely to save energy cost. Fuel oil boilers are cheaper to operate but rely on burning fossil fuels resulting in high emissions. They require a certain amount of maintenance for the boiler, chimney and resupply of the oil tank. Both systems rely directly on volatile energy prices. A shift to a less expensive system that provides warmer homes with higher thermal comfort would be desirable.

Possible alternatives for heating are discussed in Table 3. This applies for both individual heating for single properties and district heating schemes.

Table 3 Future Heating System Possibilities on Barra with Estimated Efficiency, CO2 Intensity, Cost and Suitability

System	**CAPEX +Installation £/KW**	**Fuel Cost p/kWh**	**Efficiency/ Resource**	**CO2 Intensity g/kWh**	**Suitability**
Air Source Heat Pump	High ASHP1000	Intermediate 5.2	SPF 3.0	68	+) Cost, installation -) Noise, Corrosion
Ground Source Heat Pump	Very High GSHP1500	Low 4.4	SPF 3.5	59	+) Efficiency -) Cost, installation
Water Source Heat Pump	Very High WSHP1500	Low 4.4	SPF 3.5	59	+) Efficiency -) Cost, installation, limited resource access
Biomass (Pellets)	Intermediate 500	Intermediate 7	>90%	50	+) Cost -) Imported resource, emissions
Solar Thermal	Very High 1500	Pump energy only	1000kWh/m²	almost zero	+) Durability, good for DHW -) Low resource, only for heating support

Heat pumps as well as biomass and solar thermal are available future low-carbon heating technologies. Comparing cost to current heating systems, all systems have higher investment cost. Heat pumps are most expensive in investment but have low operational cost. Solar thermal collectors cannot be a solely heating source due to low solar irradiance during the heating period. Biomass is not available on Barra and must be imported, making security of supply an issue.

Heat pumps seem to be the most viable system for several reasons. Despite high initial cost, they have several benefits including low maintenance, high user comfort, flexibility of sizing and installation and low operational cost. Air source heat pumps are easiest to install with lower installation cost. Ground source and water/seawater source heat pumps have higher seasonal performance factors but are significantly more expensive in installation due to required trenchwork for ground loops or drilling boreholes (GSHP) and pipes, inlets/outlets and pumps (WSHP), respectively.

3.1.7. District Heating Viability

The Scottish Heat Map (Scottish Government, 2018c), Figure 27, shows that main heat demand is spread around the approximately 15 mile long ring road. The highest heat density was identified in Castlebay.

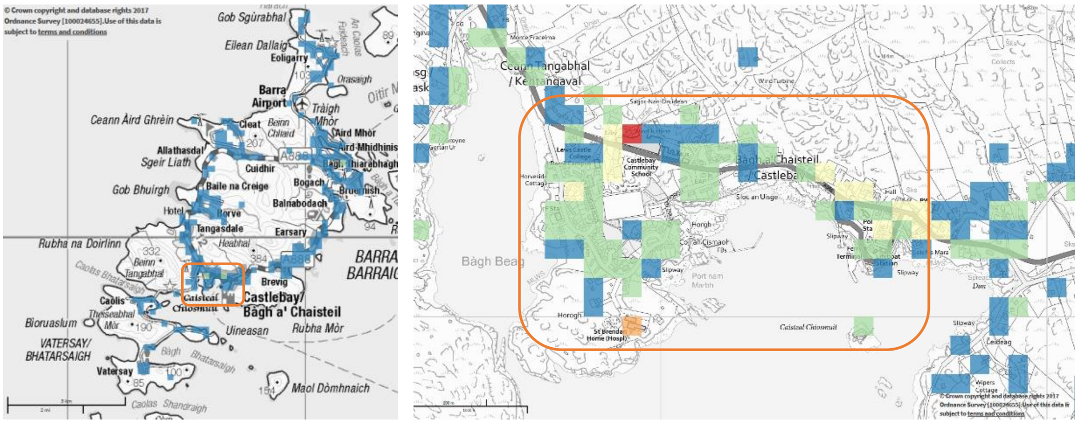

Figure 27 Left: Heat Map Isle of Barra and Vatersay. Right: Heat Map Castlebay; Highlighted Area Represents 6GWh/y Heat Demand . (Scottish Government, 2018c)

Possible district heating schemes are limited to area of high heat demand. A medium-scale (>500kW) opportunity for a district heating scheme is Castlebay. The current hospital and care home building as well as the community school, swimming pool and library building have a very high heating demand. The area highlighted in the map in Figure 27 (right) represents a total heat demand of 6GWh/y, resulting in a moderate heating demand density of 8,2GWh/km²/y. This represents 29% of heating demand on the island. Calculating a heat demand density according to Wiltshire (Wiltshire et al., 2014, p. 18) results in 1.26MW/km². This is still considerably lower than the recommended 3MW/km² for viable schemes. However, recent case studies show that small-scale district heating grids still can be viable and have significant benefits. A more in-depth study needs to be done in order to evaluate district heating on Barra.

There were several high-level feasibility studies in two student project (Auer et al., 2019; Boie and Klein, 2009) as well as a Strathclyde university internal study that indicated that traditional district heating systems are viable for Castlebay. Recommendations were made to integrate public and commercial buildings together with possible residential properties in order to achieve an economically viable scheme with a high heat density. This thesis builds upon findings of previous work: energy demand data was used for heat demand estimation and wind turbine size proposals where included for demand-supply matching.

District heating can contribute by decarbonising a significant part of the heating demand on Barra but cannot address all properties on Barra. Remote properties need to be considered as well and solutions like individual air source heat pumps could be subsidised.

3.1.8. Renewable Energy Generation

The island has abundant wind energy resources (DTU, 2018). A community owned wind turbine with a capacity of 900kW was installed in 2013 and proved very successful in operation, although facing high investment cost. The turbine generates at a very high average capacity factor of 42% (according to the operators) over the last three years, which is comparable to offshore wind turbine performance. This figure would be even higher (about 10%) if the current turbine would not be forced to shut down up to 50 days per year by the grid operator. Grid maintenance or failure forces the grid operator (Scottish and Southern Electricity Networks, SSEN) to switch to a backup diesel generator on Barra and no other generation is permitted.

Further renewable energy integration was evaluated by preceding work, but electrical loads need to be directly connected to further medium scaled wind turbines (Auer et al., 2019). District heating could offer this electrical load with certain storage capacities with a thermal store providing power to heat abilities.

3.2. Investigated Area: Castlebay

3.2.1. Overview

Castlebay is the most densely inhabited area in the South of Barra. It has the highest heat density on the Island, making it viable for district heating, as shown in chapter 3.1.7. Its location is shown in a map and pictures in Figure 28. This area consists of over a hundred households, a community school, a hospital and care home and various shops, offices and tourist accommodations.

Figure 28 Castlebay Views and Map. Top Left: Pier and Castle View (Purple in Map). Top Right: Horve Area (Green in Map). Bottom: Map with Highlighted Horve and Pier Area. Map Data: (Scottish Government, 2018c)

3.2.2. Boundary

The scope of the investigated housing was defined by the viable area of a district heating system. The central factor, deciding if district heating is economically viable, is heat demand per network length. The boundary was set to an extended Horve area. It includes 119 households, and several public and commercial buildings. A district heating grid layout is provided in Figure 29 and Appendix E. This layout represents the current building stock.

Figure 29 Proposed District Heating Grid with Labels Showing Current Energy Demand and Peak Loads.

3.2.3. Building Stock

An overview of the buildings in the Horve area, connectable to the DH scheme, is shown in Table 4. It consists of mainly residential housing with a high energy demand which. The total heat demand is 2.1GWh/y, considering future development. Two public buildings, the community school, library and swimming pool complex and the hospital and care home building are subject of redevelopment. The current buildings are EPC rated F and G and are intended to be rebuilt in a combined “Community Hub”, as discussed in chapter 3.2.4.There are few commercial buildings in the area and not all are connectable as they have own heat pump systems recently installed.

Table 4 Overview of Building Stock and Future Development Heat Demand in the Horve Area Connectable to a District Heating Scheme

Category	Count	Property	Boiler/HIU size in kW	Floor Area in m²	Specific Heat Load in W/m²	Specific Energy Demand in kWh/m²/y	Estimated Energy Demand in MWh/y	EPC Rating
Public	0	St Brendans Hospital and Carehome	240	2400	100	195.6	469.4	F
	0	Community School and Swimming Pool	948	2700	351	373.0	1007.0	G
	0	old hospital and school values	1188	5100	233	289.5	1476.5	G
	1	New hospital housing	240	2400	100	100	240	C
	1	New Community Hub	400	7063	57	70.4	497.1	B+
	1	Heritage Centre	35	108		150	16.2	E
						Total Public	**819.9**	
Residential	38	HAC: 2storey_sd_horve	35	87		551.7	16.3	
	16	HAA: 1storey_sd_noloft_Horve	35	50		187.4	9.4	F
	35	HAB: 1.5storey_sd_loftroom_Horve	35	78		187.4	14.6	F
	30	Individual detached houses	35	103		150.0	15.5	E
						Connected Properties	0.7	
						Total Residential	**1222.4**	
Commercial	1	Dunard Hostel	70	162		185.19	30.0	F
	1	Children centre/Café	40	350		102.26	35.8	D
	1	Barra and Vatersay Community Office	35	44.8		150	6.7	E
						Total Commercial	**72.5**	
						Total	**2114.9**	

3.2.4. Future Development

The existing community school complex and the hospital and care home are currently subject of redevelopment. Several options are being evaluated, and currently not decision has been made by stakeholders. One likely scenario was investigated: a new combined community hub housing healthcare, education and community.

A total floor area of 7000m² with an ECP rating of B+ and 400kW heat load was estimated by developers and planners. This results in an annual heat demand of about 500MWh/y which is only a third of the previous separate hospital and school complex.

For the old hospital complex a repurposing into housing is likely and was assumed. The annual heat demand is 240MWh/y for EPC category C retrofitted housing of 2400m² floor area.

This development poses an opportunity for the parallel development of a district heating scheme, as a relatively high heat demand could be connected without any expensive retrofit measures. Both community hub and district heating operators could benefit from this scenario.

3.2.5. Heat Demand

The 2.1 GWh/y heat demand of the buildings in the Horve area is modelled in hourly timesteps as shown in Figure 30. More detailed graphs, showing demand by sector and a summer week, are depicted in Appendix B.

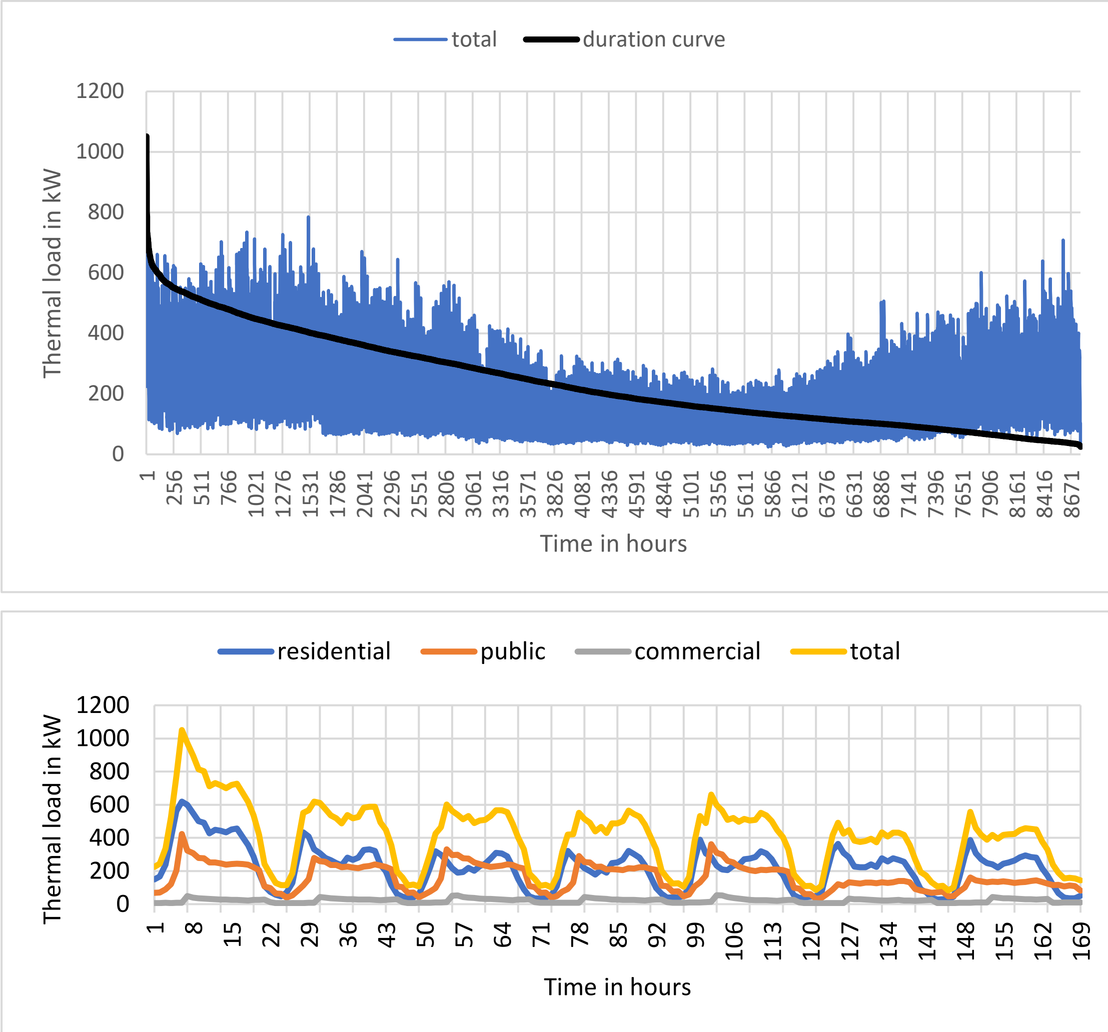

Figure 30 Simulated Heat Demand of Investigated Buildings in the Horve Area, Castlebay. Top: Thermal Load Profile and Duration Curve for one Year. Bottom: Thermal Load Profile for First Week of January

The profile was generated using annual heat demand data, available from energy audits and EPC data. This data was transferred to hourly timesteps using individual demand profiles for offices, schools, etc., available in the Software Homer Pro. Climate adjustment was done using updated Köppen-Geiger climate classifications (Peel et al., 2007).

The heat demand shows a typical pattern, varying over seasons as well as over daily and weekly user behaviours. The shown duration curve highlights that peak loads of about 1MW are only necessary for short periods of time, whereas for the rest of the year loads over 600kW are not exceeded. This peak characteristic results in oversizing of heating capacities for both individual property as well as district heating. The latter has the benefit of diversified loads resulting in lower capacities needed.

3.3. Future Heating Evaluation

This section explores future heating for the Horve area. Individual heating systems are compared to a district heating scheme in order to find the most viable solution. The chosen individual heating system for single properties is air source heat pumps. Biomass and solar thermal were dismissed, as discussed in chapter 3.1.6. For district heating, a low temperature district heating system with a seawater source heat pump was chosen. Furthermore, an ambient temperature district heating system is discussed but not dimensioned.

This evaluation focuses on economic viability by looking at system cost per generated heat using a levelized cost of heat (LCOH) approach. Efficiency is discussed by estimating seasonal performance factors (SPF). Environmental impacts are discussed and CO2 emissions in tCO2-eq are calculated.

An initial overview is given in Table 5, discussing the different systems and considering renewable energy integration aptness as well as reliability and suitability aspects. All systems have various benefits and constraints, and none is clearly in favour.

Table 5 Individual Heating vs. Low Temperature and Ambient Temperature District Heating System Comparison

System	**Energy Efficiency**	**Cost**	**Reliability**	**Renewable Energy Integration Aptness**	**Suitability**
Individual Heating with ASHP	SPF ASHP lower than GSHP or WSHP DHW boiler losses No grid losses No grid pump energy	Investment cost intermediate Operation cost low	Intermediate Electric immersion heating backup included in most ASHP Cannot easily be repaired by local companies Electricity supply considered reliable	Intermediate Smart Meter and control over ASHP required to transfer RE generation to thermal storage	Easily installed Fits most properties Several issues with ASHP: Noise Space Corrosion
District Heating Low Temperature Grid	High SPF for GSHP or WSHP Intermediate grid losses Grid pump energy	Investment cost high Operation cost intermediate	Intermediate Backup fossil fuel boiler installed HIU failures can be, central HP or grid issues cannot be repaired by local companies Electricity supply considered reliable	High Central large-scale thermal storage can easily be used to store RE generation	Environmental Impact of Seawater-Source Inlet GS boreholes low impact ASHP issues Visual impact of energy centre and thermal store
District Heating Ambient Temperature Grid	High SPF for WSHP with GS or WS grid No grid losses Grid pump energy	Investment cost high Operation cost low	Intermediate Electric immersion heating backup included in most WSHP Cannot easily be repaired by local companies Electricity supply considered reliable	Intermediate Smart Meter and control over WSHP required to transfer RE generation to thermal storage	Environmental Impact of Seawater-Source Pipe GS boreholes low impact No visual impact of large energy centre or thermal store

3.3.1. Boundary Conditions

Boundary conditions of both district heating scheme and individual and other assumptions are stated in this section.

Heating System Conversion for all Properties

The hook-up of existing buildings with low efficiency influences the design of the heating system, as certain temperature levels are required to provide enough heat.

The current radiators are either designed for high temperature systems >60°C (oil boilers) or non-existent (electric heaters). Operating these radiators with a lower temperature of 50/40/20°C (feed/return/room temperature) instead of 75/65/20 would only provide 41% of their original heat capacity (Schramek and Recknagel, 2013). Therefore, new low temperature radiators with a bigger surface and therefore a lower design feed temperature of 50/40/20°C are assumed to be retrofitted. This applies for all properties except the community hub and new developed housing, which is assumed to have underfloor heating.

District Heating Heat Sources

The district heating consists of a seawater source heat pump, an electric heater, a back-up boiler and a thermal store. It was sized using a simulation model with hourly timesteps, introduced in chapter 3.4.6..

Performance

The Seasonal Performance Factor of heat pumps was assumed as follows:

ASHP for space heating and DHW supply are estimated with a SPF of 3.0. SPF was averaged between ideal manufacturer estimations (3.3) and residential heating field trials (2.7) (Energy Saving Trust, 2016, p. 100).

WSHP with seawater source has an SPF of 3.6 based on initial estimations of temperature levels.

Funding

Two funding schemes are available. The Renewable Heat Incentive and an investment funding for district heating.

RHI is applied as shown in Appendix C. A higher subsidy in p/kWh is granted for domestic than for non-domestic properties as well as for WSHP's than ASHP's.

Investment funding for district heating was assumed to be at a maximum and is 50% of the total investment with the other 50% funding provided by a 3.5% low interest loan.

System Cost Comparison

A cost analysis based on the annuity method with constant annual cost was applied and returns levelized cost of heat (LCOH) in p/kWh, making different systems comparable (Kost et al., 2018, p. 29). This method differs from a financial analysis as overall system cost including heating equipment in buildings were factored in to make whole heating system solutions comparable. Key assumptions are as follows:

Discount rates are:

- 3.5% residential, public & commercial
- 6.8% mixed scopes for community and public

Current residential electricity price is 15.5p/kWh. For district heating a 20% lower price of 12.5p/kWh was assumed.

Maintenance cost for the DH was assumed to be 1% of the total investment or 28,000£/y.

A 20 year scope is applied for all individual systems, based on expected lifetime of residential heat pumps (Wang, 2018). A 30year scope is applied for the district heating system, based on a longer lifetime of the large-scale heating equipment.

3.3.2. Individual Heating

This individual heating scenario upgrades all properties to ASHP with low temperature (LT) radiators or underfloor heating (UFH). A cost estimation resulted in total upgrading cost of £1.9million and is shown in Table 14, Appendix D. It is separated into residential, small public and commercial properties (<50MWH/y) and big public and commercial properties (community hub and converted hospital). Cost estimations for levelized cost of heat (LCOH) are presented.

Residential

Residential heating conversion requires a high investment for the ASHP including a DHW store as well as the wet heating systems with new low temperature radiators. Total investment was estimated to £15,610 per dwelling, including installation cost.

LCOH is 8.6p/kWh (12.4p/kWh without funding).

The levelized cost for heat is intermediate due a high domestic RHI of 10.71p/kWh. It is considered less expensive than electric heaters but similar to oil boilers. Therefore, an upgrade from electric heaters is economically viable, for oil boilers less so.

Public and Commercial, Small

The cost for public and commercial properties was sized linear to their heat demand.

LCOH is 14.1p/kWh (16.3p/kWh without funding).

The levelized cost for heat is high due to a lower non-domestic RHI of 2.75 p/kWh. An upgrade is only recommended for electric panel heaters with high electricity cost.

Public and Commercial, Big

The heating cost for the proposed community hub and a converted hospital into housing were estimated with new heat pump systems and underfloor heating.

LCOH is 6.1p/kWh (7.4p/kWh without funding).

The levelized cost of heat is low due to a larger scheme size resulting in lower specific investment cost. A non-domestic RHI was applied as well. It is cost competitive against electric heating as well as oil boilers.

The overall CO_2 emission savings for all individual heating systems (SPF 3.0) are 491tCO_2-eq, saving 77% of emissions from fuel oil boilers.

3.3.3. District Heating Estimation

Preceding a full district heating system design including simulation, a high-level system estimation was done, achieving results for levelized cost of heat. This allows a comparison between individual systems, in order to decide if district heating is a viable solution for this case study.

A seawater source district heating system was designed and levelized cost of heat is presented. The system design follows a simplified approach, similar to the full analysis in chapter 3.4. System sizing was done using the duration curve (Figure 30) and fitting a heat pump with 500kW, sufficient for about 80% of demand. An electric heater, thermal store and backup boiler are integrated. A detailed cost estimation is presented in Table 15, Appendix D and summarised as follows:

The overall investment for district heating system as well as building integration including new heating interface units and radiators was estimated to £3.3million. The cost is separated into the following sectors:

- Building conversion and hook-up: £1.3million.
- District heating energy centre: £0.7million.
- District heating network: £1.3million.

With a total heat demand of 2.1GWh/y this results in the following LCOH:

- LCOH with funding: 11.8p/kWh
- LCOH without invest funding: 18.0p/kWh
- LCOH without invest funding and without RHI: 19p/kWh

These results show that the high cost for pipes and trenchwork result in relatively high cost of heat. The district heating is not viable without funding. It is less expensive than electric heating, but more expensive than other heating systems.

The overall CO2 emission savings for the district heating system (SPF of 3.6) are 509tCO2-eq, saving 81% of emissions from fuel oil boilers.

3.3.4. Future Heating Discussion

Comparing individual and district heating systems in terms of suitability and cost does not favour a specific solution in general. This section discusses different aspects of what is the most suitable future heating system.

System Cost

DH with funding results in LCOH of 11.8p/kWh. Individual ASHP's are less expensive in investment and result in lower LCOH (9.7p/kWh on average), especially for larger public buildings like the community hub (6.1p/kWh) and residential properties (8.6p/kWh) but are more expensive for smaller public and commercial buildings (14.1p/kWh) due to RHI subsidy design.

CO2 emissions

The main difference in terms of heating generation is the difference in the SPF of air source and seawater source heat pumps which is estimated to 3.0 and 3.6, respectively. Estimated heat losses of 5% contribute to higher energy demand of the DH network. This results in similar CO2 emission reductions than the individual solution, with DH slightly in favour (81% to 77% emission savings for individual ASHP's).

RE Integration

More community owned wind turbines are proposed and need specific loads as the grid is constrained. This requires electrical demand matching. A wind power to heat approach is less complex with a central plant incorporating a large thermal store. It is considered less equipment intensive and more cost efficient than decentral solutions like small scale thermal stores or batteries.

Environmental Impact

The environmental impact of the systems is of different nature. The individual ASHP's mainly affect residents by emitting noise and little visual impact of outside units. The seawater source heat pump has a high impact in the construction period due to required trenchwork. After that, the main issue is visual impact of the energy centre including a large thermal store, seawater carrying pipes and a seawater inlet/outlet. Considering an energy centre that is well integrated into the environment, the district heating is likely having low impact in the long term.

Community Ownership

The ability of community ownership of the DH scheme can be identified as the main benefit of the development. A beneficial heating upgrade could be done in a single development. It allows more affordable heating for residents with no financial ability to upgrade their heating. Furthermore, re-investment of generated revenue from adequately priced heat can be directed to other community developments. The development should generally target heating on Barra in the long-term, not excluding other residents by focusing only on one area.

Funding

Funding high investment is a crucial point for the viability of a future heating system. District heating is a long-term investment that can access public funding. Securing investment grants of 50% of the total investment together with a low interest loan of 3.5% is achievable. This allows capital being invested into island infrastructure.

Conclusion

District heating provides benefits for integrating further renewable energy systems and creates infrastructure that supports more efficient use of energy on Barra in a very large-scale approach. An initial cost estimation shows that DH is not cheaper than most individual ASHP solutions in direct comparison. CO2 emission reduction of the DH is not significantly better than individual heat pump solutions.

Therefore, other arguments than cost competitiveness are needed to justify the development of a DH scheme. The main arguments are summarised as follows:

- Infrastructure upgrade
    - Better heating can be provided for residents in the Horve area as an initial development
- Community ownership
    - A large amount of funding can be acquired and provides the community with the ability to generate steady revenue that can later be reinvested to provide e.g. heating upgrade subsidies for other residents
- Large scale impact
    - This scheme enables a large amount of heating to be upgraded in a single development and is having more impact than small scale residential subsidies like the RHI with low uptake

- Renewable energy integration enabler
    - If proposed further wind turbines should be installed the DH can act as enabler providing a significant load, benefitting the DH itself by providing lower cost of electricity

This work does not aim to decide whether DH is the optimal solution for the overall Barra energy issue. An energy roadmap which designates future goals and milestones of sustainable investment towards renewable technologies with benefits for the island is recommended. This could place the DH in a specific role as single milestone and enabler for further development. This thesis aims at providing a clear overview of possible future heating solutions and a technical investigation of a low-temperature DH network for Barra.

3.4. District Heating System Design

This section provides a technical design of a low temperature district heating system for the Horve area of Castlebay.

3.4.1. Introduction

Figure 31 shows a schematic of the proposed DH design, including temperature levels and equipment sizing. It is simplified and does not consider specific hydraulic design.

The system consists of a seawater inlet with submerged dual pumps, providing ambient heat. A heat exchanger separates the seawater from the heat pump system. Three different heat generation units provide heat at a temperature of 60°C, supplied to the grid. A minimum grid feed temperature of 55°C is required to distribute heat for space heating and domestic hot water. Space heating for newly built properties is delivered with UFH at a lower feed and return temperature. A circulation is required to keep remote areas of the grid at feed temperature, avoiding long delay times for ideally instantaneous heat supply. The return temperature was estimated to be 40°C. The main heat demands are stated and consist of residential, commercial and public properties.

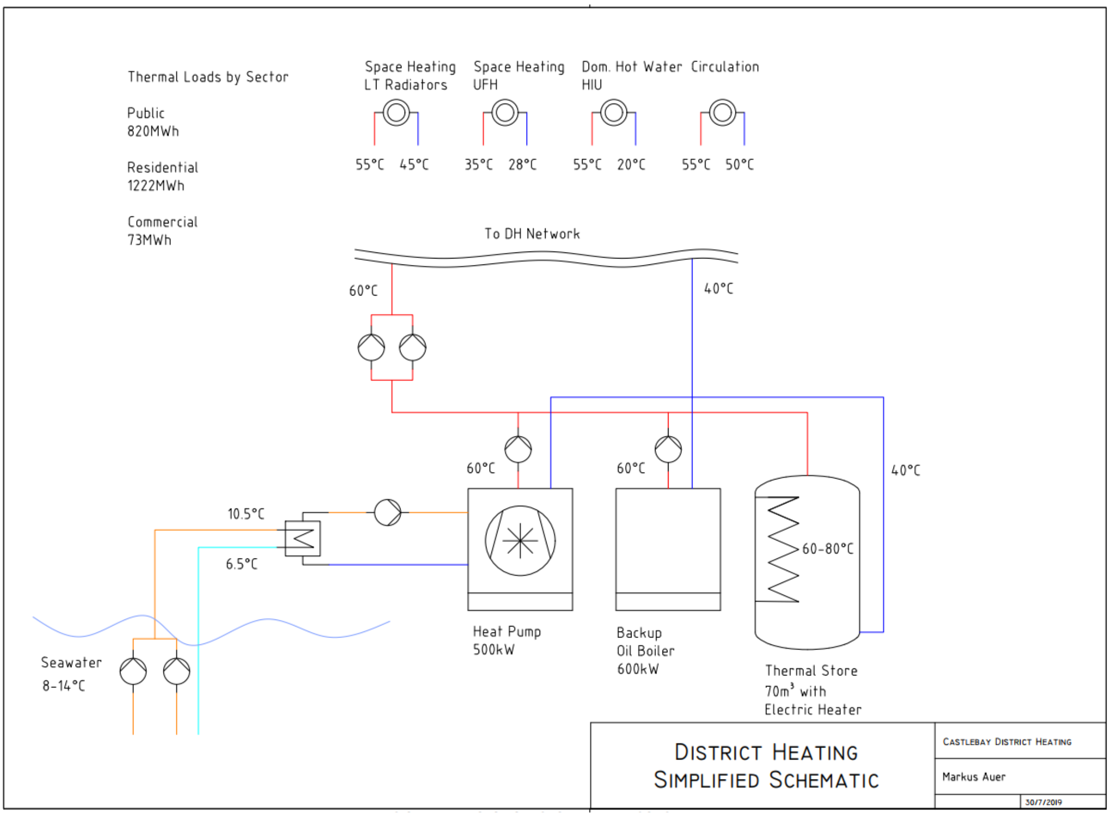

Figure 31 Simplified District Heating Schematic Horve Area, Castlebay

A proposed grid layout is shown in Figure 32 and Appendix E. The network covers an extended Horve area, connecting all main public and commercial properties, except those with newly retrofitted heating. All residential properties are covered in the graphical layout, alas a realistic connection rate of only 70% was applied. This represents the fact that not every private household is likely to change its heating.

The network is divided into a primary grid (red), distributing heat in a closed ring. This allows smaller pipe diameters as the main load (community hub) is located at the end of the ring, allowing heating water flow from both links. This contributes also to better circulation of the transmission grid. The secondary grid (green) links up multiple properties off the main grid. The tertiary grid (orange) is consisting only of building connectors, linking the DH network directly to the heat interface unit inside the building. The heat pump is circulating seawater in an open-loop system close to the proposed energy centre site.

Figure 32 Proposed District Heating Grid with Future Energy Demands, Peak Loads and Pipe Dimensioning.

3.4.2. Temperature Level Requirements

One of the most important DH design aspects is the network temperature. Both district heating system and heat pump benefit from low temperature levels as these decrease heat losses and increase efficiency. Alas, the required temperature of the system is set by the current building stock with high specific heat demand. This requires radiators with high heating capacity. The development makes use of low temperature radiators, allowing to apply a more efficient low temperature DH system. This raises cost for connecting properties, but makes the scheme viable for heat pump use, which is a necessity as shown in chapter 3.1.6.

Starting from the supply of 55°C low temperature radiators and DHW provided by HIU, a temperature cascade was calculated as follows:

Table 6 Temperature Level Cascade: Radiators & Domestic Hot Water – Heat Interface Unit Temperature drop – Grid Temperature Drop – Heat Pump Feed– Heat Pump Condenser Temperature Drop – Heat Pump Condenser

T_feed_rad-dhw	dT_HIU	dT_grid	T_feed_hp	dT_cond_hx	T_Cond
°C	K	K	°C	K	°C
55	4	1	60	5	65

A heat pump condenser temperature of approximately 65°C is required to provide 55°C for SH and DHW. Lower temperatures of DHW and SH should be pursued to lower return temperatures. This allows a reduced volume flow due to larger heat flow, thus reducing pump cost.

3.4.3. Heat Source Evaluation

Several ambient heat sources are available in the Horve area: air, ground and seawater source. Air and seawater heat sources are inexhaustible open-loop system with average temperature levels shown in Figure 33.

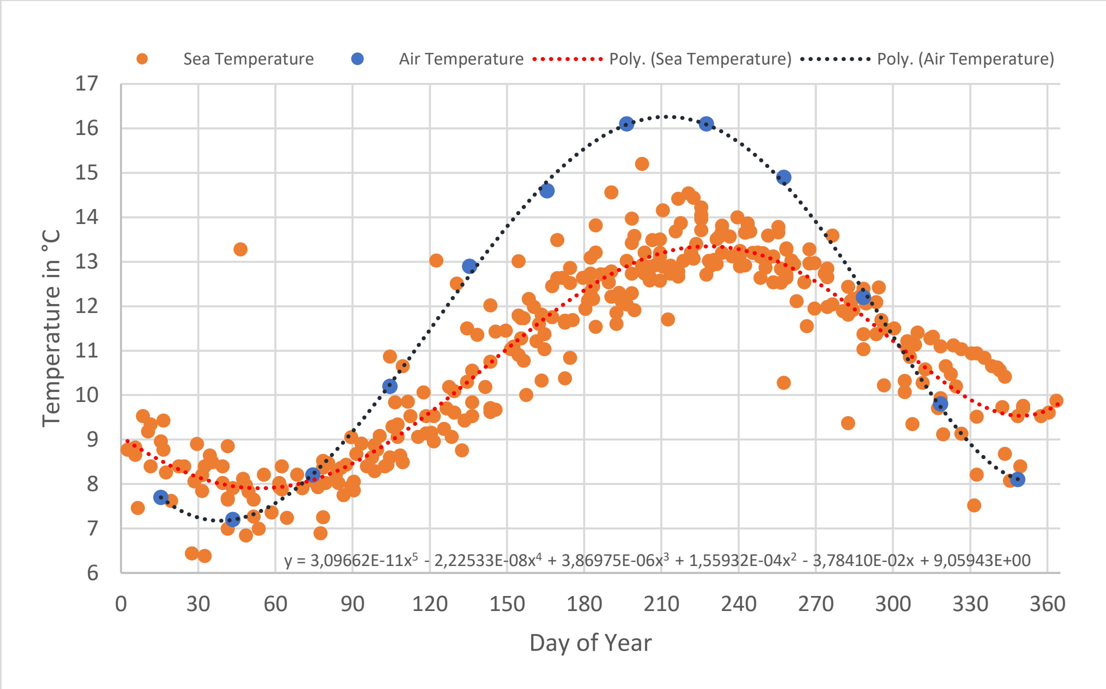

Figure 33 Measured Seawater Surface and Ambient Air Temperatures on the Western Isles Fitted with Trendlines. Equation y is Fitted Sea Surface Temperature Trendline. Data Sources: Air Temperature South Uist Range (Met Office, 2019), Seawater Surface Temperature Lochmaddy (Rasmussen Jens, 2012; Scottish Government, 2011)

Comparing air to seawater, a higher temperature of surface seawater during heating seasons can be observed. In summer, seawater surface is below air temperature. Average sea surface temperature during heating periods (oct-mar) is 9.9°C and 11.5°C during summer periods (apr-sept).

Regarding air source heat, there are various issues along the benefit of lower investment cost. High heating demands that occur from low air temperatures are directly linked to lower COP and heat capacities of ASHP’s. Also, humid island climates often lower the SPF due to icing of evaporator units. Furthermore, a high saltwater content in the air near the coastline can result in corrosion of heat pump evaporator units, as observed at ASHP on Barra. Finally, the RHI subsidy currently favours water source heat pumps, as shown in Appendix C. Therefore, air source seems not ideally.

Ground source heat is either utilised with ground loops or boreholes. Soil temperature is relatively stable below 5m depth (Florides and Kalogirou, 2007) and varies from about 7-15°C in the UK, depending on geology (British Geological Survey, 2019). These closed systems are affected by the fact that energy is extracted from the soil, resulting in constantly lower temperatures over years of use (Acuña, 2010). Several

Kelvin temperature drop have been observed by Rybach (2001) With combined use for heating and cooling or implementation of excess renewable heat in summertime, it is possible to regenerate cooled down soil temperatures. For example, the ETH Zürich network, as introduced in 2.4.3, is constantly regenerated and varies seasonally between 8-22°C.

As there is no cooling demand in this DH scheme, regeneration is only possible with a more expensive integration of renewable energy. Excess wind energy or solarthermal could be used. Alas, high cost of about £1k per kW for GSHP boreholes persist (Smart Renewable Heat, 2019). This is likely to be more expensive than seawater source equipment cost. Therefore, ground source seems not ideally.

Seawater source is considered the most viable source of ambient heat as there are no major disadvantages while temperature levels are likely to achieve a higher SPF than other systems. Their benefits are shown in various applications (Spitler and Mitchell, 2016) and can justify higher operational cost for seawater pumps.

For a seawater source heat pump, a temperature cascade was designed according to Table 7. A weighted average temperature of 10.5°C was calculated by estimating 2/3 of heat demand occurring in winter.

Table 7 Temperature Level Cascade: Seawater Inlet – Seawater Heat Exchanger Temperature Drop – Seawater Outlet – Seawater Mean Temperature – Heat Pump Evaporator Temperature Drop – Heat Pump Evaporator

T_sea_in	**dT_sea_hx**	**T_sea_out**	**T_mean_sea**	**dT_evap_hx**	**T_evap**
°C	K	°C	°C	K	°C
10.5	4	6.5	8.5	5	3.5

3.4.4. Heat Pump Performance

Coefficient of performance as a function of sea surface temperature was calculated using equation 3. ε_{carnot} of 0.65 was applied for large, advanced heat pumps, as shown in Figure 16. A constant heat pump feed temperature of 65°C was applied. Figure 34 shows that COP varies from about 3.7 in February-March to 4.1 in July-August.

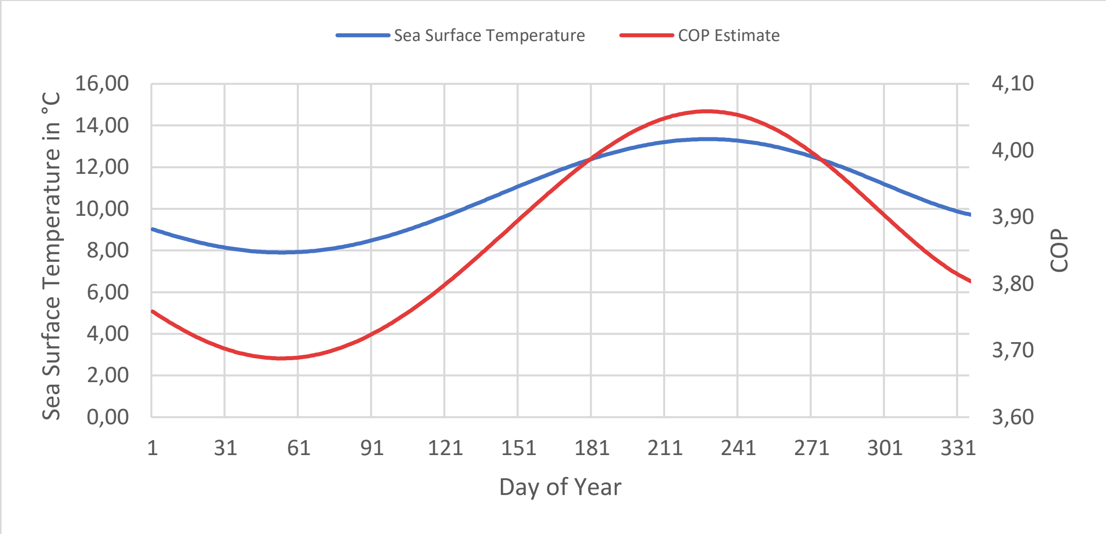

Figure 34 Estimated COP as a Function of Sea Surface Temperature

In order to determine a SPF linked heat demand and seawater temperature, COP's were weighted against thermal load, which was shown in Figure 30. A SPF of 3.81 was estimated, which is a good result in comparison to individual heat pump systems (Energy Saving Trust, 2016) or existing heat pump DH schemes in Europe (Figure 15), which normally achieve around 3.0 on average for similar schemes.

3.4.5. Network Dimensioning

A simplified pipe dimensioning was conducted in order to achieve results for investment and operation cost and thermal losses. Results for each pipe category are as follows:

Seawater Inlet

A maximum thermal extraction power of 400kW was defined for the seawater inlet pipe. This considers a 500kW heat pump with a COP of 3.5 during peak heating period, leaving a 10% margin.

Seawater is cooled with a temperature difference of 4K. This results in a maximum seawater flow of 86m³/h. With a pipe dimensioning requirement of flow velocities <2m/s a specific pressure difference of < 250Pa/m can be achieved.

The chosen pipe is stainless steel DN160. This results in a required pump head of 1bar and a mechanical pump power of 1400W. There is no head to overcome even though the system is not closed, as water inlet and outlet are at the same level. Other pipe friction arises from various bends and fittings, a heat exchanger as well as inlet and outlet structures. Another 400W of mechanical pump power was estimated, resulting in 1800W pump power for full load. Assuming 4380h of full load equivalent use, 7.8MWh of electrical power is required. This is only 0.4% of the total DH heat demand.

District Heating Network

The DH network was separated into 5 different subsections. For simplification, no diameter reductions were designed along these sections. All pipes are using standard insulation and are either separated feed and return "single" pipes or combined "twin" pipes. Pipe sizing together with pressure and heat losses are shown in Table 8.

Table 8 Pipe Dimensions and Specific Pressure and Heat Losses

Section	Pipe	Specific Pressure Loss in Pa/m	Specific Heat Loss in W/m
Main to circle	Single DN125	104.7	25.1
Main split in circle 1	Single DN90	108.4	17.2
Main split in circle 2	Single DN90	108.4	17.2
Secondary Pipe 15 dwellings avg	Twin DN63	76.5	7.2
Tertiary Pipe House Hookup 2 dwellings avg	Twin DN32	100.1	7.1

The total heat loss of the system was estimated to 14% of total heat demand, being higher than initially estimated due to a rather low heat density and only standard insulation of pipework.

3.4.6. Heat Generation and Storage Sizing

Heat generation and storage was sized using a 1-hour timestep energy-balance simulation model. This allows optimisation of equipment size and indicates that the full heat demand can be met.

The model does not consider actual control algorithms of heating equipment or thermal and hydraulic models and is therefore only a simplified approach based on energy balances. No storage heat losses were applied.

The working principle of the model is based on the hourly thermal load profile and different heat generation units and a storage. The heat generation is designed to work in a merit-order, preferring the heat pump. If the heat pump capacity is reached, the thermal store delivers heat. The electric heater comes in place and if this is still not sufficient, the backup boiler is started. The thermal store is loaded by the heat pump only in this scenario.

The results are as follows:

- 1200kW maximum DH grid capacity (including heat losses of 14%)
- 500kW Heat pump (sufficient for 7200h or 93% of heat demand)
- 100kW Electric heaters in thermal store for excess wind and peak load supplement; Temperature above 60°C possible. HP electric capacity is only about 120kW, 20s0kW wind turbine proposed (delivers 5% of heat demand)
- 600kW backup oil boiler (needed for 0.1% of heat demand, but sufficient for 8750h of the year, or all heat loads in combination with thermal store)
- 70m³ Thermal store for peak load supplements and RE integration (delivers 2% of heat demand and has equivalent capacity as the maximum grid capacity)

The system was designed aiming for most cost-efficient use of equipment, avoiding oversizing of the heat pump system. On the other hand, the thermal store was chosen to be of larger size to support wind energy implementation. Together with additional electric immersion heaters in the store, this enables a high capacity of shifting renewable power to heat. A backup oil boiler is necessary to avoid any downtimes of the grid in case of maintenance or failure of the heat pump system but is scarcely used.

The simulation model results are shown in Figure 35 for two weeks of January, being the highest thermal load of the year. A full year simulation is shown in Appendix F.

The simulation shows the highest thermal load throughout the year is 1200kW, occurring during the first day of January. Only for these 10 hours per year, the co-generation of heat pump, electric heater and thermal store cannot provide enough heat. This can be observed by a thermal store level of zero. In this situation a backup fuel oil boiler must cover the peak load, which totals in an energy demand of 1900kWh over the year.

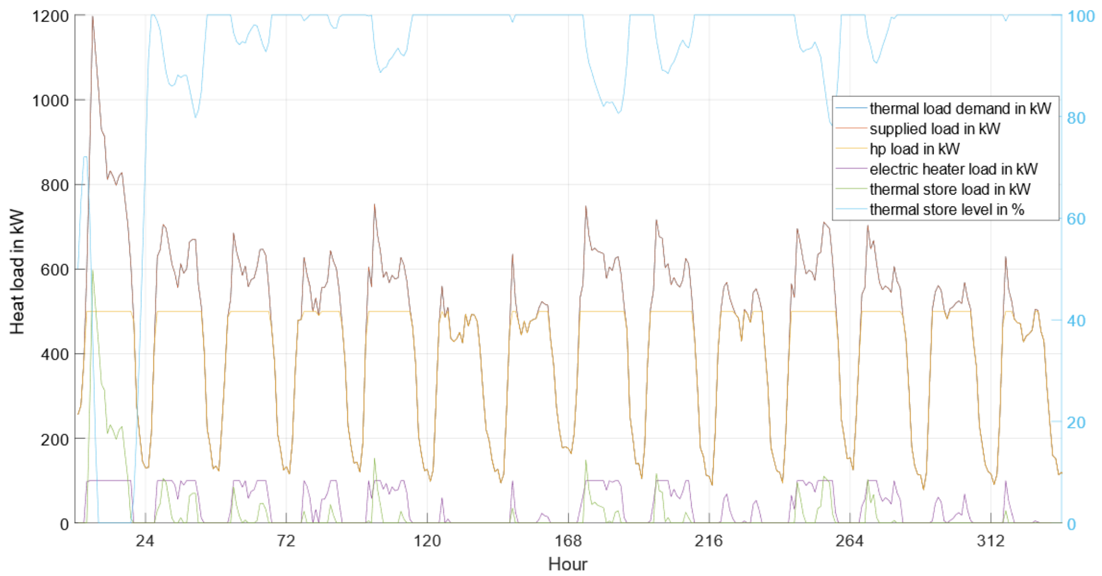

Figure 35 District Heating Simulation Model Results. Thermal Load and Heat Generation for First Two Weeks of January.

3.4.7. Heat Interface Units

Consumer Heat Interface Units (HIU) are necessary to connect the district heating to consumers while separating the systems hydraulically. They mainly consist of a heat exchanger, a circulation pump, a heat meter and a temperature mixing circuit if necessary. Manufacturers provide standard designs that vary slightly in design but do provide standard capacities starting from 35kW for single dwellings. This high heat capacity is required for providing instantaneous DHW. Hot water for residential use is normally designed to provide a flow of about 12l/min at temperature levels of 45-60°C.

Space heating suitability with HIU’s for dwellings in the Horve area was investigated in Table 9. As properties are mainly low EPC and high heat demand, space heating capacity was estimated to 10kW.

A calculation of available SH capacity by a 35kW DHW HIU is shown in Table 9. A low temperature difference of LT radiator systems of only 10K for 55/45 feed and return temperature raises issues with available heat load from the heat exchanger. It is only 5.8kW, as flow capacity is limited to 0.5m³/h with standard sized HIU heat exchangers for single dwellings.

This means that for properties with high heat demand it is either necessary to use HIU's with larger heat exchangers or low temperature heating systems like convector radiators or UFH. This is no technical issue but raises cost.

Table 9 Heat Interface Unit Specifications and Calculated Heat Output

DHW			SH		
Volume Flow	11	l/min	Volume Flow max	0.5	m³/h
Feed Temperature	55	°C	Feed Temperature	55	°C
Cold Water Temperature	10	°C	Return Temperature	45	°C
Temperature Difference	45	°C	dT	10	°C
cp Water	4.19	kJ/kgK			
Density Water	1000	kg/m³			
Q_SH	34.6	kW	Q_DHW	5.82	kW

3.4.8. Community Hub Integration

A new community hub for the Isle of Barra and Vatersay is proposed and is likely to include a new-built school, hospital, care home and community facilities in a combined large-scale scheme located where the current school in Castlebay is. The total floor area is about 7000m². An EPC rating of B+ is proposed, resulting in 400kW heat load. ASHP are likely being used for space heating and hot water.

If the hub is connected, mutual benefits arise. For the community hub, there is limited space on-site for heating equipment. A DH heat exchanger requires less space than an individual heat pump and does not cause noise emissions. Furthermore, the capital cost for a DH connection was estimated to about a sixth of an ASHP.

The DH network could benefit from a lower return temperature if UFH and decentralised DHW booster heat pumps are used. These systems provide a high thermal comfort in terms of SH, as well as hygienical DHW for sensitive areas like health care.

A financial assessment should carefully weigh benefits to eventually higher life cycle costs for heating at the community hub. The LCOH estimated for an individual (6.1p/kWh) vs a DH (10.8p/kWh) supply is in favour for individual ASHP.

If the community hub is not connected, LCOH of the DH scheme rises from 10.8 to 12.6p/kWh. Therefore, the connection of the hub is crucial for the economic viability of the DH development.

3.4.9. Wind Energy Integration

Further implementation of community owned wind energy is proposed. These turbines are restricted to be connected in private wire or virtual private wire schemes, so they must be physically or virtually connected and balanced to suitable loads. There are various loads proposed for the private wire scheme, including the DH. Its suitability for direct uptake of wind power for heating is investigated.

A wind turbine for the Castlebay area is proposed of about 200kW capacity. The district heating serves as an electrical load with the heat pump as main consumer. The electrical heat pump capacity is about 131kW, as it has a thermal capacity of 500kW with an average COP of 3.81. Another 5% of the HP demand was added for auxiliary loads like pumps. This electrical capacity is exceeded by the wind turbine for 501h per year. Therefore, a 100kW immersion heater was incorporated to enable the DH to fully uptake the generated wind capacity. The heater is implemented into the thermal store with a size of 70m³.

A simplified simulation model that includes wind power and HP electrical power together with a thermal store was created and is shown in Figure 36 and Appendix G.

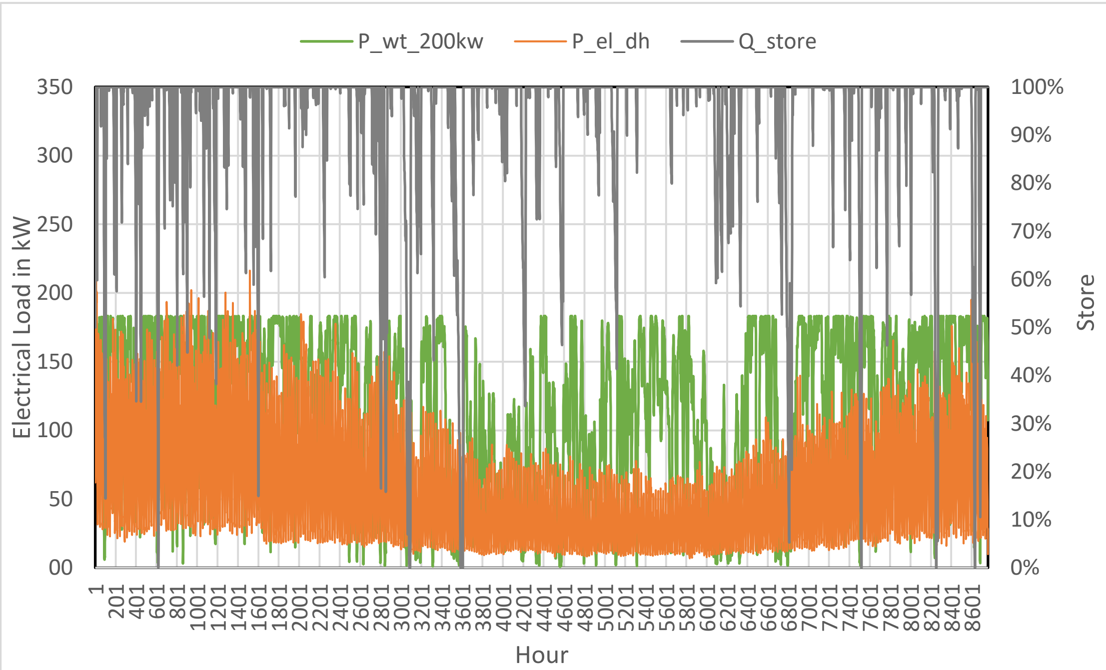

Figure 36 Wind Energy Integration Simulation Model Results. 200kW Wind Turbine Output, Electrical Power Demand District Heating including 5% of HP Power for Auxiliary, 70m³ Thermal Store Level. Wind Turbine Output From: (Renewables.ninja, 2019)

The simulation results show that DH demand and wind turbine output match relatively good during heating period and less in summer. Investigating the main energy balances of this system in Table 10, this observation can be confirmed. The wind generation is almost double the required electricity demand for the district heating, due to very good wind resources on Barra. Almost all electricity demand, 499 out of 572MWh/y, can be covered by the turbine(s). Adding a store enables a theoretical 100% coverage of wind energy.

Another finding is that the renewable energy storage ability is limited to 73MWh/y. The thermal store of 70m³ or 1.6MWh (20K ΔT) is likely oversized. With a reduced size of 30m³, still 58MWh/y can be stored. From this perspective a smaller, less expensive thermal store can be installed. If necessary, the amount of storable energy could be doubled by boosting temperatures with the electric immersion heater to e.g. 80°C, while keeping the same store size.

Table 10 Wind Energy Integration Simulation Figures: Heat Demand of DH Network, Electricity Demand of DH Heat Pumps and Auxiliary, 200kW Wind Turbine Electricity Generation, Directly Matched Wind Generation to DH Demand, Thermally Stored Electricity Uptake.

Heat Demand	Electricity Demand	Wind Generation	DH Direct Match	Stored Electricity
MWh/y	MWh/y	MWh/y	MWh/y	MWh/y
2074	572	1006	499	73

3.4.10.Emission Reduction Potential

CO2 emission savings are shown in Table 11. A DH scheme with electricity supplied by wind turbines has the potential to avoid emissions entirely. 634tCO2-eq/y could be avoided annually.

Table 11 Annual CO2 Emission Savings for Heat Pumps to Counterfactual Fuel Oil Boiler

Heating Type	Fuel Oil	Electricity	ASHP	DH WSHP	DH WSHP with Wind Turbines
Total in tCO2-eq/y	634.2	430.5	143.5	115.3	0
Savings in tCO2-eq/y		204	491	519	634.2
Savings in %		32%	77%	82%	100%

3.4.11. Financial Analysis

A cost comparison using levelized cost of heat (LCOH) was done in chapter 3.3. Unlike a financial analysis, the aim was to compare whole-system cost of different types of heating and expressing them in one benchmarking figure: LCOH in p/kWh.

This section investigates a more realistic financial analysis by taking only cost into account that is covered by a DH developer, e.g. no heating system cost for a new development like the community hub. Furthermore, not all building retrofit cost is covered by the DH development. It would not be fair to offer free heating system upgrades for Horve residents only. A reasonable cost distribution between developers and homeowners is proposed.

The main conditions and results of the analysis are as follows:

Financial Design

Actual cost is calculated with no investment into heating equipment for new developments and only partial investment for upgrading residential (80% funding by DH developer) and business (30%) properties. For homeowners, a low but reasonable connection cost of £2000 (i.e. they only pay for the HIU) have been considered to motivate residents switching to the DH scheme. A further funding opportunity (SEEP) has been considered to fund installation cost of £600 per dwelling (Scottish Government, 2019).

This measure reduces the total investment from 3.3 to 2.7 million.

The loan for the full investment (excluding 50% public funding) was already applied in the initial comparison and is kept to a duration of 18years with an interest rate of 3.5%. Total loan costs are £493.000.

Public subsidies are applied as before and were assumed to be 50% of the total investment. This is optimistic but can be achieved for projects with the scope of reducing GHG emissions.

Cost Optimisation

Lower electricity cost is estimated, as new wind turbines in the Castlebay area are assumed. A 200kW turbine was investigated, suggesting a levelized cost of energy of about 8p/kWh (instead of 12.5p/kWh)

This reduces 30year electricity cost from 2.2 million to 1.76 million

From finding in chapter 3.4.4, a higher annual SPF can be assumed, being 3.81 (instead of 3.6)

This further reduces 30year electricity cost from 1.76 million to 1.66 million

RHI Funding Optimisation

The funding structure of the renewable heat incentive (RHI) has a unique algorithm of funding generated heat in a two-tier system. The tier is calculated by multiplying the heat pump capacity in kW by 1319 in order to get the limit between tier 1 and tier 2 in kWh. As shown in Appendix C, a much higher tariff of 9.56p/kWh is paid at tier 1 then at tier 2 with 2.85p/kWh. This seems to stimulate equipment oversizing for the benefit of higher RHI incomes. This is not likely to favour a more efficient use of resources or equipment but is a fact to deal with.

For this reason, a sensitivity analysis has been done to find out if a higher heat pump capacity can benefit the LCOH of the DH. The heat pump cost where estimated to be a constant £600/kW for seawater heat pumps. Results are presented in Figure 37.

Both heat pump cost and RHI are rising linear and are almost identical. The cost difference of a 400kW to 800kW heat pump is £240.000 for the heat pump investment versus £247.000 for the RHI income. Alas, the LCOH is rising with higher heat pump capacities. This can be explained by the financial design of the scheme. A higher investment results in a higher loan value and therefore higher loan cost.

This investigation shows that an oversizing of the heat pump for the sake of generating higher RHI is not beneficial. The fact that heat pump cost will not rise linearly with size maybe influences the outcome, but it is unlikely to be significantly different. The main reason for oversizing the heat pump would rather be provision for future DH growth, while being less expensive if done in the initial development of the scheme.

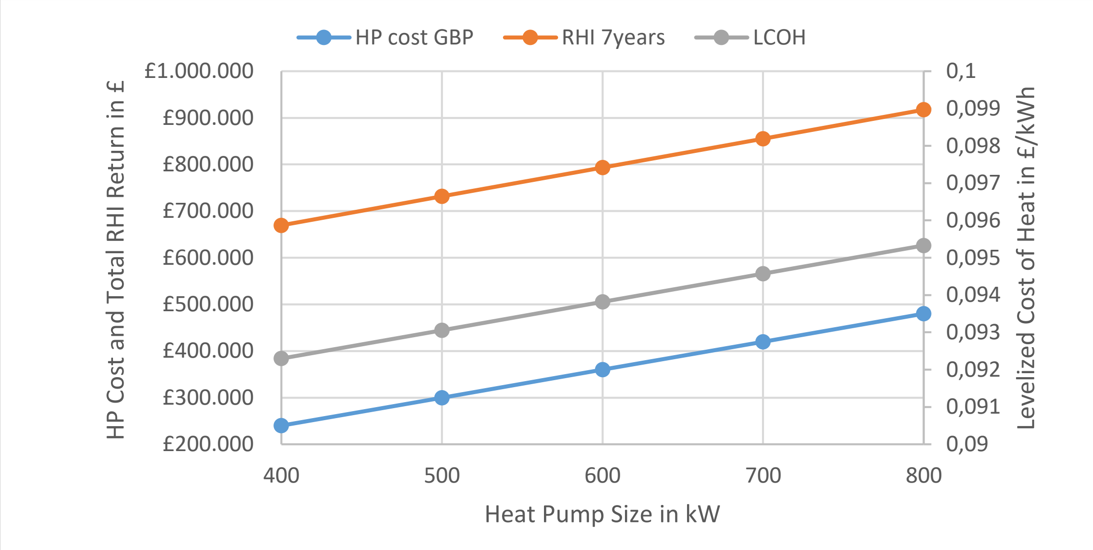

Figure 37 RHI Sensitivity Analysis. LCOH for Different Heat Pump Sizes

Results

The results of the financial analysis with the presented optimisation measures are presented for investment cost and LCOH. They are as follows:

- Building conversion and hook-up: £0.7million.
- District heating energy centre: £0.73million.
- District heating network: £1.34million.

With a total heat demand of 2.1GWh/y this results in the following LCOH:

- LCOH with funding: 8.7p/kWh
- LCOH without invest funding: 13.9p/kWh
- LCOH without invest funding and without RHI: 15.0p/kWh

The investment cost of £2.77million are still very high, with the DH network (3720m of pipes) being the most expensive part.

The LCOH was reduced to 8.7p/kWh and is lower than DH cost for medium temperature networks estimated by DECC (2016, p. 12).

The optimised DH, compared to ASHP induvial heating retrofit equivalents (chapter 3.3.2), is more expensive for big pubic/commercial properties (6.1p/kWh), about the same for residential properties (8.6p/kWh) and less expensive than for small pubic/commercial properties (14.1p/kWh).

A simplified, non-discounted, cashflow and capital analysis is shown in Figure 38. This allows visualising the changing cashflow over time with a capital starting with zero. After a loan take-out of the full 50% of the investment, RHI payments for 7 years and loan repayments over 18 years result in non-linearity over the investigated timespan of the DH. The accumulated capital after 30years is £1.7million. The lifespan of the DH is likely to be over 30 years, as the main expenditure, the pipework, is stated to have a 50year lifespan. So main reinvestment will be needed for new or refurbished heat pumps, circulation pumps or valves, etc. This leaves a margin for revenues to be taken out for other community projects on Barra and can be assessed by risk analysis.

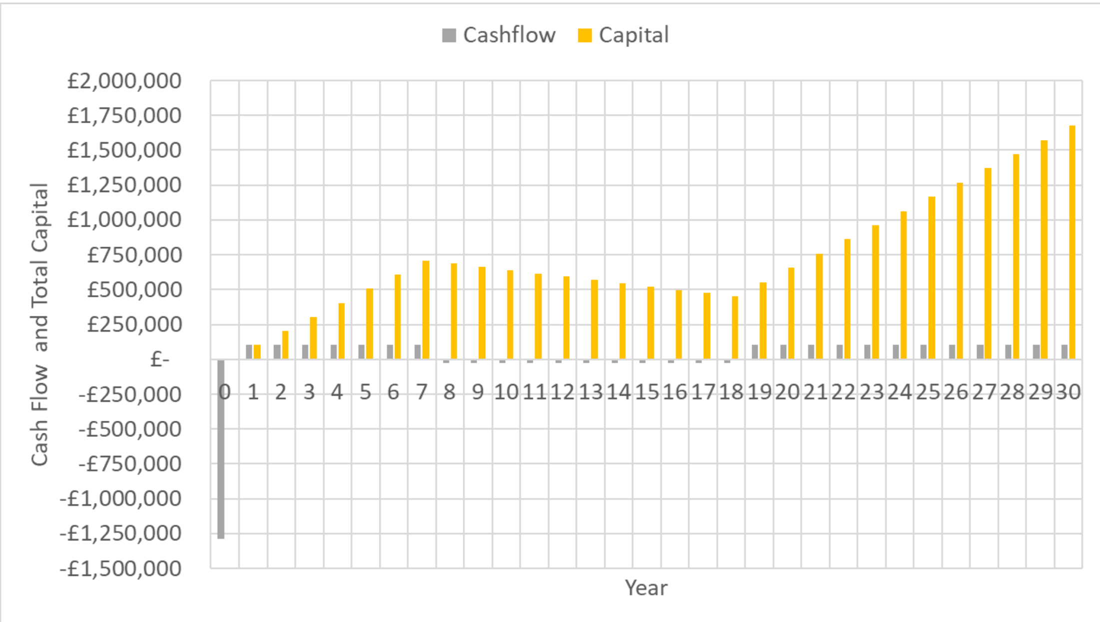

Figure 38 Simplified, Non-Discounted Cashflow and Capital Over 30 Years

Discussion

From a financial view on LCOH, the DH still does not seem to have significant benefits to individual heating solutions in the long term.

However, a benefit is that initial investment cost is lower for all DH costumers connecting to the scheme. This lowers cost barriers for homeowners, paying only £2000 for a lower-cost, higher-comfort heating if they have electric heating and similar cost and higher-comfort only if they have fuel oil heating.

Another point of view can be achieved by looking into cost per CO2 saving, as presented by DECC (2016, p. 53). A price range of 80 to 230 £/tCO2 was stated for various DH benchmark models. For this DH development total cost £5.73million

(CAPEX and OPEX over 30years) avoid emitting 15,570tCO_2. This results in specific emission reduction cost of 368£/tCO_2 or 301£/tCO_2 if electricity is provided by zero-emission wind turbines. This is clearly above the cost of the provided benchmark schemes and can be explained by a rather low heat density resulting in high DH network cost.

Governmental subsidies need to be very high to reach economic feasibility and amount for £1.39million in investment and £0.73million in operation (RHI). Transferring this to CO_2 reduction cost, gives an overview how efficient funding can be applied to mitigate CO_2 emissions. This results in cost of 136£/tCO_2 or 111£/tCO_2 for a WSHP, and a WSHP supplied by zero-emission electricity, respectively.

A fair amount of public funding should be agreed on, considering the given results. Reasonable CO_2 emissions savings and community benefits should be acquired by the received subsidies.

4. Conclusions

The Horve area in Castlebay has been investigated and current and future heating solutions were identified. The current heating situation is suboptimal, as high cost and high emission heating is prevalent in energy intensive, low EPC buildings.

The currently predominant electric panel and storage heaters are very expensive in operation and are known to increase fuel poverty. The second dominant heating system, fuel oil boilers, are moderately expensive but highly CO2-intensive. For future climate change mitigation, these systems must be replaced by low-carbon solutions in the long term.

Future heating solutions were identified in an individual and district heating approach. The most promising solution are heat pumps. A comparison of levelized cost of heat allowed direct system cost comparison over their lifecycle.

Air source heat pumps are most suitable for individual residential (8.6p/kWh) and larger public or commercial properties (6.1p/kWh). This is in the same price range as fuel oil heating, if not cheaper for larger capacities. ASHP still face downsides like high corrosion risk from salt-saturated air, icing from damp climate conditions and noise emissions from outside units.

An initial district heating scheme has been developed in order to determine if it is more viable than retrofitting individual heating systems. The initial district heating design showed that it is slightly above the price of individual heating but provides other benefits. Therefore, a more detailed and optimised district heating scheme was designed and simulated. A total annual heat demand of 2.1GWh/y can be met almost solely by a 500kW WSHP with a 70m^3 thermal store. A 100kW electric heater is proposed to utilise full wind power to heat abilities. A 600kW fuel oil boiler is necessary for security of supply.

The district heating scheme has several benefits including high efficiency, less environmental impact and community ownership opportunities with a possibly high public subsidy rate. The main disadvantage is the very high price in investment, resulting in moderate 8.7p/kWh for delivered heat. This is less expensive than electric heating, about the same as fuel oil heating or individual ASHP for residential properties, but more expensive than ASHP for large public or commercial buildings.

A total cost of 2.7million must be funded, whereof already £1.3million are needed for pipework. Existing buildings need to be retrofitted with heat interface units and low-temperature radiators, being highly intrusive and expensive.

The impact of a proposed combined community hub integrating education, healthcare and community purposes in Castlebay was investigated. It is crucial for economic viability of the district heating scheme that this development is connected. Benefits for both developments arise. Alas, for the community hub higher operation cost, i.e. cost per kWh heat delivered, need to be weighed to beneficial lower investment cost, i.e. no own heat generation equipment required, and reasonable pricing needs to be agreed on.

The ambient heat source seawater has been identified as most viable. Temperatures typically vary from as low as 8°C in February/March to as high as 14°C in August/September. An average temperature was weighted against heat demand and is 10.5°C, resulting in a seasonal performance factor of 3.81. This can be considered as a good average heat pump performance.

A proposed new development of 200kW wind turbines was simulated and coupled with heating demand of the district heating. The simulation showed that directly integrating wind energy into heating is possible due to well correlating supply-demand patterns and storage abilities. 50% of generated electricity supply meet almost 100% of district heating demands utilising a 70m^3 thermal store.

Overall, the district heating development does not stand out as perfect solution but is viable. It can provide a zero-carbon heating supply for the Horve area, constituting 29% of heating demand on Barra. It should carefully be evaluated against a possible community led upgrade to individual ASHP solutions.

If district heating is implemented, an overall scope needs to be defined to allow benefits for not only Horve residents that are connecting to the scheme. This could be achieved by reinvesting generated returns into other developments, enabling the whole island community to upgrade their homes to a low-emission and lower cost energy infrastructure. A future energy roadmap for Barra is recommended to place future heating, with or without district heating, in a long-term plan next to other community energy projects in a more holistic view.

5. Further Work

5.1. District Heating Tool Development

This work brings up the more general question under what circumstances district heating is a better solution for rural communities than individual heating and building upgrades.

A decision is not easily made, as many factors come in place. This makes an initial analysis time consuming, as a high amount of data needs to be gathered and processed. Currently available GIS based heat maps like the Scottish Heat Map (Scottish Government, 2018c) are good tools for identifying possible district heating opportunities. A feasibility study as a next step can only be done by specialists using either proprietary or programmed tools. This acts as a barrier for potential communities or local authorities who are interested in this technology if no initial funding can be provided. Therefore, more research and development need to be spent on initial decision-making tools, speeding up the process and providing easily accessible information on district heating suitability.

5.2. Comparative Study District Heating

Castlebay is not clearly in favour of a district heating grid, due to a low heat density. This is a key factor for district heating feasibility and a minimum heat density of $3MW/km^2$ is recommended by Wiltshire (2015, p. 18). For example, an urban city centre like Glasgow has a heat density of $47MW/km^2$ (Scottish Government, 2018c). The Horve area in Castlebay with 2.1GWh/y at an area of about $0.4km^2$ has a heat density of $0.6MW/km^2$.

A comparative study of areas of high heat density in the Western Isles or whole Scotland can serve as a benchmark for unclear regions like Castlebay. Denser populated areas are likely to be more economically viable, but there is no clear tipping point where individual heating upgrade is in favour of district heating.

Two example regions were identified on the Western Isles, being similar in area, property mix and seawater access as Castlebay. They are presented to showcase if there are better suited sites for district heating. Both areas show significantly higher heat densities than Castlebay, making them suitable for a more detailed comparison.

Benbecula

The Finlas of Aird area on Benbecula (Figure 39) consists of a high amount of social housing properties, a hospital and a school. The area has an annual heat demand of 5GWh/y (whereof 1GWh/y for public buildings) at an area of 0.327km² resulting in a heat demand density of 2.1MW/km².

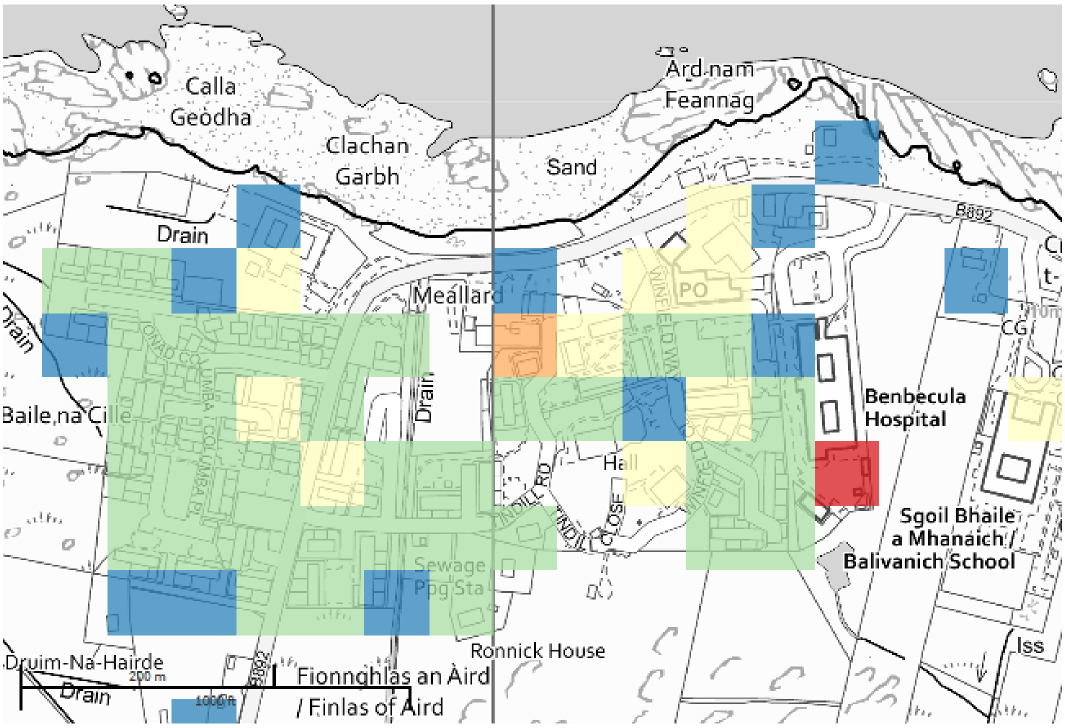

Figure 39 Heat Map Finlas of Aird, Benbecula (Scottish Government, 2018c)

At less area than Castlebay and a 2.5 times higher heat demand, this is a likely more viable area for district heating.

Stornoway

As the capitol of Harris and Lewis and a population of about 8,000 Stornoway has the highest heat density on the Western Isles. The central area around the pier (Figure 40) offers mixed use properties with an annual heat demand of 30GWh/y (whereof 3GWh/y for public buildings) at an area of 0.273km². This results in a heat demand density of 12.5MW/km².

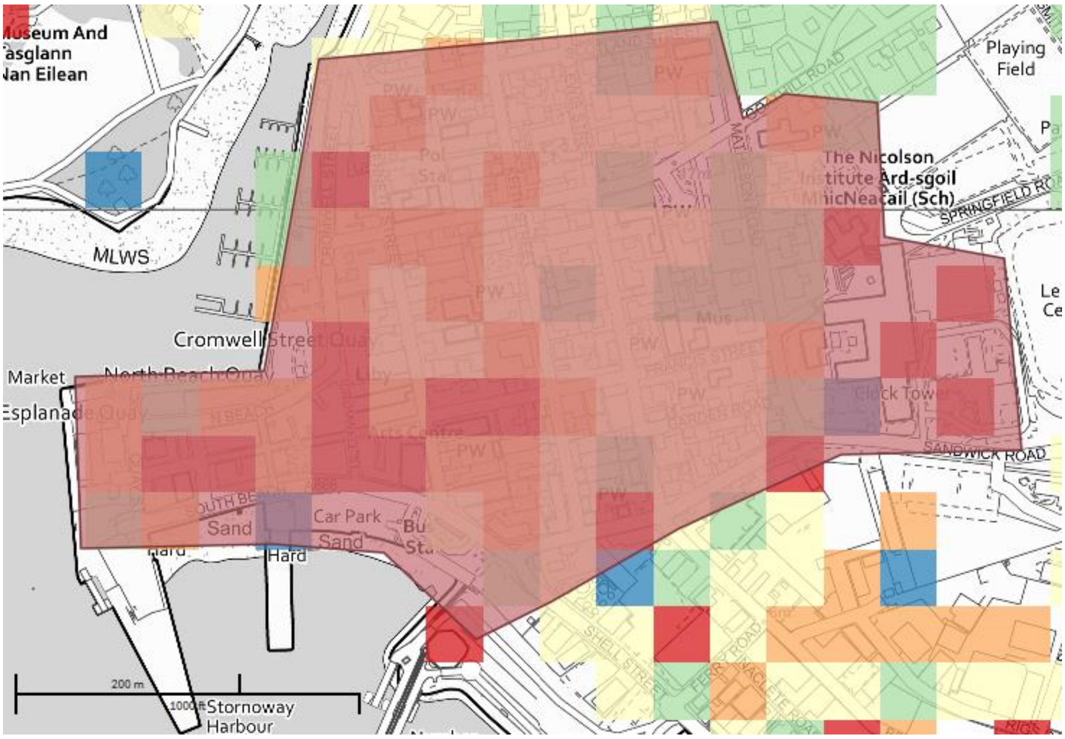

Figure 40 Heat Map Stornoway Central Pier Area with Highlighted DH Extent (Scottish Government, 2018c)

The central pier area of Stornoway offers a high heat demand in a densely populated area. This is more than 20 times the heat density of Castlebay. This seems like an ideal area for district heating, if current heating systems are not already retrofitted.

In summary, there are areas on the Western Isles which are better suited for district heating than Barra. A comparative study of potential district heating areas in the Western Isles (or whole Scotland) should be conducted and can help public and community organisations identifying suitable areas and act as a benchmark for unclear areas.

5.3. Isle of Barra District Heating Refinement

This work evaluated future heating solutions and a district heating design was proposed. However, due to limited resources this work cannot substitute a thorough technical feasibility study with validated tools and data. The following work packages are recommended:

- Do a more detailed heat demand estimation of residential properties by acquiring heating bills
- Use a more detailed, validated simulation model for the DH sizing and wind turbine integration, considering more precise models that include control algorithms, thermal dependencies, efficiencies and losses, equipment constraints, etc.
- Do a cost estimation with more detailed and recent pricing databases and consider possible price increases for installation cost on the Western Isles
- Look into cost for GSHP Boreholes vs Seawater Pipework in more detail to get assurance that seawater source is the optimal solution
- Validate results, especially for equipment sizing and wind turbine integration with another model
- Do an overall system optimisation of the DH network and heating equipment capacities
- Do a sensitivity analysis of LCOH influencing parameters such as electricity cost, heat demand changes, investment cost changes, etc.
- Identify possible funding from UK and Scottish Government
- For retrofitting existing buildings, investigate booster heat pumps instead of low-temperature radiator retrofit
- Look into viability of ambient temperature grid + decentralised heat pumps compared to the proposed low-temperature grid with central heat pump

References

Acuña, J., 2010. Improvements of U-pipe Borehole Heat Exchangers. KTH School of Industrial Engineering and Management, Stockholm.

Andrews Tipper, H., 2013. Decentralised Energy For a Sustainable Future | Carbon Trust [WWW Document]. URL https://www.carbontrust.com/news/2013/01/decentralised-energy-powering-a-sustainable-future/ (accessed 6.25.19).

Auer, M., Huebl, S., Fernandez Cardona, S., Raja, E.J., MacKinnon, B., Sicim, A., 2019. Community Energy Isle of Barra & Vatersay [WWW Document]. URL https://www.strath.ac.uk/research/energysystemsresearchunit/courses/projectwebsites/ (accessed 7.17.19).

Averfalk, H., Ingvarsson, P., Persson, U., Gong, M., Werner, S., 2017. Large heat pumps in Swedish district heating systems. Renewable and Sustainable Energy Reviews 79, 1275–1284. https://doi.org/10.1016/j.rser.2017.05.135

BEIS, 2019. Updated energy and emissions projections: 2017, Department for Business, Energy & Industrial Strategy [WWW Document]. GOV.UK. URL https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2017 (accessed 6.29.19).

BizEE Software Limited, 2019. Degree Days - Handle with Care! [WWW Document]. URL https://www.energylens.com/articles/degree-days (accessed 7.11.19).

Boie, W., Klein, D., 2009. Community development projects for the supply of heat and electricity from renewables in the Isles of Barra and Vatersay.

BP Global, 2019. Energy demand by sector | Energy economics | Home [WWW Document]. BP global. URL https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/demand-by-sector.html (accessed 4.19.19).

British Geological Survey, 2019. BGS Reference and research reports - Ground source heat pumps [WWW Document]. URL https://www.bgs.ac.uk/reference/gshp/gshp_report.html (accessed 8.1.19).

Brown, W., 2012. Household Electricity Survey A study of domestic electrical product usage.

Bruce, A., 2019. Carbon Intensity [WWW Document]. URL https://carbonintensity.org.uk/ (accessed 4.19.19).

Building Research Establishment, 2012. Standard Assessment Procedure (SAP 2012).

Carson, N., Davies, S., Shields, G., Jones, P., Hillgarth, T., 2008. Decentralised Energy-Business opportunity in resource efficiency and carbon management. Cambridge.[Online], Available: http://www. cpi. cam. ac. uk/scptaskforce.

CLUE - Climate Neutral Urban Districts in Europe, 2009. SEAWATER HEATING SYSTEM, DUINDORP/ SCHEVENINGEN.

CO2.Earth, 2018. Earth’s CO2 Home Page [WWW Document]. CO2.Earth. URL https://www.co2.earth/ (accessed 11.24.18).

Coimhearsnachd Bharraidh agus Bhatarsaidh Ltd, 2012. Coimhearsnachd Bharraidh agus Bhatarsaidh Ltd [WWW Document]. URL http://www.isleofbarra.com/coimhearsachdbharraigh.htm (accessed 6.29.19).

Community Energy Scotland, 2019. Community Energy Scotland - About Us [WWW Document]. URL https://www.communityenergyscotland.org.uk/about-us.asp (accessed 6.25.19).

Community Energy Scotland, 2015. Community Energy Scotland - ACCESS [WWW Document]. URL https://www.communityenergyscotland.org.uk/access.asp (accessed 6.29.19).

David, A., Mathiesen, B.V., Averfalk, H., Werner, S., Lund, H., 2017. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 10, 578. https://doi.org/10.3390/en10040578

DECC, 2016. Heat Pumps in District Heating Department of Energy & Climate Change [WWW Document]. GOV.UK. URL https://www.gov.uk/government/publications/heat-pumps-in-district-heating (accessed 7.1.19).

DTU, 2018. Global Wind Atlas - Technical University of Denmark [WWW Document]. Global Wind Atlas. URL https://globalwindatlas.info (accessed 11.26.18).

Edmunds, C., Galloway, S., Frame, D.F., 2018. Lessons learned from local energy projects in Scotland, in: CIRED Workshop on Microgrids and Local Energy Communities 2018.

EMEC, 2019. Press release: Energy system of the future to be demonstrated in Orkney : EMEC: European Marine Energy Centre. URL http://www.emec.org.uk/press-release-energy-system-of-the-future-to-be-demonstrated-in-orkney/ (accessed 6.29.19).

Energy Saving Trust, 2016. Analysis from the Energy Saving Trust’s heat pump field trial [WWW Document]. GOV.UK. URL https://www.gov.uk/government/publications/analysis-from-the-first-phase-of-the-energy-saving-trust-s-heat-pump-field-trial (accessed 7.2.19).

ETH Zurich, 2019. Erdspeicher [WWW Document]. URL https://ethz.ch/de/die-eth-zuerich/nachhaltigkeit/nachhaltiger-campus/umwelt/energie/erdspeicher.html (accessed 7.15.19).

European Climate Foundation, 2012. Roadmap 2050.

European Commission, 2018. Cleaner Air - Environment - European Commission [WWW Document]. URL http://ec.europa.eu/environment/air/cleaner_air/ (accessed 11.22.18).

European Environment Agency, 2019. Heating and cooling degree days [WWW Document]. European Environment Agency. URL https://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days-2/assessment (accessed 7.15.19).

Field, C.B., Barros, V.R., Mastrandrea, M.D., Mach, K.J., Abdrabo, M.-K., Adger, N., Anokhin, Y.A., Anisimov, O.A., Arent, D.J., Barnett, J., 2014. Summary for policymakers, in: Climate Change 2014: Impacts, Adaptation, and

Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 1–32.

Fintry Development Trust, 2019. Fintry Development Trust – doing good stuff in Fintry. URL http://fintrydt.org.uk/ (accessed 6.28.19).

Fintry Development Trust, 2018. Smart Fintry – About the Smart Fintry project. URL http://smartfintry.org.uk/ (accessed 6.29.19).

Florides, G., Kalogirou, S., 2007. Ground heat exchangers—A review of systems, models and applications. Renewable Energy 32, 2461–2478. https://doi.org/10.1016/j.renene.2006.12.014

Frederiksen, S., Werner, S., 2013. District heating and cooling. Studentlitteratur Lund.

Gaba, E., 2008. Topographic Map of Scotland [WWW Document]. Wikipedia. URL https://en.wikipedia.org/w/index.php?title=Scotland&oldid=904346427 (accessed 7.2.19).

Gosling, N., 2019. Energy Strategy for the Queens Quay Regneration Project.

Horak, M., 2019. Stärkste Großwärmepumpe Mitteleuropas pumpt in Wien - Neue Herzschlagader für die Wiener Fernwärme geht ans Netz. Wien Energie Blog. URL https://blog.wienenergie.at/2019/03/06/staerkste-grosswaermepumpe-mitteleuropas-pumpt-in-wien/ (accessed 5.11.19).

IEA, 2018. World Energy Outlook 2018. International Energy Agency.

International Energy Agency, 2015. ANERGY NETWORK AT CAMPUS ETH HÖNGGERBERG (ZURICH) - SWITZERLAND.

Iona Renewables, 2019. What we do [WWW Document]. Iona Renewables. URL https://www.ionarenewables.org/roadmap (accessed 7.15.19).

IPCC, 2014. Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Kelly, N., 2018. Electrical Power Systems.

Klima- und Energiefonds, 2017. Factsheet Ölheizung.

Kost, C., Shammugam, S., Jülich, V., Nguyen, H.-T., Schlegl, T., 2018. Levelized cost of electricity: Renewable energy technologies. Fraunhofer Institute for Solar Energy Systems ISE.

Li, H., Svendsen, S., Gudmundsson, O., Kuosa, M., Rämä, M., Sipilä, K., Blesl, M., Broydo, M., Stehle, M., Pesch, R., 2017. Future low temperature district heating design guidebook: Final Report of IEA DHC Annex TS1. Low Temperature District Heating for Future Energy Systems.

Local Energy Scotland, 2019. What is Local Energy? - Local Energy Scotland [WWW Document]. URL https://www.localenergy.scot/what-is-local-energy/ (accessed 6.25.19).

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., Mathiesen, B.V., 2014. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy 68, 1–11. https://doi.org/10.1016/j.energy.2014.02.089

Marczinkowski, H.M., Østergaard, P.A., 2019. Evaluation of electricity storage versus thermal storage as part of two different energy planning approaches for the islands Samsø and Orkney. Energy 175, 505–514. https://doi.org/10.1016/j.energy.2019.03.103

Met Office, 2019. South Uist Range UK climate averages [WWW Document]. Met Office. URL https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gf4wr9twt (accessed 8.1.19).

Meteoblue AG, 2019. Climate (modelled) Castlebay - meteoblue [WWW Document]. URL https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/castlebay_united-kingdom_2653609 (accessed 7.11.19).

Murty, P.S.R., 2017. Chapter 1 - Introduction, in: Murty, P.S.R. (Ed.), Electrical Power Systems. Butterworth-Heinemann, Boston, pp. 1–3. https://doi.org/10.1016/B978-0-08-101124-9.00001-2

npower, 2014. West Whitlawburn Housing | Energy saving schemes | npower [WWW Document]. URL https://www.npower.com/energy-efficiency/home-energy-saving-schemes/our-partners/wwhc/ (accessed 6.24.19).

Ofgem, 2018. Non-domestic RHI guidance volume 2: Ongoing Obligations and Payments [WWW Document]. Ofgem. URL https://www.ofgem.gov.uk/publications-and-updates/non-domestic-rhi-main-guidance (accessed 7.27.19).

OFGEM, 2016. Ofgem’s Future Insights paper 2 -The decarbonisation of heat.

Ommen, T., Thorsen, J.E., Markussen, W.B., Elmegaard, B., 2017. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. Energy 137, 544–555. https://doi.org/10.1016/j.energy.2017.05.165

Options Group of Companies, 2015. Options Group of Companies: Federation of Community Power Co-operatives Celebrate Earth Day and Promote Renewable Energy Co-ops. Options Group of Companies. URL http://optionsgroupofcompanies.blogspot.com/2015/04/federation-of-community-power-co.html (accessed 6.25.19).

Østergaard, P.A., Jantzen, J., Marczinkowski, H.M., Kristensen, M., 2019. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renewable Energy 139, 904–914. https://doi.org/10.1016/j.renene.2019.02.140

Pearson, D., Stajic, Z., 2015. Star Emerson - District sized heatpumps, experiences from Drammen.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and earth system sciences discussions 4, 439–473.

Pfemeter, C., 2016. Bioenergy in Austria.

Rasmussen Jens, 2012. Scottish Coastal Observatory - Loch Maddy Site: LTM Loch Maddy. https://doi.org/10.7489/951-1

Renewables.ninja, 2019. Renewables.ninja [WWW Document]. URL https://www.renewables.ninja/ (accessed 8.5.19).

Rybach, L., 2001. Design and performance of borehole heat exchanger/heat pump systems. Proc. European Summer School of Geothermal Energy Applications, Oradea/Romania (CD-ROM).

Ryden, Dawn Developments, 2019. Home - Queens Quay, Clydebank [WWW Document]. Queens Quay. URL https://www.queens-quay.co.uk/ (accessed 7.15.19).

Salpakari, J., Mikkola, J., Lund, P.D., 2016. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. Energy Conversion and Management 126, 649–661. https://doi.org/10.1016/j.enconman.2016.08.041

Schmidt, D., 2018. Low Temperature District Heating for Future Energy Systems. Energy Procedia 149, 595–604. https://doi.org/10.1016/j.egypro.2018.08.224

Schramek, E.-R., Recknagel, H., 2013. Taschenbuch für Heizung+ Klimatechnik. Oldenbourg Industrieverlag, München.

Scottish Government, 2019. Energy efficiency: Energy Efficient Scotland - gov.scot [WWW Document]. URL https://www.gov.scot/policies/energy-efficiency/energy-efficient-scotland/ (accessed 8.6.19).

Scottish Government, 2018a. Energy in Scotland.

Scottish Government, 2018b. Climate Change Plan: third report on proposals and policies 2018-2032 (RPP3).

Scottish Government, 2018c. Scotland Heat Mapping [WWW Document]. URL http://heatmap.scotland.gov.uk/ (accessed 7.11.19).

Scottish Government, 2017. The future of energy in Scotland: Scottish energy strategy.

Scottish Government, 2011. Scotland's Marine Atlas: Information for The National Marine Plan [WWW Document]. URL http://www2.gov.scot/Publications/2011/03/16182005/26 (accessed 5.23.19).

Smart Renewable Heat, 2019. Ground source heat pump borehole cost. Smart Renewable Heat. URL https://smartrenewableheat.com/blog/ground-source-heat-pump-borehole-cost/ (accessed 8.1.19).

Smeed, M., Fodiak, J., Snodin, H., 2014. Scottish Islands Renewable Project Grid Access Study.

Spitler, J.D., Mitchell, M.S., 2016. 8 - Surface water heat pump systems, in: Rees, S.J. (Ed.), Advances in Ground-Source Heat Pump Systems. Woodhead Publishing, pp. 225–246. https://doi.org/10.1016/B978-0-08-100311-4.00008-X

SSE Utilities, 2015. Wyndford Estate. SSE Utilities. URL https://www.sseutilitysolutions.co.uk/insights/case-studies/wyndford-estate/ (accessed 6.24.19).

SSEN, 2019. SSEN statement on Western Isles and Shetland Needs Case consultations [WWW Document]. URL https://sse.com/newsandviews/allarticles/2019/03/ssen-statement-on-western-isles-and-shetland-needs-case-consultations/ (accessed 6.29.19).

Star Renewable Energy, 2019. neatpump.com | Latest News | Heatpump Design Renewable Energy Glasgow UK | Water Source Heatpumps | UK Heatpumps |

Green Energy | Renewable Resources | Alternative Energy | Energy Future | Energy Information | River Source Heat Pump [WWW Document]. URL http://www.neatpumps.com/news/star-renewable-energy-to-showcase-queens-quay.aspx (accessed 7.15.19).

Stetz, T., Marten, F., Braun, M., 2013. Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany. IEEE Transactions on Sustainable Energy 4, 534–542. https://doi.org/10.1109/TSTE.2012.2198925

Tomorrow, 2019. electritcityMap: Live CO2 emissions of electricity consumption [WWW Document]. URL http://electricitymap.tmrow.co (accessed 5.27.19).

Trecco Ltd, 2019. District Heating Networks [WWW Document]. Treco Ltd. URL https://www.treco.co.uk/district-heating (accessed 7.10.19).

Trnka, G., 2018. Heizkostenvergleich - Heating Cost Comparison [WWW Document]. Österreichische Energieagentur – Austrian Energy Agency. URL https://www.energyagency.at/fakten-service/heizkosten/thermisch-saniertes-gebaeude.html (accessed 6.4.19).

UK Government, 2019. Fuel poverty statistics [WWW Document]. GOV.UK. URL https://www.gov.uk/government/collections/fuel-poverty-statistics (accessed 7.18.19).

UK Government, 2018. Energy Trends: renewables [WWW Document]. GOV.UK. URL https://www.gov.uk/government/statistics/energy-trends-section-6-renewables (accessed 6.4.19).

UK Government, 2015. Community Energy [WWW Document]. GOV.UK. URL https://www.gov.uk/guidance/community-energy (accessed 6.25.19).

United Nations, 2018. Sustainable Development Goals: Goal 7 Energy [WWW Document]. United Nations Sustainable Development. URL https://www.un.org/sustainabledevelopment/energy/ (accessed 11.3.18).

Voluntary Action Barra & Vatersay, Coimhearsnachd Bharraidh agus Bhatarsaidh, Castlebay & Vatersay Community Council, Northbay Community Council, Hebridean Housing Partnership, Barratlantic Ltd, Comhairle nan Eilean Siar, Local Energy Scotland, Home Energy Scotland, Community Energy Scotlan, Wood Environment & Infrastructure Solutions UK Limited, 2018. Local Energy Plan for Barra and Vatersay.

Wang, Z., 2018. Heat pumps with district heating for the UK's domestic heating: individual versus district level. Energy Procedia 149, 354–362. https://doi.org/10.1016/j.egypro.2018.08.199

Warners Group Publications, 2014. An affjordable district heating system in Norway [WWW Document]. Heat Pumps Today. URL http://www.heatpumps.media/2/post/2014/03/an-affjordable-district-heating-system-in-norway.html (accessed 7.15.19).

Werner, S., 2017. International review of district heating and cooling. Energy 137, 617–631. https://doi.org/10.1016/j.energy.2017.04.045

West Coast Energy Ltd, 2006. Barra and Vatersay On-Shore Wind Energy Feasibility Study.

Wiltshire, R., 2015. Advanced district heating and cooling (DHC) systems. Woodhead Publishing.

Wiltshire, R., Williams, J., Woods, P., 2014. A technical guide to district heating. Building research establishment.

World Nuclear News, 2016. Small reactors for heat and power in Russia - World Nuclear News [WWW Document]. URL http://www.world-nuclear-news.org/NN-Small-reactors-for-heat-and-power-in-Russia-1212161.html (accessed 7.1.19).

Zervos, A., 2018. Renewables 2018 Global Status Report. REN21.

Zottl, A., Nordman, R., Miara, M., 2012. Benchmarking method of seasonal performance. The IEE project SEPEMO-Build.

Appendices

A. Climate Data Barra

B. Thermal Loads Castlebay and Load Duration Curve

C. Subsidies: Renewable Heat Incentive (RHI)

D. Cost Estimation Future Heating

E. District Heating Grid Layout

F. District Heating Simulation

G. Wind Energy Integration

A. Climate Data Barra

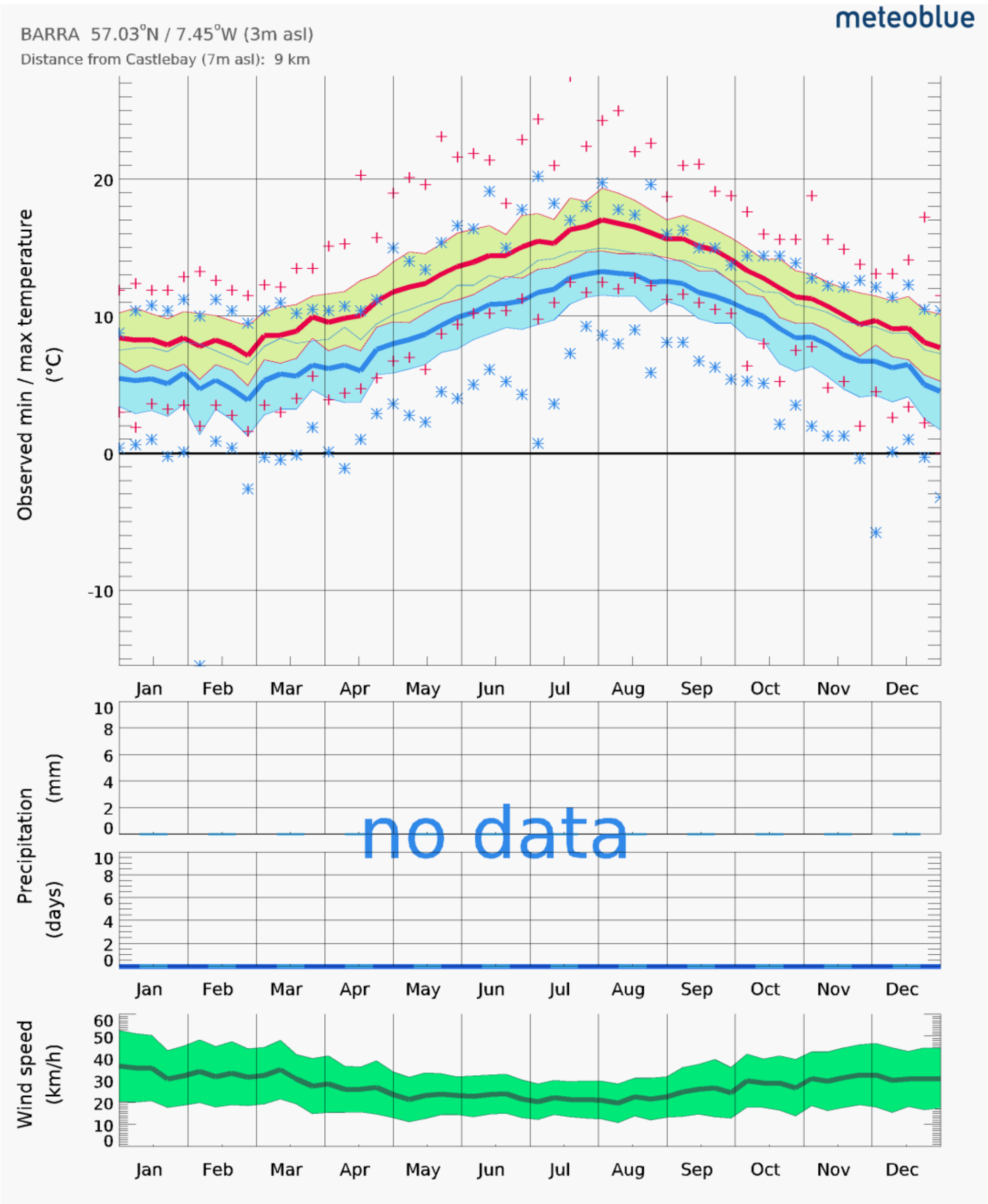

Figure 41 Observed Climate Data Castlebay (Meteoblue AG, 2019)

B. Thermal Loads Castlebay and Load Duration Curve

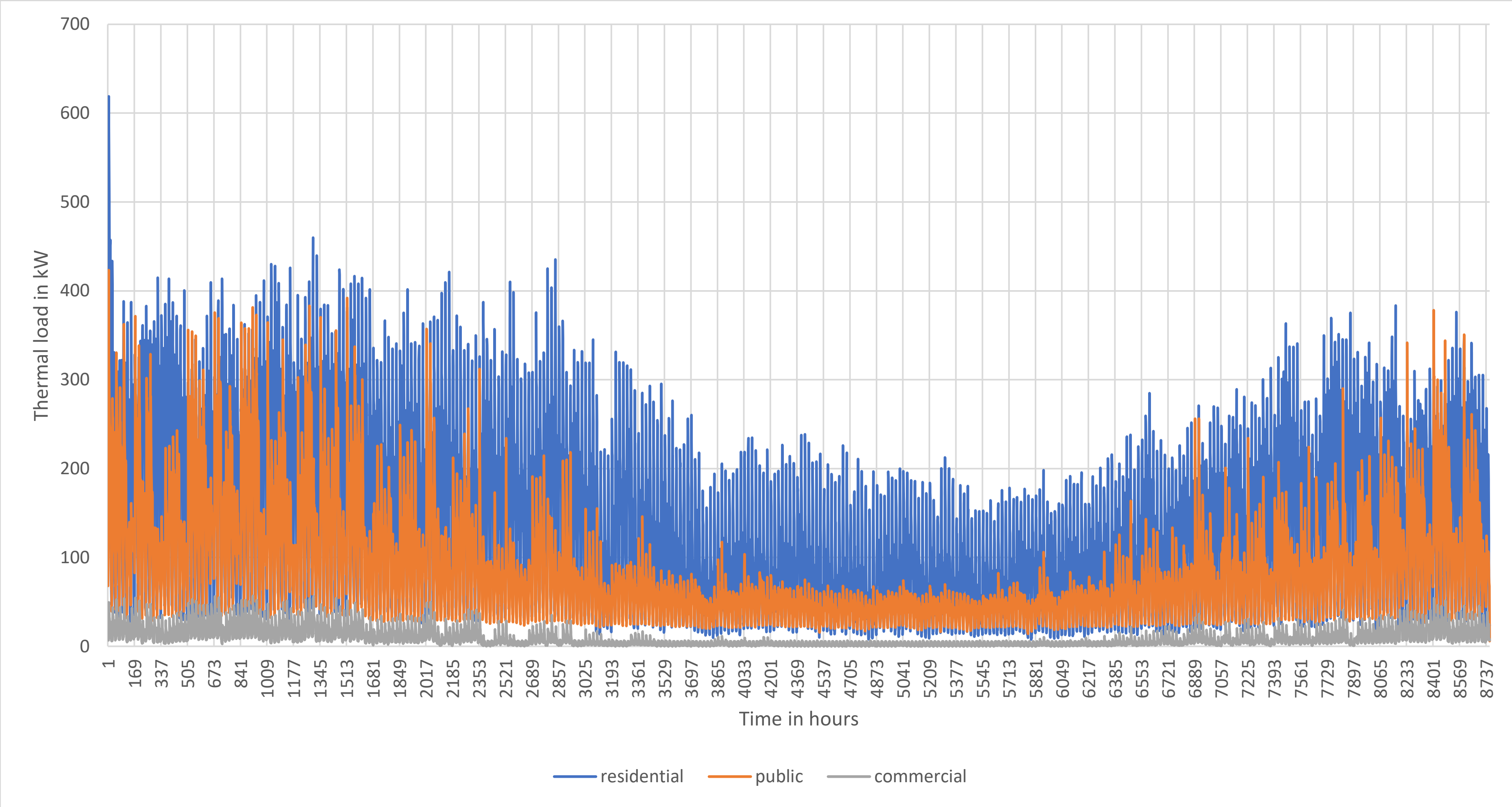

Figure 42 Thermal Loads Overview Castlebay by Sector

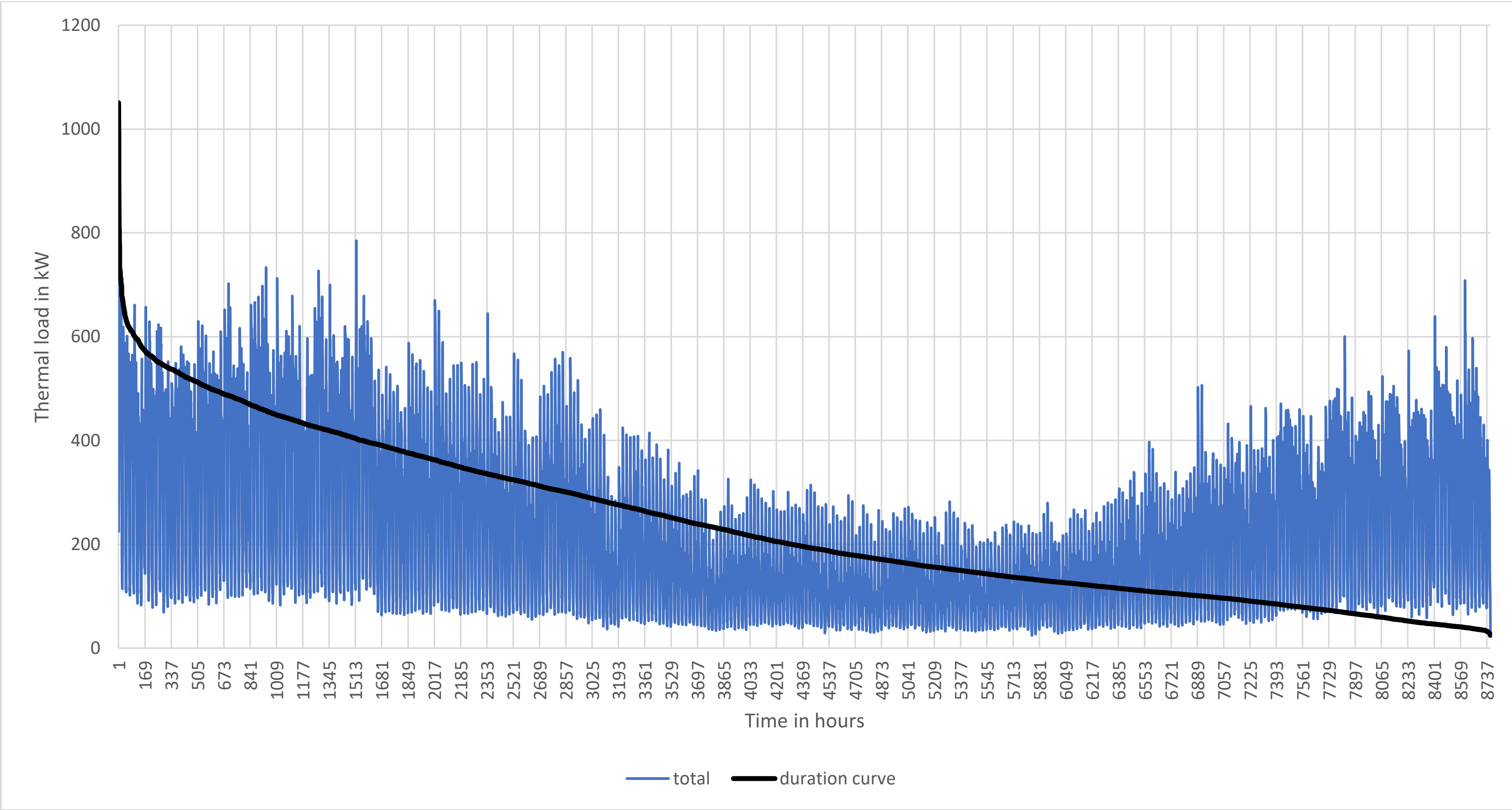

Figure 43 Total Thermal Loads Castlebay and Duration Curve

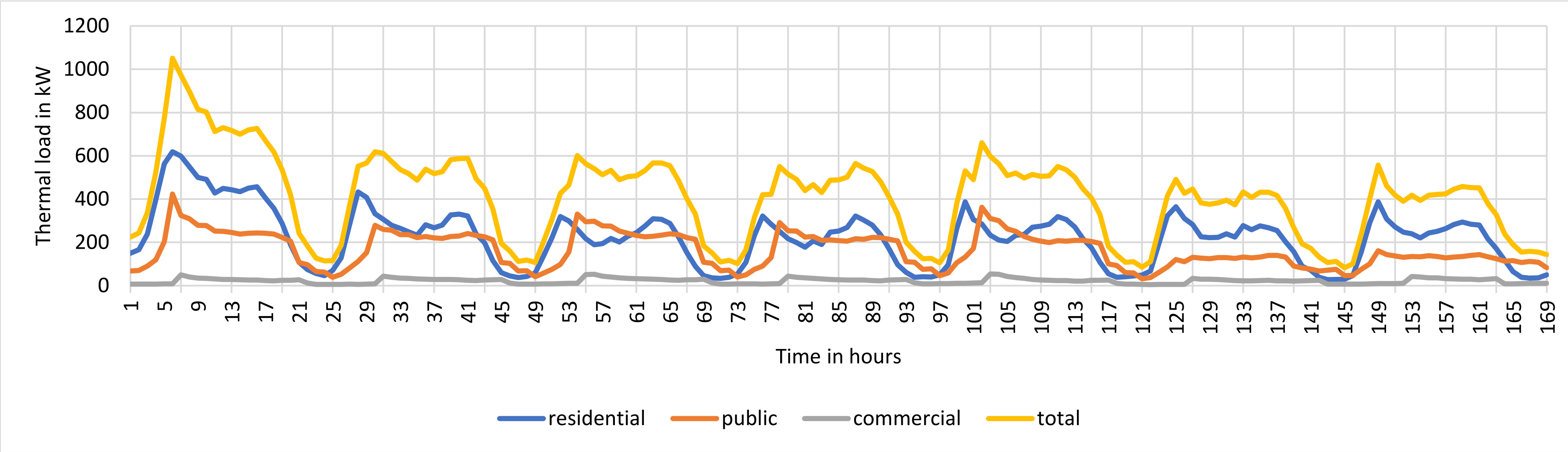

Figure 44 Thermal Loads Castlebay Winter (1/1-7/7)

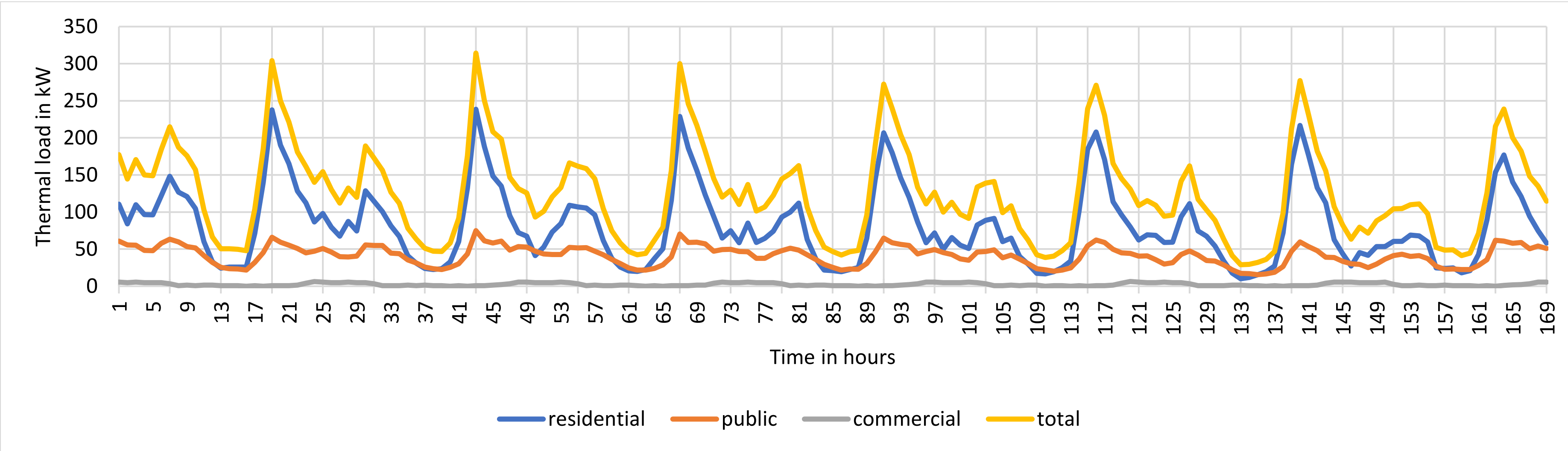

Figure 45 Thermal Loads Castlebay Summer (21/6-28/6)

C. Subsidies: Renewable Heat Incentive (RHI)

Table 12 Domestic RHI Tariffs 2019. Available at: https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-domestic-rhi/current-future-tariffs

Applications submitted	Biomass boilers and stoves (p/kWh)	Air source heat pumps (p/kWh)	Ground source heat pumps (p/kWh)	Solar thermal (p/kWh)
01/01/2019 - 31/03/2019	6.74p	10.49p	20.46p	20.66p
01/04/2019 - 30/06/2019*	6.88p	10.71p	20.89p	21.09p
01/07/2019 - 30/09/2019	6.88p	10.71p	20.89p	21.09p
01/10/2019 - 30/12/2019	If any new tariff changes are to be made due to degression, the announcement by BEIS would be made by 1 August 2019.			

Table 13 Non-Domestic RHI Tariffs. Available at: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi

Eligible Technology	Eligible Sizes	Accreditation date	Tariff Rate 2019/20 (p/kWh)	Tier	Adjusted by:
Small water/ground-source heat pumps	Less than 100Kwth	before 21 January 2013	5.53		RPI
Large water/ground-source heat pumps	100kWth and above	before 21 January 2013	4.06		
Water/ground-source heat pumps	All capacities	between 21 January 2013 and 31 March 2016	9.81	Tier 1	
			2.93	Tier 2	
		on or after 1 April 2016	9.56	Tier 1	CPI
			2.85	Tier 2	
Air source heat pumps	All capacities	before 1 April 2016	2.81		RPI
		on or after 1 April 2016	2.75		CPI

Ofgem states in their Non-domestic RHI guidance (Ofgem, 2018):

The scheme includes small businesses, hospitals and schools as well as district heating schemes where one installation serves multiple homes.

Tiered payment: For small and medium biomass installations with a date of accreditation before 20 September 2017 and ground or water source heat pumps the first 1,314 hours (15% of a year) will be payable at the higher Tier 1 tariff.

This tariff structure operates on a 12 month basis, starting with the date of accreditation or its anniversary. The regulations specify that during that 12 month period, an initial amount of heat generated by the installation up to the equivalent of 1,314 hours (15% of a year)or 3.066 hours (35% of a year)of an installation's installed heating capacity will be payable at the (higher) Tier 1 tariff; dependent on the date of accreditation and technology type. Any further heat generated during that 12 month period will be payable at the (lower) Tier 2 tariff. At the start of the next 12 month period, the initial amount of heat will again be payable at the higher Tier 1 tariff. We consider the 'initial heat' threshold to be crossed when the EHO exceeds the tier threshold

D. Cost Estimation Future Heating

Table 14 Cost Estimation of Upgrading Heating to Individual ASHP Systems

Residential	Name	Position	Name	Count	Cost per Unit	Total
	Residential Property	1	Air Source Heat Pump 10kW	1	£ 8,806.00	£ 8,806.00
		2	DHW Store 200l	1	£ 500.00	£ 500.00
		3	Radiators LT	6	£ 759.00	£ 4,554.00
		4	Plumbing Installation	20	£ 30.00	£ 600.00
		5	Electrical Installation	5	£ 30.00	£ 150.00
		6	Installation Material	1	£ 1,000.00	£ 1,000.00
					Sum	£ 15,610.00
			Number of properties	83.3	Total	£ 1,300,313.00
Public&Commercial Small	**Name**			**Energy demand in MWh/y**	**Scale factor***	**Total**
	Heritage Centre			16.2	£ 1.08	£ 16,858.80
	Fire Brigade			24.1	£ 1.61	£ 25,080.07
	Dunard Hostel			30	£ 2.67	£ 41,626.67
	Children centre/Café			35.8	£ 2.39	£ 37,255.87
	Barra and Vatersay Community Office			6.7	£ 0.45	£ 6,972.47
				112.8	Total	£ 127,793.87
Public and Commercial Big	**Name**	**Position**	**Name**	**Count**	**Cost per Unit**	**Total**
	Community Hub	1	Air Source Heat Pump 400kW	400	£ 600.00	£ 240,000.00
	7063m²	2	DHW Store 2000l	1	£ 4,000.00	£ 4,000.00
		3	Underfloor Heating 7000m²	7063	£ 10.00	£ 70,630.00
		4	Plumbing Installation	480	£ 30.00	£ 14,400.00
		5	Electrical Installation	40	£ 30.00	£ 1,200.00
		6	Installation Material	1		£ -
					Sum	£ 330,230.00
	Converted Housing Hospital	1	Air Source Heat Pump 200kW	200	£ 600.00	£ 120,000.00
	2400m²	2	DHW Store 2000l	1	£ 2,000.00	£ 2,000.00
		3	Underfloor Heating 2400m²	2400	£ 10.00	£ 24,000.00
		4	Plumbing Installation	240	£ 30.00	£ 7,200.00
		5	Electrical Installation	30	£ 30.00	£ 900.00
		6	Installation Material	1	£ 12,000.00	£ 12,000.00
					Sum	£ 166,100.00
					Total	**£ 1,924,436.87**

Table 15 Cost Estimation of Upgrading Heating to District Heating System

District Heating Cost Estimation						
Building connection and upgrade						
Residential	**Name**	**Position**	**Name**	**Count**	**Cost per Unit**	**Total**
	Residential Property	1	Heat Interface Unit 35kW incl. meter and pump	1	£ 2,000.00	£ 2,000.00
		2	District Heating Hookup	1	£ 2,500.00	£ 2,500.00
		3	Radiators 1500W LT	6	£ 759.00	£ 4,554.00
		4	Plumbing Installation	20	£ 30.00	£ 600.00
		5	Electrical Installation	5	£ 30.00	£ 150.00
		6	Installation Material	1	£ 1,000.00	£ 1,000.00
					Sum	£ 10,804.00
			Number of properties connected	83.3	Total	£ 899,973.20
Public and Commercial Small	**Name**			**Energy demand in MWh/y**	**Scale factor***	**Total**
	Heritage Centre			16.2	£ 1.08	£ 11,668.32
	Fire Brigade			24.1	£ 1.61	£ 17,358.43
	Dunard Hostel			30	£ 2.67	£ 28,810.67
	Children centre/Café			35.8	£ 2.39	£ 25,785.55
	Barra and Vatersay Community Office			6.7	£ 0.45	£ 4,825.79
				112.8	Total	£ 88,448.75
Public and Commercial Big	**Name**	**Position**	**Name**	**Count**	**Cost per Unit**	**Total**
	Community Hub	1	Heat Interface Unit 400kW incl. meter and pump	1	£ 20,000.00	£ 20,000.00
	7063m²	2	DHW Store 2000l	1	£ 4,000.00	£ 4,000.00
		3	Booster HP DHW	1	£ 2,000.00	£ 2,000.00
		4	Underfloor Heating 7000m²	7063	£ 10.00	£ 70,630.00
		5	Plumbing Installation	360	£ 30.00	£ 10,800.00
		6	Electrical Installation	20	£ 30.00	£ 600.00
		7	Installation Material	1	£ 10,000.00	£ 10,000.00
					Sum	£ 118,030.00
	Converted Housing Hospital	1	Heat Interface Unit 200kW incl. meter and pump	1	£ 15,000.00	£ 15,000.00
	2400m²	2	DHW Store 2000l	1	£ 2,000.00	£ 2,000.00
		3	Underfloor Heating 2400m²	2400	£ 10.00	£ 24,000.00
		4	Plumbing Installation	240	£ 30.00	£ 7,200.00
		5	Electrical Installation	30	£ 30.00	£ 900.00
		6	Installation Material	1	£ 5,000.00	£ 5,000.00
					Sum	£ 54,100.00
					Total	£ 172,130.00

District Heating System	Name	Position	Name	Count	Cost per Unit	Total
	Energy Centre	1	Seawater Pump	1	£ 5,000.00	£ 5,000.00
		2	Seawater Pipe DN160 Stainless Steel incl civil works per m	203	£ 300.00	£ 60,900.00
		3	Seawater Inlet	1	£ 10,000.00	£ 10,000.00
		4	Seawater HX	1	£ 7,500.00	£ 7,500.00
		5	Water Source Heat Pump 400kW	400	£ 600.00	£ 240,000.00
		6	Electric Heaters	100	£ 80.00	£ 8,000.00
		7	Backup oil boiler	600	£ 200.00	£ 120,000.00
		8	Thermal Store 70m³	1	£ 40,000.00	£ 40,000.00
		9	Network Pumps	2	£ 4,000.00	£ 8,000.00
		10	Plumbing Installation	480	£ 30.00	£ 14,400.00
		11	Electrical Installation	160	£ 30.00	£ 4,800.00
		12	Installation Material	1		£ 36,800.00
		13	Building Cost per m²	250	£ 500.00	£ 125,000.00
					Sum	£ 680,400.00
	Network	**Position**	**Name**	**Count**	**Cost per Unit**	**Total**
		1	Main to circle Single DN160	150	£ 619.00	£ 92,850.00
		2	Main circle 1 Single DN90	670	£ 462.00	£ 309,540.00
		3	Main circle 2 Single DN90	670	£ 462.00	£ 309,540.00
		4	Secondary Pipe 15 dwellings avg Twin DN63	785	£ 377.00	£ 295,945.00
		5	Tertiary Pipe House Hookup 2 dwellings avg Twin DN32	1445	£ 232.00	£ 335,240.00
					Sum	£ 1,343,115.00
					Total	£ 2,023,515.00
				Investment cost for whole DH system		£ 3,302,096.95

E. District Heating Grid Layout

Figure 46 Proposed District Heating Grid with Future Energy Demands, Peak Loads and Pipe Dimensioning.

F. District Heating Simulation

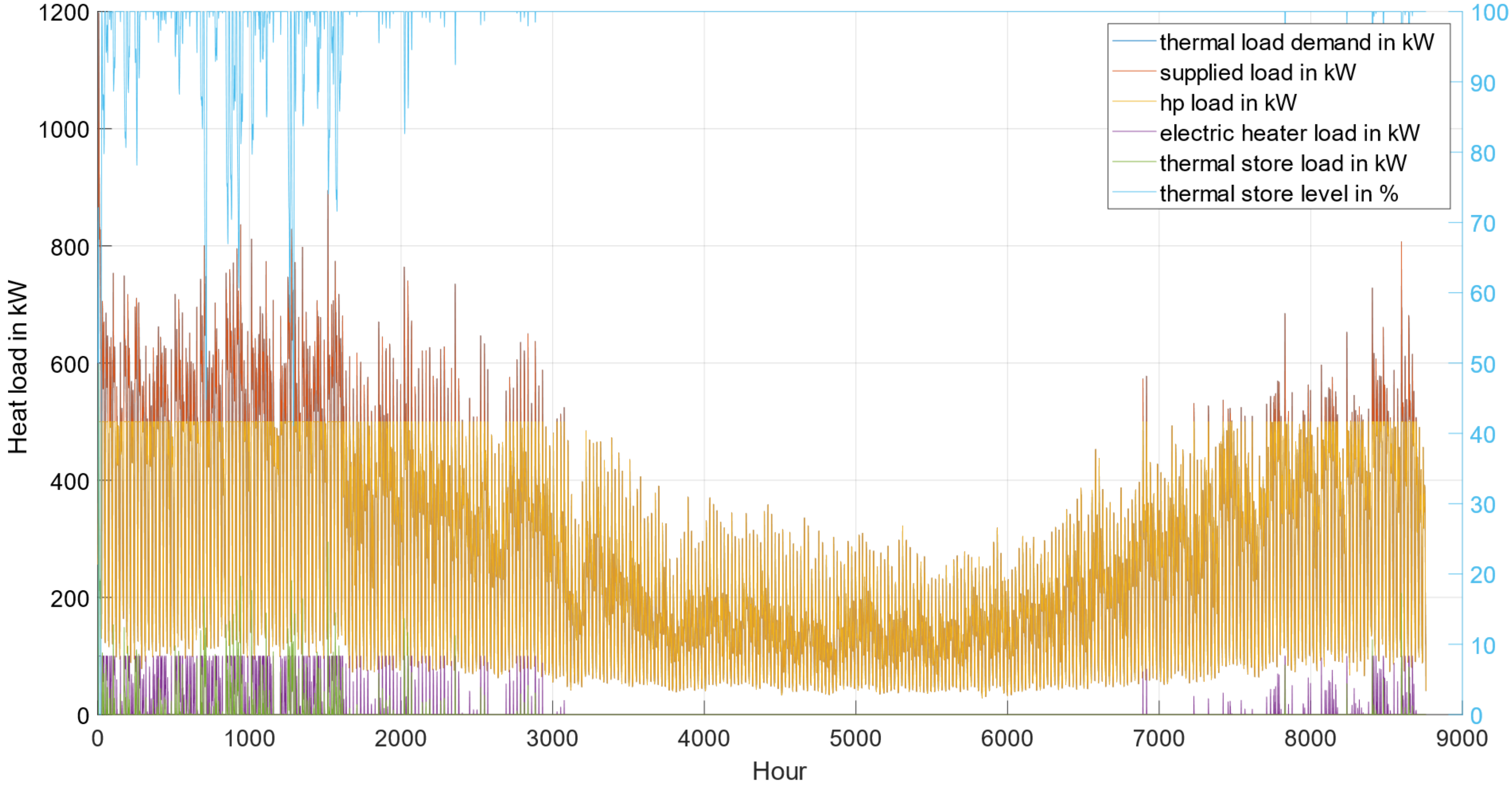

Figure 47 District Heating Simulation Model Results. Thermal Load and Heat Generation for a Whole Year.

G. Wind Energy Integration

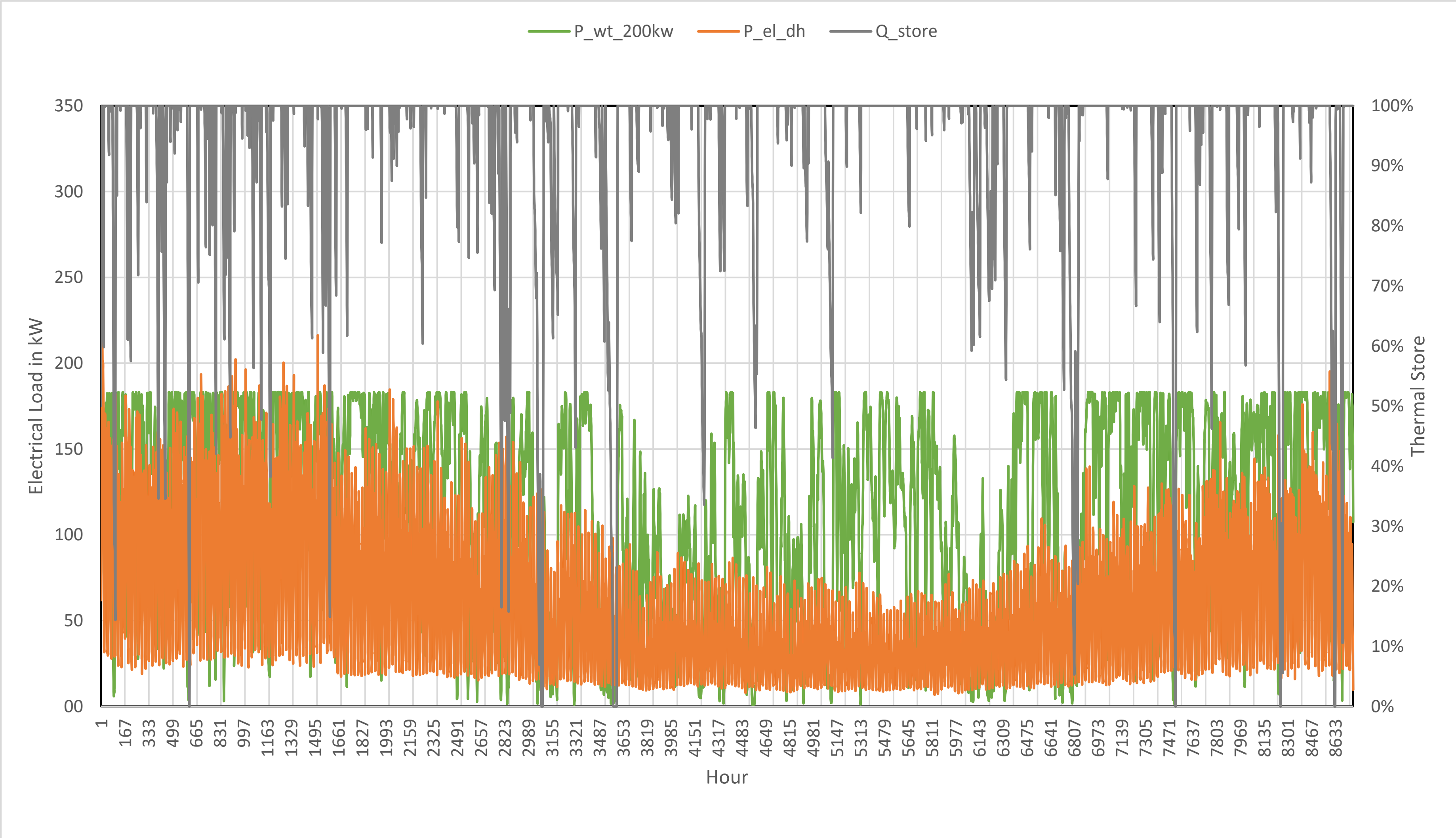

Figure 48 Wind Energy Integration Simulation Model Results. 200kW Wind Turbine Output, Electrical Power Demand District Heating including 5% of HP Power for Auxiliary and 70m³ Thermal Store Level