Department of Mechanical and Aerospace Engineering

Assessing the feasibility of a district heating scheme for Bowmore, Islay.

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Abstract

Heating is responsible for 50% of our carbon emissions. One means of reducing this is through district heating networks. District heating networks apply the economies of scale to heating, making sources of heat not viable for individual properties viable on the community scale.

District heating is not prevalent or well understood by Scottish markets. This report aims to address this deficit in knowledge in two ways: Firstly by conducting a feasibility study of a potential district heating scheme for Bowmore, Islay applying the guidelines set out by CIBSE in ‘Heat networks: code of practise for the UK’. Secondly this report will offer a critique of these guidelines, aiding future feasibility studies.

The feasibility study is conducted by means of site visits, consultation with potential stakeholders, the use of GIS mapping software, computer modelling of Bowmore’s thermal load and use of the governing literature and professional publications. The critique of the CIBSE guide is conducted *a posteriori*, in reflection of the lessons learnt whilst applying its guidelines.

The report estimates the heating load of Bowmore, offers a financial summary of meeting this load with a Biomass burning boiler and identifies several sources of other low carbon heat to be investigated further. The relevant technical, economic, social and environmental design factors are considered to give a thorough assessment of the schemes feasibility.

In accordance with its aims this report has two implications to the wider field. The findings can be used by the proponent -Argyle and Bute council- as a pre-feasibility study of the proposed scheme. The findings can also be used to advise the study of similar schemes offering a deeper understanding of the CIBSE guidelines.

Acknowledgements

I would like to thank the following people for their help and advice with this thesis;

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Without their help this thesis could not have been as valuable a learning experience as it has been. Thank you to the others for their moral support and assistance.

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Nomenclature

Q - Heat measured in watts

$\dot{m}$ - Mass flow rate

c_p - Specific heat capacity of water, kilojoule per kilogram per kelvin

ΔT - Temperature difference

U - Heat transfer coefficient

T_{ml} - log-mean temperature difference

CO^2 – Carbon dioxide

ΔP_c - Localised pressure loss

ΔP_d - Distributed pressure loss

FC- factor of confidence

QDHW - heating water flow rate required to meet peak domestic hot water demand

QHTG - heating water flow rate required to meet peak heating demand

T_γ - Design temperature drop

ΔT_β - Temperature drop across heat exchangers

DFR - design flow rate for downs stream hot water outlets

MFR - maximum possible flow rate for downstream hot water outlets

K- Kelvin

DH- District heating

W- Watt

W/K- Watt per kelvin

kW - Kilo watt

kWh - Kilo watt hour

MW- Megawatt

MWh- Megawatt hours

MWh/yr- Megawatt hours per annum

GWhr- Gigawatt hours

GWh/ye- Gigawatt hours per annum

PHD – Peak heat demand

m/s- meters per second

βmin - ratio of minimum load (DHW + district heat losses) to the peak load

βm = average load as fraction of maximum load (utilisation factor)

COP- co-efficient of performance

> “Heating and cooling remain neglected areas of energy policy and technology, but their decarbonisation is a fundamental element of a low-carbon economy.” [1]

1- Introduction

District heating (DH) networks are increasingly being seen as a means to meeting the UK’s climate reduction targets [2]. As with other novel technologies that facilitate the switch from a fossil fuel and nuclear energy system to a sustainable energy based system it is a topical area of research. DH networks are seen as a potential solution to the ‘energy trilemma’ [3].

They offer a means of meeting the following goals:

- To reduce greenhouse gas emissions through the use of a wide range of low carbon and renewable sources
- To improve security of energy supply by diversifying the energy sources for heating and reducing our dependence on fossil fuel imports
- To offer a more cost-effective source of low carbon energy [2]

Scotland currently has an untapped potential for DH with 2% of our heat being supplied in this way. This is far below other European countries. The share of selected EU countries population served by DH is show in Figure 1.

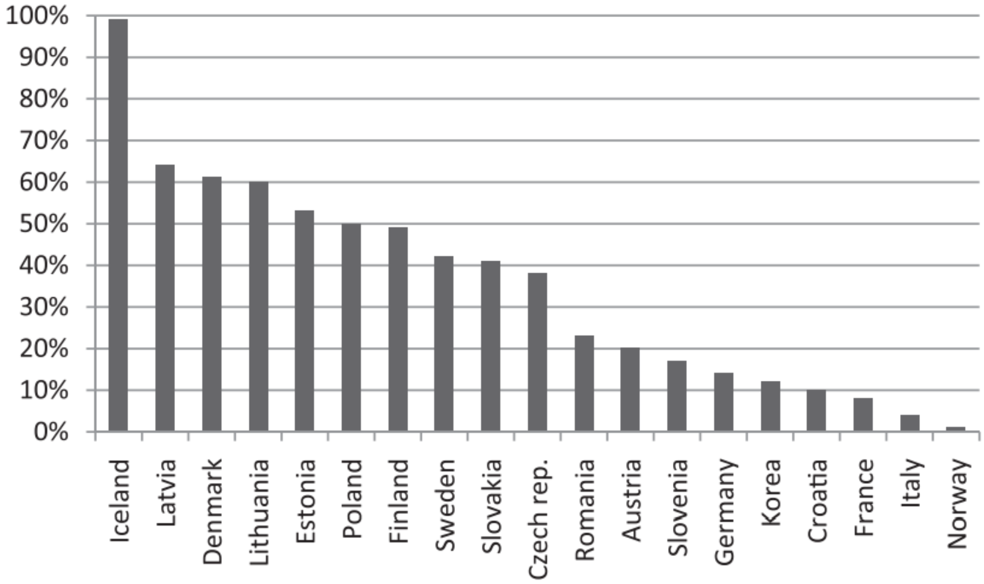


Figure 1- share of selected EU countries population served by DH

This paper aims to address this discrepancy by assessing the feasibility of a DH scheme serving the population of Bowmore on Islay. The project was proposed by Argyle and Bute council and work is undertaken with information provided by the local authority. The work applies the best practise recommendations of the Chartered Institution of Building Services Engineers CIBSE guide [4] to the study area in order to assess the feasibility and allow a critical evaluation of the guide itself.

2- Literature Review

The back bone of this report is a feasibility study done with reference to the most up to date literature. The literature review extends beyond this section, with the technical aspects to literature contained within their relevant sections.

2.1 District heating

District heating is a method of supplying heat to a range of end users from a centralised location as shown in Figure 2. DH provides several key benefits to the wider community it serves.

- Large carbon savings are possible-DH schemes allow incorporation of renewable energy technologies including sustainably sourced biomass or geothermal being used as alternatives to fossil fuels.
- Economies of scale – Heating on a larger scale can be supported for technologies not feasible on individual properties (e.g. biomass / energy from waste)
- Future proof – DH networks have the capacity to change their fuel source for any reason such as economic or ease of supply.
- Minimise maintenance using one central plant – Increases ease of maintenance for example individual gas checks are not required.

DH schemes also offer benefits to the individual end users;

- Reliability- Back up systems and robust design ensure reliable supply of heat. Pulling of community resources can ensure swift maintenance and repair.

- Tenant Comfort- DH works with modern easy to use systems which are often an upgrade from existing aged systems. The result is greater tenant comfort. The systems are silent (compared to regular boilers). [5]
- Tackling fuel poverty- DH schemes should be able to offer cheaper heat at customer level. (https://www.gov.uk/government/news/scotlands-first-prime-ministers-big-society-award-winner-west-whitlawburn-housing-co-operative)
- Aesthetics and Environment-Air emissions are the responsibility of the DH operator and DH connection requires no ventilation or fire protection.

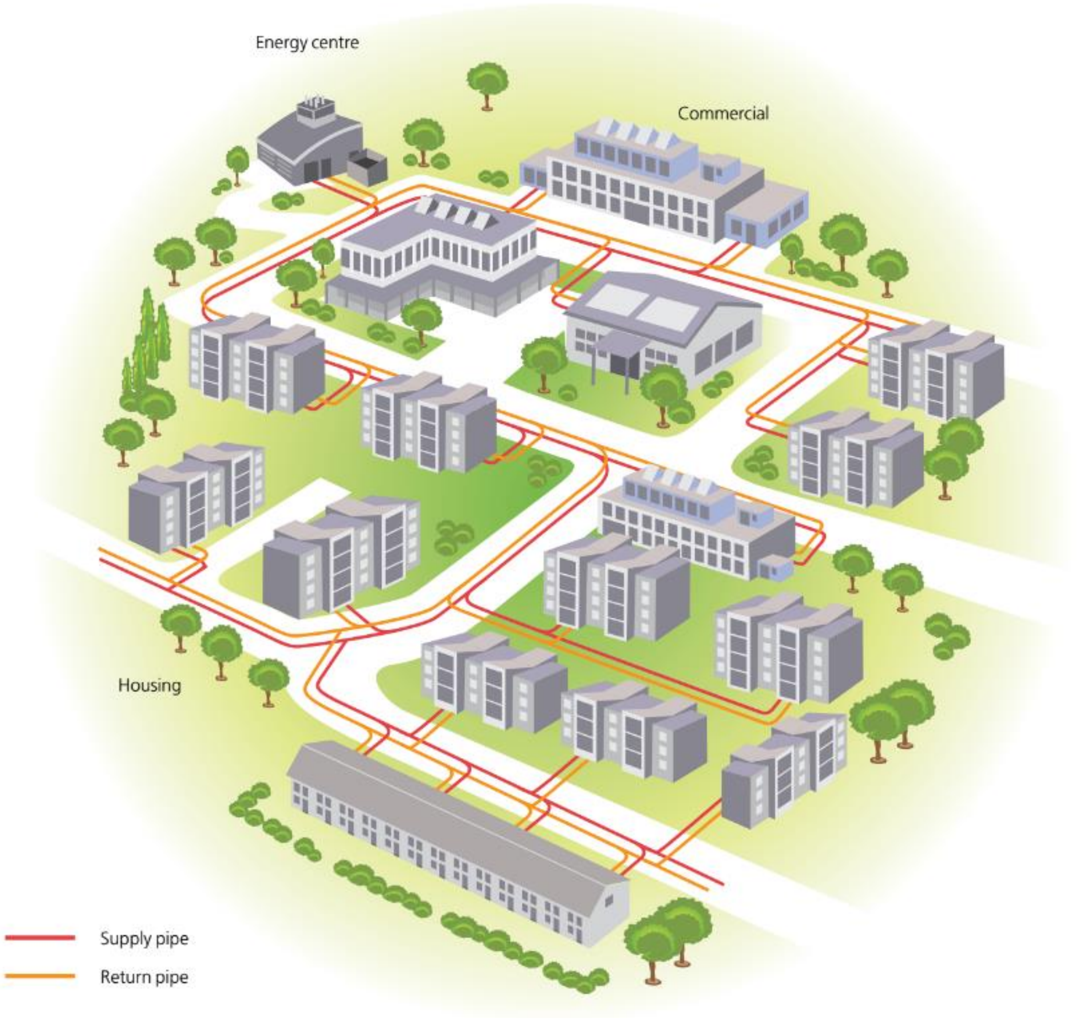


Figure 2- DH network diagram[6]

District heating (DH) is by no means a new concept. The first systems were implemented in 1880 in the USA and the design of these systems remained unchanged until 1930. This first generation used steam as a heat carrying medium passing through concrete ducts, steam traps and compensators with the heat being delivered through steam condensation in radiators [7].

These systems resulted in high heat losses due to the high temperature of the steam and poor insulation of pipes by today's standards. Steam based systems are still used in Manhattan and Paris while the DH in Salzburg, Hamburg and Munich have been recently replaced.

The second generation of DH featured pressurised water with supply temperatures over 100°C. Water was delivered through water pipes in concrete ducts, shell and tube heat exchangers connected to radiators. Systems of his design were prominent in the USSR, however often lacked in quality or robustness but were implemented on ideological grounds.

The third generation of DH is often referred to as "Scandinavian District Heating technology" where a main feature of the technology was the use of pre-fabricated parts during the construction phase. It is in this third generation that the use of alternative, cheaper, fuel types becomes prevalent. The drive for both cheaper fuel and security of supply were a response to the actions of the Organisation of the petroleum exporting countries (OPEC) who rapidly increased the price of the fossil fuels they had monopoly over. The alternative fuels used in these systems were derived from locally available sources. For example in Iceland the availability a geothermal heat has driven much of its development in DH, see Figure 1.

2.2 Fourth generation district heating

This is a concept pioneered largely by the 4DH research centre in Denmark. The fourth generation is composed of five constituent parts [7].

1. The use of low-temperature district heating to meet the heat demands in energy efficient buildings. These buildings can either be the existing housing stalk retrofitted to improve thermal efficiencies or new low energy buildings.
2. Improved distribution network and lower distribution temperatures to minimise distribution losses.
3. Deriving heat from renewable sources, whether recycled low grade waste heat, sustainable biomass, solar thermal or other sources.
4. Implemented as part of smart energy system. Smart energy systems are an integrated network of electricity, gas, fluid and thermal grids.
5. Secure and productive legislative frameworks supported by strategic investments.

The design of a 100% renewable energy system is covered in several studies [8, 9] and is analysed [10]. These systems are typically a balance between dispatch able and non-dispatch able energy sources. Dispatchable power such as biomass, biogas or waste incineration are used to supplement the inherent short terms deficits in energy sources such as wind power or photovoltaics. A fundamental part of 100% renewable energy systems is reducing demand. This is discussed at length [11] as well as discussing the least costly methods of doing so.

A smart energy system is one comprised of DH networks integrated with electricity networks and transport networks [12]. These smart grids aim to form a symbiotic synergy between these different sectors, optimising the use of energy.

Several studies namely the heat map Europe study [13] conclude DH is a technology which should be considered as a means to meet climate reduction targets , however, highlights the need for progress towards lower temperature and demand reduction measures [14]. One postulated solution is for the construction of zero energy buildings. This, however, does not address the existing housing stock which is predicted to form the majority of Europe's housing for the foreseeable future.

There are four main trends running through the development of DH, displayed in Figure 3,

1. Lower distribution temperatures
2. Reducing the materials used for distribution
3. Prefabrication
4. Divergence of fuel types

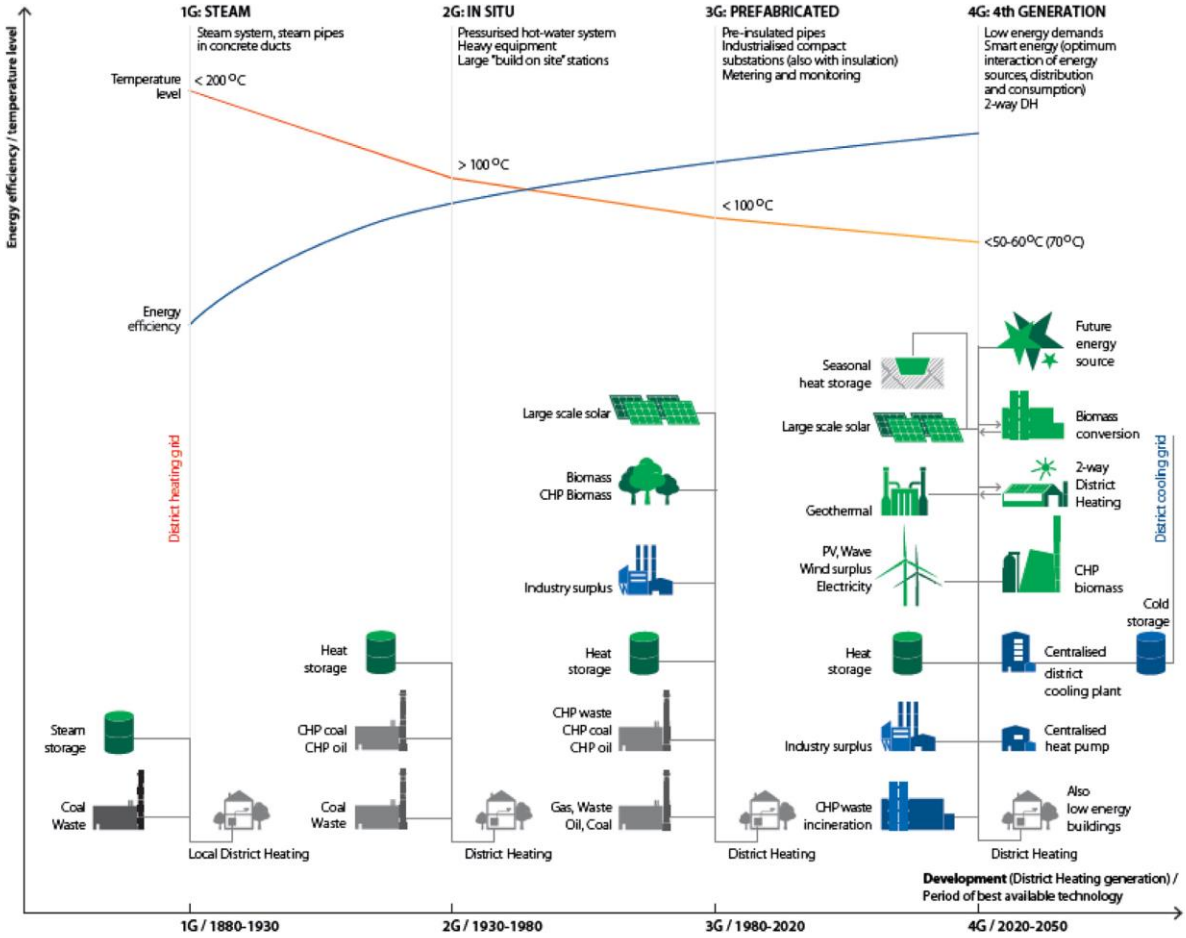


Figure 3- Illustration of trends in district heating [7]

2.3 Barriers to district heating in Scotland

Despite the advantages of DH heating, there exists barriers which have limited its implementation in Scotland. These include a lack of experience and expertise in the relevant technologies on both the supplier side and the potential customer's side, the uncertainty and high installation costs increasing the perceived risk of the project [15] and DH heating schemes having a relatively poor track records in terms of convenience and results. The prospect of poor results stems from incorrect sizing of plants, high system losses, resulting in higher fuel bills.

Other barriers to DH schemes include to difficulties of installation to existing housing stocks. This often requires significant engineering works resulting in disruption to communities for the duration of the work. DH is a technology which has a huge number of social aspects to it. This ultimately results in large admin costs and other issues which result from schemes with large number of stakeholders.

The capital cost required for a district heating network is substantial. In the absence of government grants, this money has to be recovered through the price energy sold. In order to attract investment in the scheme it has to be of sufficient size with a large uptake. This results in the energy supply company (ESCo) forming a monopoly over the energy supply to a community. There is a risk of people disconnecting from the network or using other heating sources resulting from a loss of revenue for the ESCo. Here lies a balance between infringing on consumer rights and offering an attractive investment. [16]

A solid and stable policy environment is critical to all long term renewable projects. With recent political instability, cuts to RHI payments and political moves such as the dismantling of Department of energy and climate change (DECC) it cannot be said that such an environment is present in Scotland at this time.

2.4 CIBSE Heat networks: Code of Practice for the UK

The document Heat networks: Code of Practice for the UK [4] document produced by CIBSE and Association for Decentralised Energy (ADE) .

The document aims to set minimum and best practise standards for developers, providing assurance to shareholders regarding the design installation and commissioning of a project. The code aims to provide quantified and measurable outputs aiding heat networks to operate more efficiently.

“This Code of Practice is therefore written to:

- Improve the quality of feasibility studies, design, construction, commissioning and operation by setting minimum requirements and identifying best practice options.
- Deliver energy efficiency and environmental benefits.
- Provide a good level of customer service.1
- Promote long-lasting heat networks in which customers and investors can have confidence.”[4]

The scope of the document is not limited by the size of the scheme or the type of buildings being used. It does, however, exclude district cooling and energy service requirements where building regulations need to be followed.

The CIBSE guide is structured in stages; feasibility studies, design, construction, commissioning and operation with each one containing a number of objectives. Each objective is composed of a series of minimum requirements which must be met in order to meet the objective. The guide also aims to assist the contractual arrangements by defining the responsibilities of each stakeholder in the scheme.

2.5 Location Specificity

DH is a technology which is largely location specific. The most profitable systems are those which serve high density heat loads such as developed city centres, urban area or high rise flats. Due to transmission losses and the economics of scale low density areas such as small villages are often seen as unsuitable for DH. There are exceptions to this depending on locally available heat or other favourable conditions.

In order to allow identification of areas suitable for DH the Scottish government complied to the Scottish heat map. The Scottish heat map is a GIS tool displaying the density of heat demand down to 50m^2 including domestic usages, offices, hospitals, business and industrial loads [17]. The map can be viewed in Figure 4.

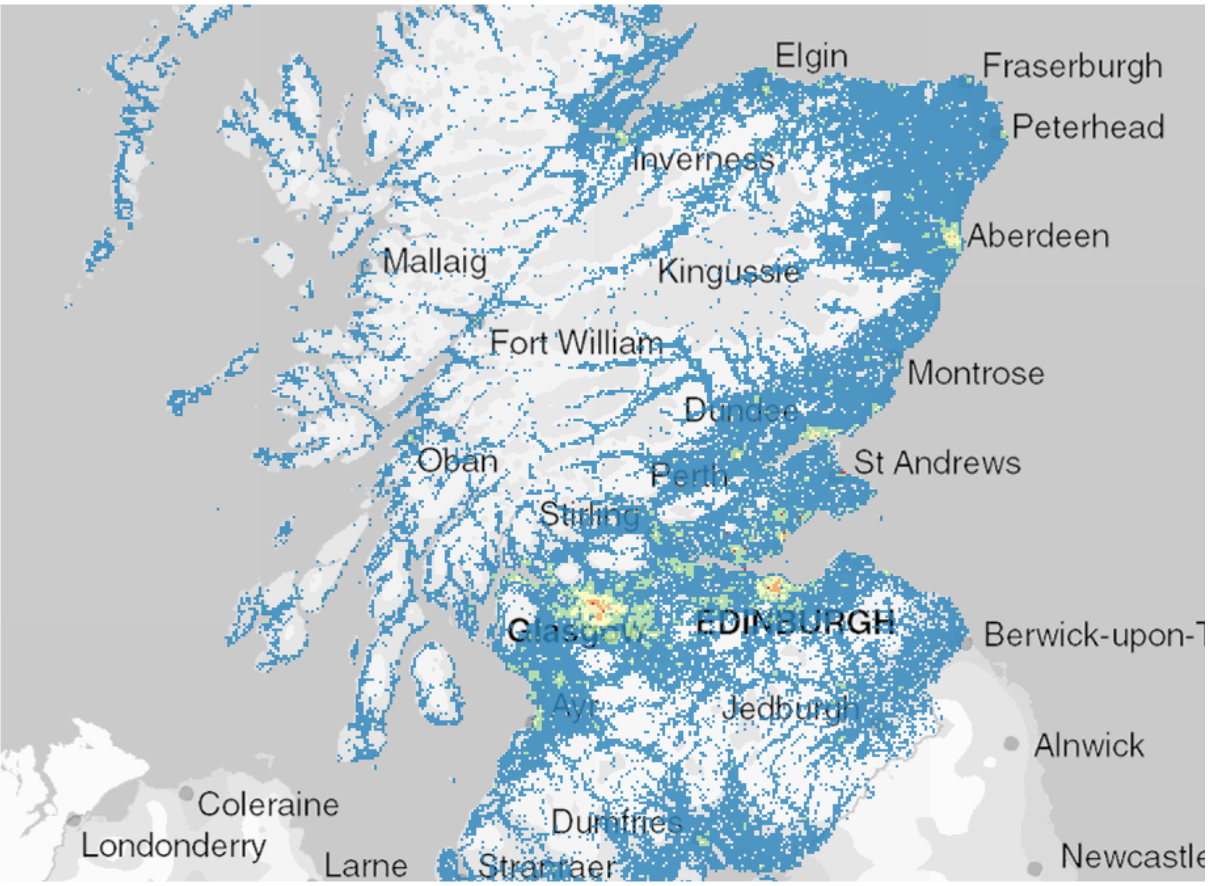


Figure 4-GIS heat map Scotland

In addition to mapping Scotland's heat demand the tool also identifies possible sources of renewable heat. Figure 5 displays the mapping of geothermal reserves. In Scotland this comes from disused coal mines. Drawing heat from abandoned mines is a topic covered here [18-20]. There are no coal mines on Islay. This example is used to illustrate the workings of the Scottish heat map.

These two methods of cross referencing do not address the heat maps accuracy over small scales, with distributed heating loads in rural communities. An aggregate result over a highly populated city centre will be likely to be more accurate than over the small population sized used in this survey.

Each data layer in the map is compiled using data either provided by the building in question or through the use of a proxy.

The heat map has additional layers of data each mapping respectively;

- Heat demand
- Energy supply

- Tenure agreements
- District heating schemes operational and planned

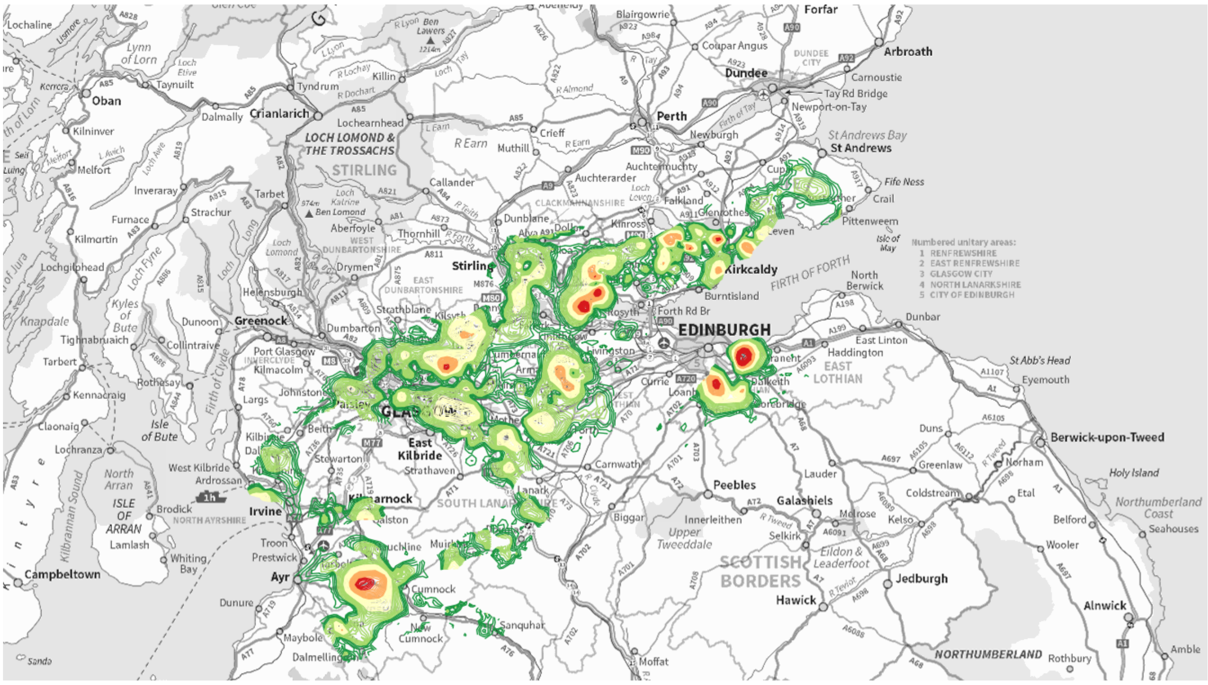


Figure 5-Scottish heat map of geothermal resource

The identification of suitable sites for new district heating schemes is key. The Scottish government commissioned to Scottish heat map to achieve this goal. There are similar initiatives else where such as the Danish buildings register (BBR) which is currently being updated to display the heat demand, creating a heat atlas. This register is soon to contain savings potential, current supply and the cost of retrofitting each building [21]. Beyond the total heat demand it is this spatial distribution and other factors of a site which determine its suitability.

The report [17] makes the following recommendations for areas where renewable heat can have the greatest impact.

Primary areas;

- Off-gas areas
- Sites with existing waste heat from industrial process both on and off gas grid.
- Area in close proximity Landfill sites

Secondary areas;

- Heat clusters in close proximity
- Heat clusters containing public buildings (i.e hospitals, schools) to act as anchor demands.

2.6 Critical review of Scottish heat map relevant to district heating schemes

The map is compiled from a variety of sources giving a variation in the accuracy. The base heat map was formed using observed carbon emissions data taken from National air emissions inventory (NAEI) files as a proxy. This had been cross referenced in two ways;

- It was first compared to the averaged average heat use per head in Scotland in the three largest cities, cross referencing the averaged data with that of the heat map. This gave figures 'roughly' about the expected average [17].
- The paper [17] sights a cross referencing done between the Scottish heat maps output for Edinburgh city centre and the more detailed study done as part of "Powering Edinburgh into the 21st century" [22]. The two reports are not said to give 'precise matches' but give a similar heat density profile.

Heat maps are subject to limitations. The limitations within their data acquisition stage can lead to inaccuracy in their results. The primary issues with heat maps include;

- The economics of DH networks are more accurately assessed through the linear heat density (heat demand per unit of length of heating) rather than the heat demand density per unit area. Heat demand per unit area and linear heat density do always correlate. This is particularly true in areas where there are large open spaces such as gardens or fields.
- Heat maps do not account for diversity in load factor. Infrequent large peak loads will appear to give a large annual consumption, however, these will be difficult to match with a district heating scheme making unsuitable locations appear unsuitable.
- Further knowledge of the tenure/owner ship of properties is needed and paramount to the success of the scheme. High levels of small scale private ownership in the absence

of community bodies or partnerships will be difficult to elicit investment from and maintain working relations with [6].

- The detail of the Scottish heat map is limited to 50m^2 due to the Data protection Act 1998 even if information at greater detail is available. This will ultimately limit the accuracy of the data.

Due to heat losses the efficiency of the distribution network is related to the length of piping. The publication [23] documents the losses in several European countries in relation to their linear heat density. Figure 6,Figure 7 and Figure 8 show the losses graphically. The results shown are for systems over 1000m in length.

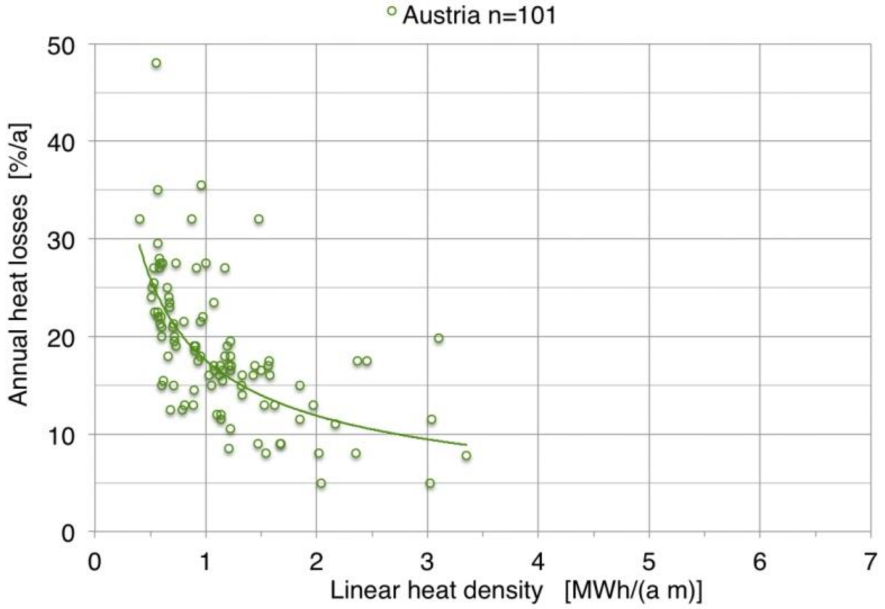


Figure 6-Heat distribution losses as a function of the linear heat density of district heating plants in Austria[23]

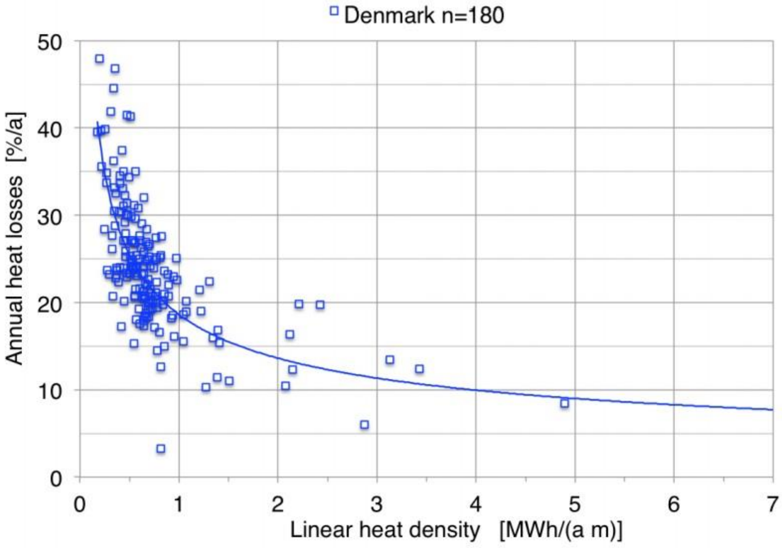


Figure 7-Heat distribution losses as a function of the linear heat density of district heating plants in Denmark[23]

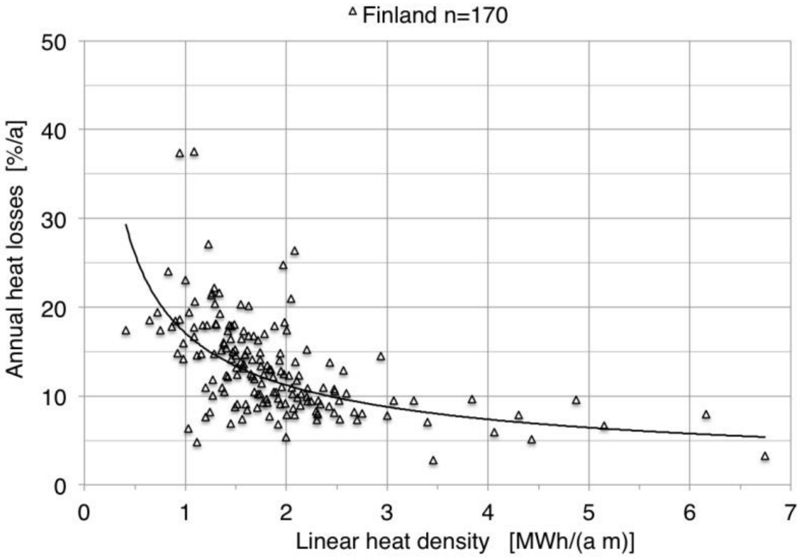


Figure 8-Heat distribution losses as a function of the linear heat density of district heating plants in Finland[23]

These graphs demonstrate how linear density of a network is critical to limiting the losses.

2.7 Bowmore, Islay

Located on the western edge of Scotland Islay is exposed to the brunt of the Atlantic weather coming. The landscape is predominately bog, improved grassland or heater. The predominant land use is grazing of live stock. The island is famous for its natural beauty, bird life and whisky.

Figure 9-Paps of Jura from Islay

Bowmore is part of the Argyle and Bute council area and is particularly remote. It has no mains gas connection but does have mains electricity. The fuel used on the island is imported by ferry.

Islay is famous for its whisky, hosting 11 distilleries on the island. The fertile soil for growing barley and abundance of peat on the island make the island ideal for the purpose. The main industry in Bowmore is the Bowmore distillery which has a production capacity of 2,000,000 litres of alcohol per- annum. The distillery serves as both a manufacturing plant but also as a visitor attraction with a visitor centre site offering tours.

Figure 10-Bowmore distillery

Bowmore is the administrative capital and largest town on Islay. The town sits on the edge of the large bay- Loch Indaal. The population of the town according to the 2006 census was 860 a decrease from the 862 recorded in 2001. Despite the static population there has recently been homes built on the outskirts of the town due to changes in the population demographic.

Figure 11 identifies the tree largest loads in Bowmore as taken from the Scottish heat map marked in red and orange.

A- Bowmore high school and primary school
B- Bowmore distillery
C- Islay hospital & Gortonvogie Residential Care Home

The other heating loads in Bowmore are predominately domestic. The town features a number of restaurants and hotels as tourism forms the bulk of the other industry in the town.

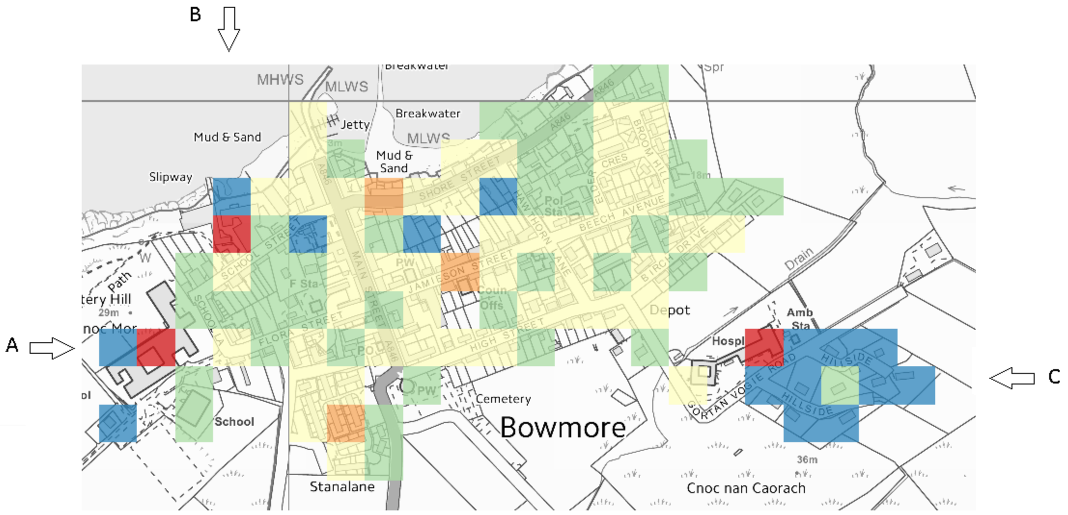


Figure 11-Scottish heat map-Bowmore 50m^2 resolution

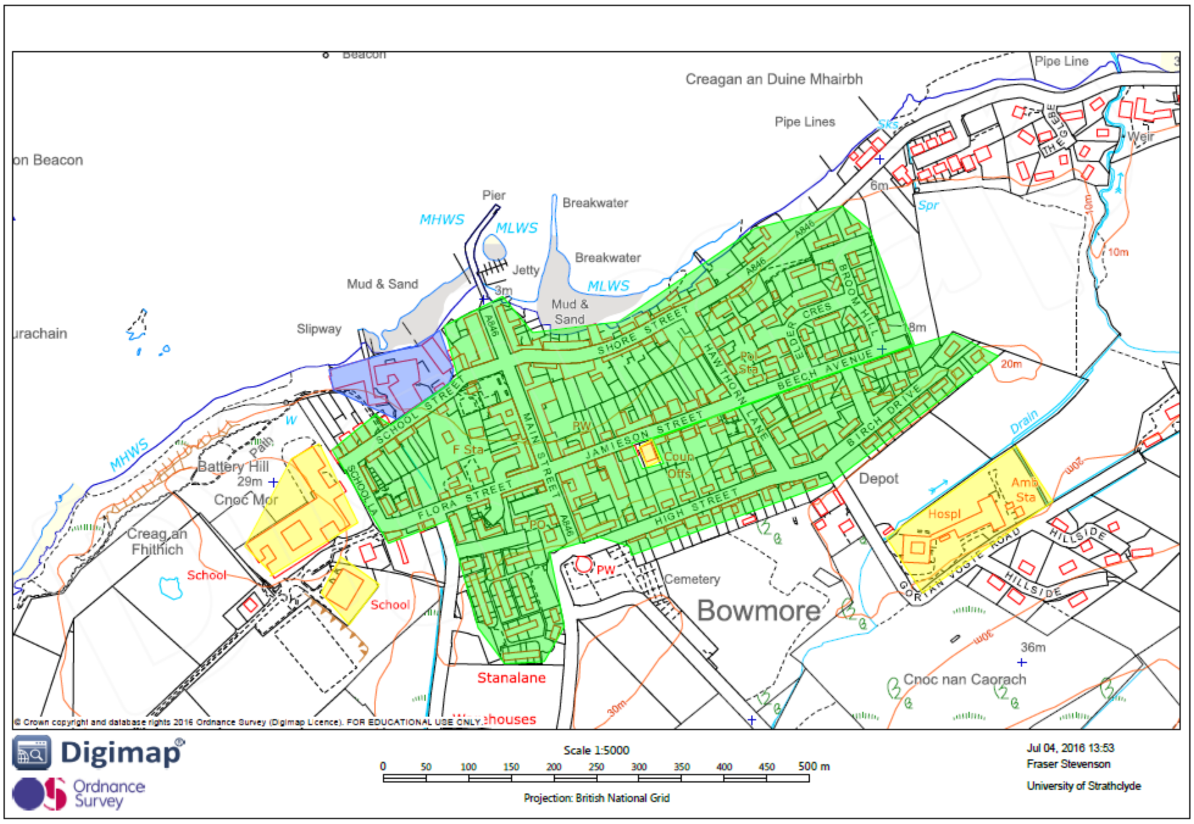


Figure 12-map of Bowmore highlighting domestic, industrial and local authority buildings

Key – Green- Domestic loads. Blue- Distillery, Industrial. Yellow- Council operated buildings, Hospital, High school. Primary school.

Initial indicators of the feasibility of district heating schemes can be derived from the heat demand density. This is a simple calculation based on the annual demand and gross area of the site.

$$Heat\ demand\ density = \frac{annual\ heat\ consumption\ (MWh)}{8760\ x\ gross\ area\ (km^2)}$$

Results from the Scottish heat map are used to estimate this for the study area in Bowmore. The report generated can be view in appendix 1.

Annual heat demand: 10GWh/yr

Area: 0.329km2

$$Heat\ demand\ density = \frac{10{,}000(MWh)}{8760\ x\ 0.329\ (km^2)}$$

$$Heat\ demand\ density = 3.469\ MWh/km^2$$

Typically area with heat-demand densities greater than 3MWh/km^2 are considered worth investigating for DH[24].

As previously discussed linear heat density is another key factor. This can will be calculated once the length of the required distribution network is known (Chapter 4.5).

These provisional results using the high level screening offered by the Scottish heat map show that a DH scheme is Bowmore is worth taking to the feasibility study stage.

2.8 Fuel Poverty

“An individual is defined as fuel (or energy) poor if they are unable to adequately heat their home through a lack of resources and because of the inefficiency of the housing insulation and heating. The concept of fuel poverty is thus multidimensional, depending on household income, the cost of energy and the energy efficiency of an individual's home.”[25]

As with many rural communities- particular those off the mains gas grid- Islay’s population face high levels of fuel poverty. A recent study carried out by Changeworks estimated the fuel poverty level per household based on data from the Scottish House Condition Survey (SHCS)[26] coupled with the 2011 Scottish census [27] and EPC registered data.

The Figure 13 below displays the findings of the fuel poverty report. Point A indicates Bowmore on Islay, in the highest bracket for fuel poverty at between 61.7-92.1% of households below the threshold. This provides an obvious incentive to offer district heating in Bowmore.

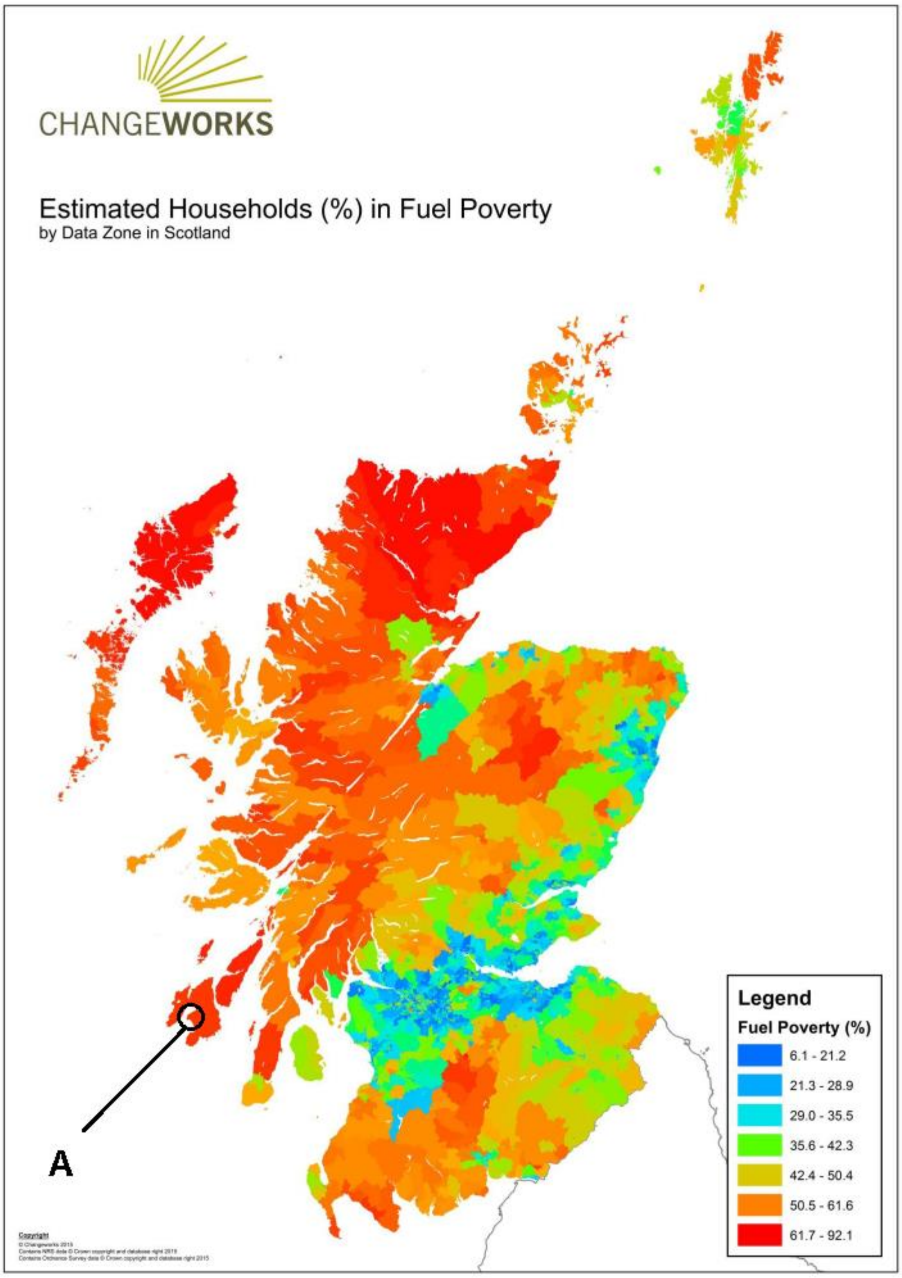


Figure 13-Fuel Poverty map of Scotland, Bowmore highlighted as point A

2.9 Degrees day method

The Degree days (DD) method is used to give an indication of the external environments variance from a base temperature. This base temperature is the theoretical external temperature where no extra heating or cooling is required [28].This is a parameter used when modelling buildings performance [29]. The accuracy of the DD calculation is heavily dependent on the quality of the climatic data available. The climatic data used for this calculation is taken from [30]. Temperature readings are taken at half hourly time steps at the weather station on Islay. The degree days are calculated using the tool [31]. Monthly DD are shown in table (4).

Table 1-Degree days for Islay

Month starting	HDD (K.day)	% Estimated
01/07/2015	137	0.1
01/08/2015	111	0
01/09/2015	146	0.1
01/10/2015	195	0.2
01/11/2015	241	0
01/12/2015	275	0
01/01/2016	337	0.03
01/02/2016	353	0.03
01/03/2016	329	0
01/04/2016	303	0
01/05/2016	178	0
01/06/2016	108	0.07

3- Scope, Approach and Methodology

3.1 Aim

To assess the feasibility of a district heating scheme in Bowmore, Islay.

3.2 Approach

The initial step in the methodology was establishing contact with representatives of Argyle and Bute council. From here a site visit it was undertaken under the supervision of the Energy and Building Services Performance Manager. Through site visits to local wood chipping plants, consolations with relevant stakeholders and discussions with the Islay energy trust, a firm understanding of the context within which this study is set was developed. The political and social contours of the area must be incorporated into the study.

Next the project followed the new guidelines set out by the CIBSE guide in order to assess

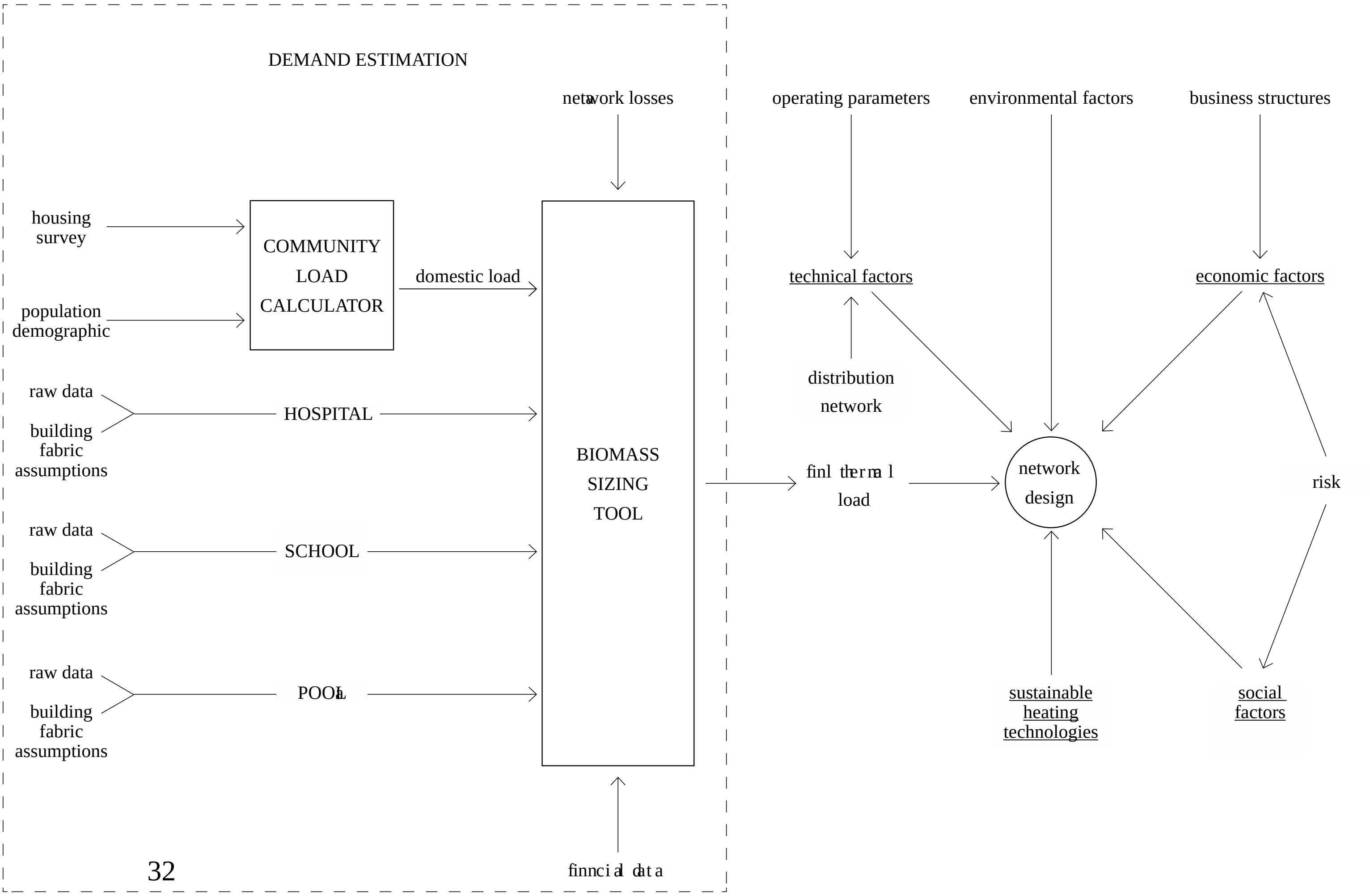


Figure 14-schematic of feasibility methodology used in thesis

the feasibility of a district heating scheme in Bowmore, through assessing the relevant technologies, modelling the relevant parameters and make relevant assumptions of the proposed schemes feasibility. In doing so the project will allow a critical evaluation of the CIBSE guide, assessing its effectiveness in aiding future feasibility studies of such a project.

Where necessary the most appropriate modelling software is selected and used along with appropriate model inputs derived from various sources including relevant literature and professional documentation. The annual heat and peak heat demands for example are modelled using the Community load calculator tool and the plant using the biomass sizing tool with data inputs from measurements and using available sources. A schematic of this methodology has been drawn and is expressed in the schematic shown in Figure 14 for illustrative purposes.

The necessary data has been obtained from a number of sources-identified where used- and further depth to the work has been gained through telephone interviews with other relevant stakeholders i.e the RSBP on Islay.

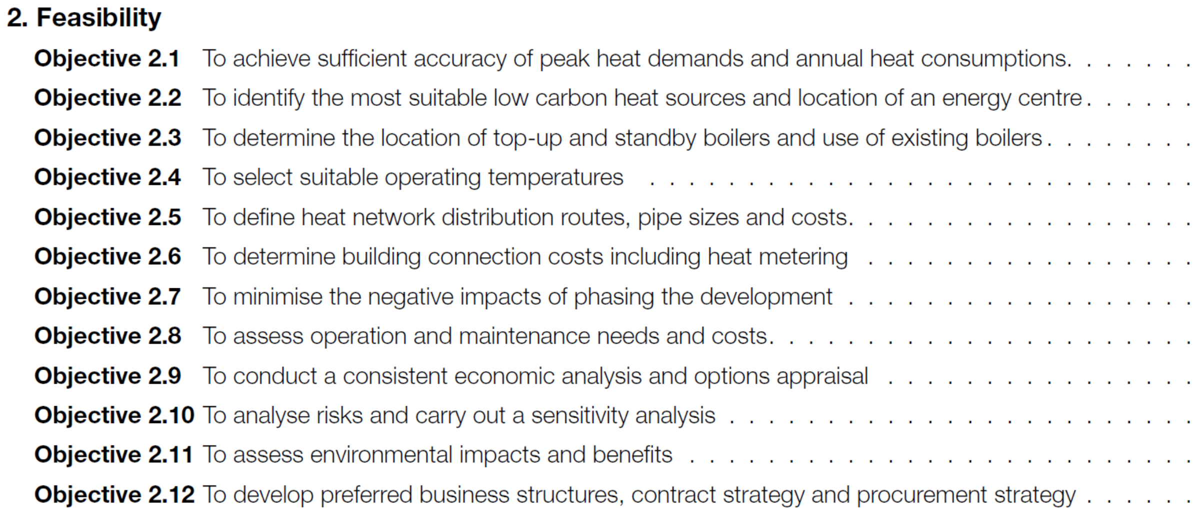
Particular attention is given to the contractual agreements and business structures which are possible for such a scheme as this ultimately underpins the feasibility.

The thesis is structured as follows;

Chapter 2 contains a literature review outlining the theory being the progress in DH.

Chapter 4 ‘Feasibility study’ contains the descriptions of the modelling carried out, discussion of the steps involved in meeting the guidelines set out by the CIBSE document. In these sections the working and considerations given to each of the points shown in Figure 14 can be found.

Chapter 4 is split into 11 sections, addressing the objectives of the CIBSE guide



2. Feasibility

Objective 2.1 To achieve sufficient accuracy of peak heat demands and annual heat consumptions. . . . . . .
Objective 2.2 To identify the most suitable low carbon heat sources and location of an energy centre . . . . . .
Objective 2.3 To determine the location of top-up and standby boilers and use of existing boilers . . . .
Objective 2.4 To select suitable operating temperatures . . . .
Objective 2.5 To define heat network distribution routes, pipe sizes and costs. . . . .
Objective 2.6 To determine building connection costs including heat metering . . . .
Objective 2.7 To minimise the negative impacts of phasing the development . . . .
Objective 2.8 To assess operation and maintenance needs and costs. . . . .
Objective 2.9 To conduct a consistent economic analysis and options appraisal . . . .
Objective 2.10 To analyse risks and carry out a sensitivity analysis . . . .
Objective 2.11 To assess environmental impacts and benefits . . . .
Objective 2.12 To develop preferred business structures, contract strategy and procurement strategy . . . . . .

Figure 15-Objectives of feasibility study from CIBSE [4]

Chapter 5 contains a summary of the results and conclusions to this study in addition to a critique of the CIBSE guide and suggestions for further work.

3.3 Scope

The scope of this investigation is determined by time and resource constraints. Within the scope are

- A feasibility study of district heating in Bowmore
- Assessment of relevant technologies and their environment and socio economic impact on the local community
- Design considerations set out in the CIBSE guide [4].

Out with the scope of the report is

- Detailed design of network
- Specification of district heating components to be used
- Retro fitting of domestic dwellings to reduce demand
- Novel technologies which are not widely accepted i.e biogas from distillation by products.
- Designs for increased capacity of the network as no large scale development of Bowmore is currently planned.
- Reference to district cooling
- dispersion models of biomass emissions
- acoustic surveys and planning permission requests

4- Assessing the feasibility of a district heating scheme for Bowmore

The feasibility study of this report is conducted in accordance with the procedure published by CIBSE in a document titled Heat Networks: Code of practise for the UK [4].

The feasibility section of the guidelines is composed of 12 objectives listed in figure (15). The 12 objectives form the following sub chapters of this thesis. The methodology, theoretical thinking and assumptions made at each step of the study are explained in these chapters. Where it is felt sufficient detail or data relevant to the aims of this report is lacking from, this structure then this included.

4.1 Assessment of Peak and Annual Energy Demand

The initial investigation required for this report is an assessment of the Peak energy Demand (MW) and the annual Energy consumption (GWh/yr) of the study area.

Peak demand- The maximum heat load that will be required of the network at any given time. This often determines the diameter of the piping and the ultimate cost of the network [4].

Annual energy demand- The overall consumption determines the revenue generated by the scheme and to a large extent the size of the low carbon plant [4].

Several methods for estimating the heat demand of Bowmore are used, as outlined in the following sections. Combinations of modelling and metered readings were used in accordance with CIBSE best practise guidelines;

- Heat demands are estimated on a monthly basis and where possible daily and hourly.
- Space heating demands and systems loses are considered.
- The degree days method is used to estimate baseline data on typical yearly records.
- There is appropriate consideration given to thermal storage, occupancy patterns and climatic data relevant to Islay.
- Hot water demands are included.

- The findings are compared to comparable schemes as a method of validation and cross referencing.

The load demands were calculated from the available data for each available demand type then compiled using the biomass sizing tool to estimate a final load for Bowmore. The load types are subdivided based on the form of the available data, described in the preceding sub-chapters.

The biomass sizing tool is software developed by the Carbon saving trust in partnership with the University of Strathclyde. It aims to help designers appropriately assess the feasibility of a biomass heating scheme before the detailed design phase without the need for detailed analysis. Its main purpose is to calculate the correct size of a biomass boiler, buffer vessel size, auxiliary boiler, fuel store and thermal storage tank. The tool is designed to account for system efficiencies and other factors.

4.1.1 Domestic thermal load analysis – Community load calculator

The domestic load is calculated using the detailed building simulation programme input sizing method of the biomass sizing tool. This requires an input of the estimated thermal energy demand and a series of assumptions made about the building stalk.

In absence of a detailed housing study or knowledge of existing demands the domestic thermal energy demand for Bowmore was estimated using the Community Demand Profile Generator Tool developed by the University of Strathclyde [32]. The tool considers the factors which effect the heating load to be;

- Differing housing stock
- Differing occupancy types
- Differing consumer behaviour

The heating demand profile generator (H.D.p) is a software tool which is based on the results from 480 ESP-r models, one for each combination of the inputs. The algorithm running the tool is represented in Figure 16.

The community load calculator requires a housing survey and information regarding population demographics.

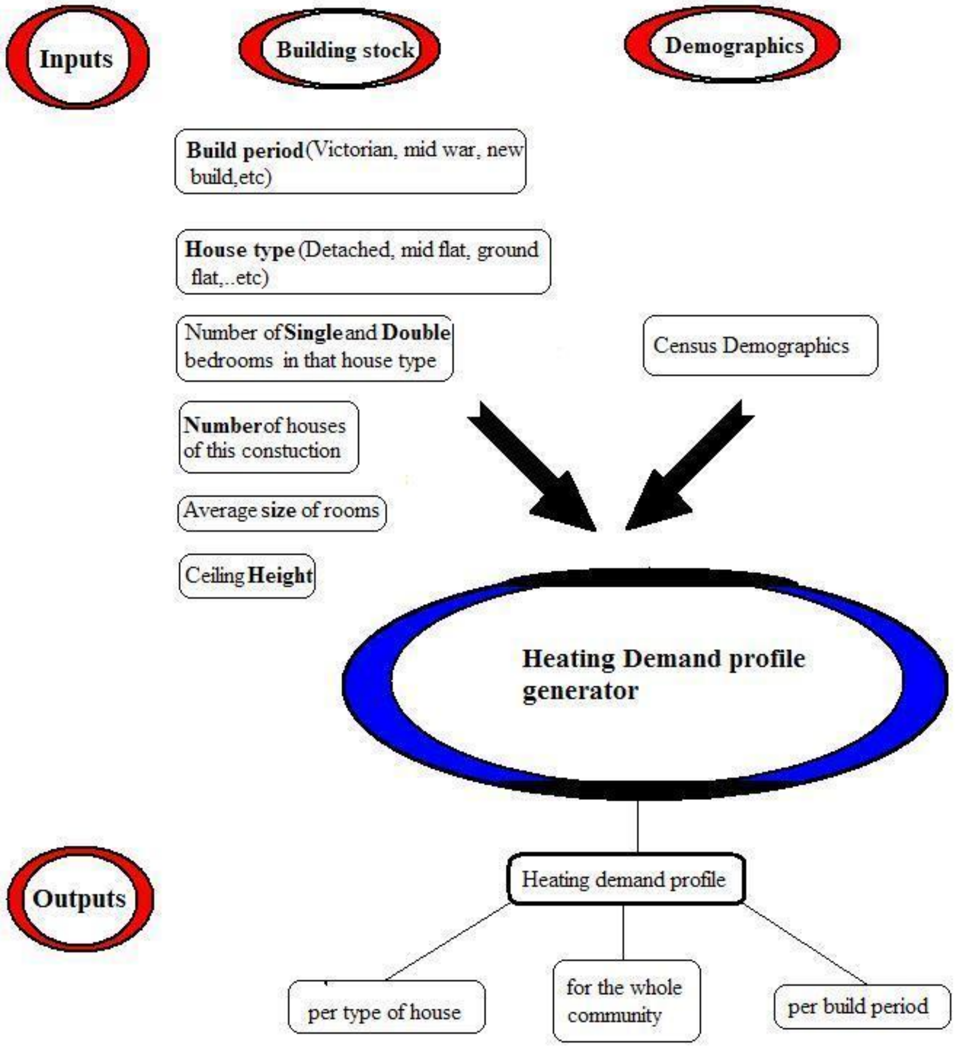


Figure 16-Schematic outline of the "Heating Demand profile generator" tool

Key to the calculation of the domestic heating load is the population demographics of Bowmore which gives an indication of the occupancy patterns.

4.1.1.1 Population Demographics - Community load calculator

The demographics used for the study are based on the results from a reference study of the Riverside Community[33], Stirling and the 2011 census results [34] from Argyle and Bute region. The demographics for Riverside in Stirling can be viewed in appendix 2. In general, Riverside is made up of a younger, working professional community while Argyle and Bute and extension Islay features an older population.

The census results for both council areas are shown in table (1) population of each region in age ranges. The household types for both regions that were used in the study are shown in table (2).

Table 2- Census results

Age	Stirling	Argyle and Bute
0-15	16.7%	15.3%
16-29	20.5%	14.8%
30-44	16.8%	15.1%
45-59	21.8%	22.9%
60-74	16.0%	21.2%
75+	8.2%	10.7%

Table 3-House hold type

House hold type	Stirling	Argyle and Bute
Single adult	23%	30%
Single Pensioner Adult	23%	13%
Two adults	21%	16.70%
Two adults with children	15%	15.15%
Two pensioners	5%	14%
Two adults and at least 1 pensioner	9%	8%
Three adults	10%	4%

The population demographics are used to estimate the occupancy patterns. The occupancy patterns are a large determinant of the thermal load as homes which are occupied during the day tend to require heating at this time. The aged population will there for effect the thermal load, increasing the day time levels and increasing the diversity factor.

4.1.1.2 Housing stock – Community load calculator

A housing survey was conducted of the homes in Bowmore. Each house was counted and assigned to one of the four categories offered by the Community load calculator tool.

- Terraced
- Semi detached
- Detached
- Top and bottom

As the housing stock in Bowmore is relatively uniform this was deemed to suffice in accuracy. An example of each type of home is shown in Figure 17.The housing stock is made up of either 1950's social housing, Victorian fishing cottages or detached renovated properties.

Figure 17-Examples of each dwelling type. TL-top and bottom TR-semidetached, BL-Terraced, BR- Detached

The results of the housing survey are displayed in table 4.

Table 4-Housing survey results

Dwelling type	Number of homes
Semidetached	155
Terraced	136
Detached	30
Top and bottom	16

These figures were then used in the community load calculator tool in order to define the heating demand for the 327 homes.

The hourly load profile generated was then input into the biomass sizing tool making the following approximations.

4.1.1.3 Biomass sizing tool

The following data is input into the Biomass sizing tool concerning building fabrics. The corresponding definitions for each variable are given in appendix 3.

General data

Outdoor design temperature	8°C
Building thermal mass	Medium
Level of insulation	Medium
Area of glazing	Low
Level of occupancy	Long
Total building floor area	50m2
Typical Occupancy	2

Casual Gains

To estimate the casual gains the following variables are defined for the domestic dwellings.

Gain Type		
People	130W [28]	W/person
Lighting	20	W/m^2
Equipment	1 PC per 2 person	

Occupancy data

Building type: Domestic		
DHW	5	L/person
Typical occupancy	2	People
Ventilation rate when occupied	12.5 [28]	Litres/s/person

Design day Results

The final hourly domestic load for the design day can be viewed in Figure 18. It displays the morning peak expected as everyone wakes up and a more dispersed peak in the evening with a minimum points displayed at 0100am and 1200am. The peak domestic load is identified at 1336 during the morning spike.

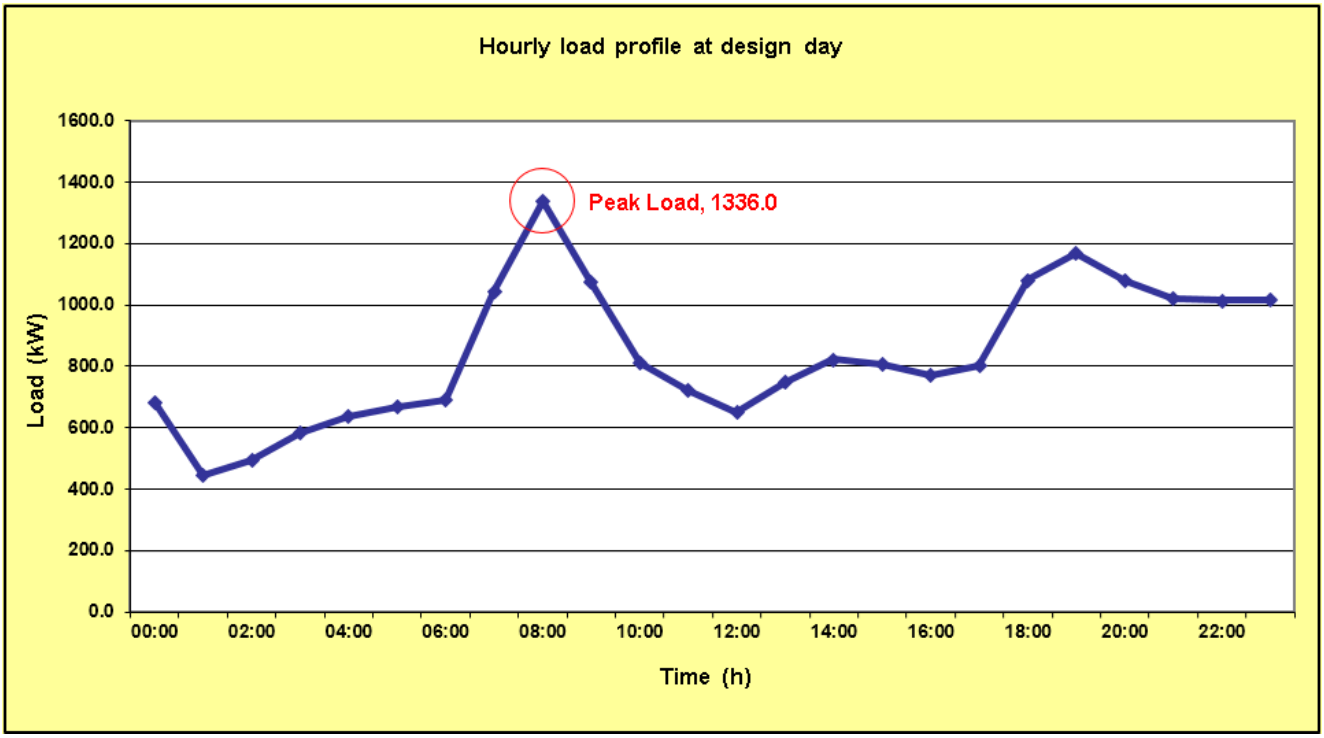


Figure 18-Domestic heating load at design day including hot water

4.1.2 Hospital and residential home thermal load analysis

The hospital and residential care home load is calculated using the heat meter measurement input method. The raw data supplied by the Islay hospital & Gortonvogie Residential Care Home is shown below in Figure 19 and Figure 20. These graphs show the daily (19) and monthly (20) outputs of the buildings biomass heating system. From this the annual heating demand for the year is estimated and the peak demand is calculated analytically.

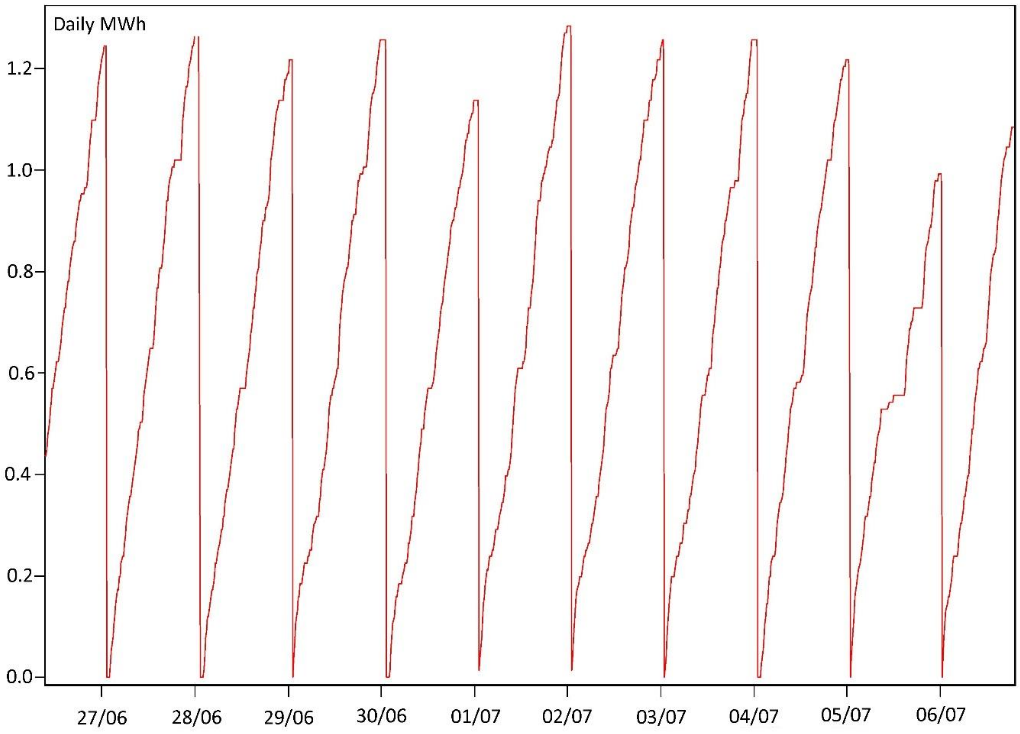


Figure 19-Cumulative daily output from biomass boiler

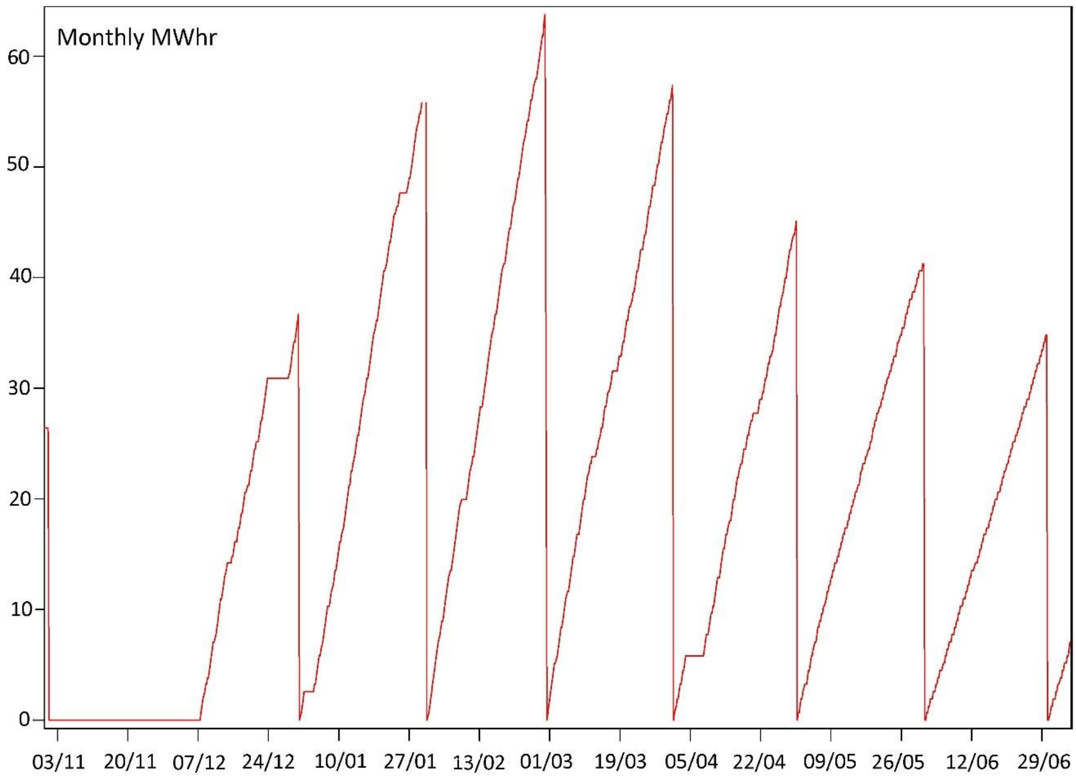


Figure 20-Cumulative monthly output from biomass boiler 2015-2016

This output data from the hospital's boiler system is assumed to be equal to the buildings heating demand.

The following input variables at selected to model the hospital and care home as part of the heat meter measurement input method. The corresponding definitions for each variable are given in appendix 3.

Total Building floor area: 2015m^2

Total Occupancy: 30

Data Input

Building: Hospital	
Variable	Input
Design temperature	8 °C
Building thermal mass	Heavyweight
Area of Glazing	Medium
Level of insulation	Medium
Area of Glazing	Medium
Level of occupancy	Long

Casual Gain: Input

Gain Type		
People	90W [28]	W/person
Lighting	9	W/m^2
Equipment	1 PC per person	

Occupancy data

Building type	Hospital	
DHW	5	L/person
Typical occupancy	30	People
Ventilation rate when occupied	12 [28]	Litres/s/person

Design day results

The hourly load profile is deemed to be accurate given the accuracy of the data supplied. It is also noted that the heating demand of the building is relatively constant given its continual occupancy pattern and tight temperature thresholds.

Peak demand:56kW

Casual Gain: 26.8 kW

Average DHW: 9.84 kW

Ventilation heat losses: 434W/K

4.1.3 School buildings thermal load analysis

The heating demand for the high school and primary school buildings were calculated using the biomass sizing tools monthly fuel bill estimation method. The input were based on the raw data displayed in Figure 21 provide by Argyle and Bute council in conjunction with approximations made based on the relevant literature.

		Date of reading						
Meter	Digital Integrator Serial Number	07.03.15	11.06.15	10.08.15	04.9.15	06.11.15	11.02.16	09.05.16
HM1 Back-Up Boiler	69212587	1983200	2254100	2254100	2290800	2424000	2910800	3209900
HM2 Biomass Boiler	13431377	547610	839970	839970	839970	903730	1006810	1201090
HM3 Bowmore PS	69212585	226030	290790	290860	296710	319290	382280	430690
HM4 Islay HS	69850071	0	0	0	24100	187600	721000	1152600

Figure 21-Data supplied regarding school buildings heating demand

The following assumptions were made regarding the buildings fabric and internal gains. Definitions for these parameters are given in appendix 3. The absence of a night-time heat demand demonstrates the assumption that the building envelope was insulated to a high standard at the time of fitting the existing boiler.

Building information	
Outdoor design temperature °C	5
Desired internal design temperature °C	17
Buildings floor area m^2	7520
Buildings thermal mass	Medium weight
Level of insulation	Medium
Area of glazing	Medium
Level of occupancy	Short
Typical occupancy (persons)	246 [35]

Design Day results

The annual heating demand was calculated to be 2.8MWhr/yr. The monthly fuel bill method uses the degree day’s method and the annual heating demand to estimate the design day load. The following hourly demand profile was generated. Showing a peak load of 121 kW.

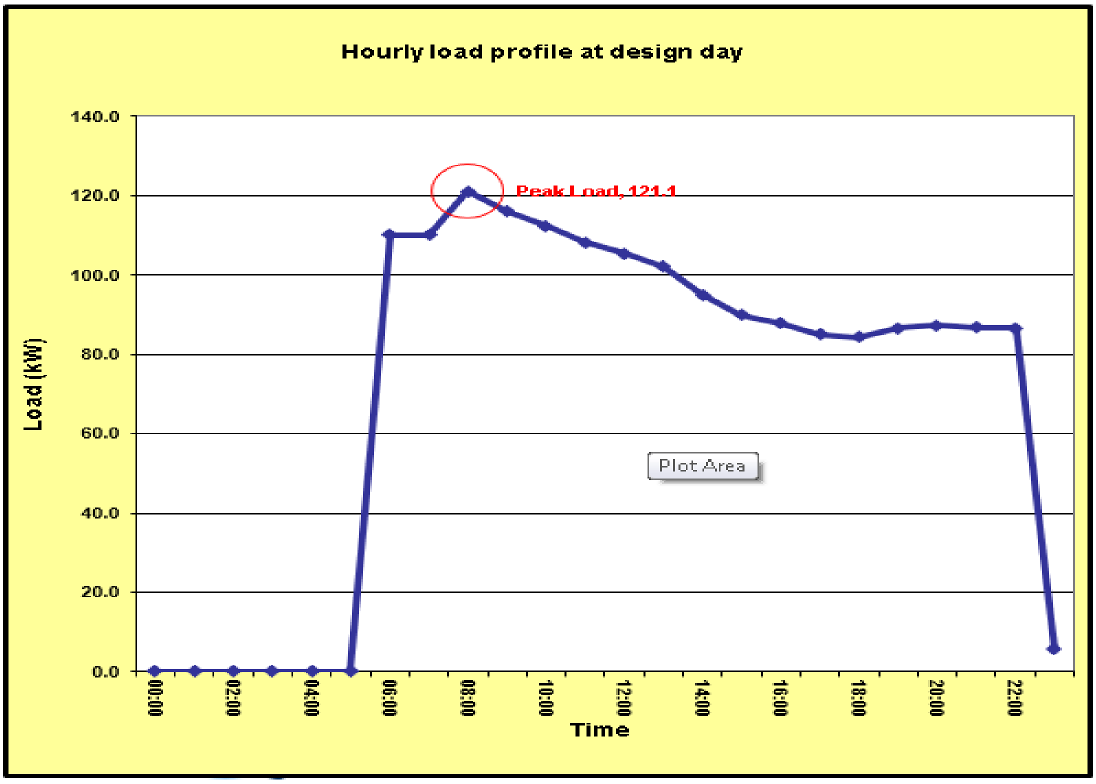


Figure 22-Thermal load of schools at design day

4.1.4 Swimming Pool and leisure centre

The embedded monthly demand calculator method was used to estimate the heating demand. In the absence of supplied data the following characteristics for the pool are estimates based on sources [36] and [37].

General info

Type of Pool	Public pool (no water features)
Is a pool cover used outside operating hours	Yes
Operating hours per day	Short
Ground Insulation	Yes
Heating days per week	5
Pool water temperature	29°C [36]
Outdoor design temperature	-3°C

Dimensions of swimming pool and pool hall

Pool	
Length	25m
Width	15m
Pool hall	
Floor area	600m2
Height	4m

Occupancy, ventilation and heat recovery

Average number of bathers	10
Ventilation rate outside operating hours	50%
Type of heat recovery system	Heat pump dehumidifier

Results

Heat loss breakdown and DHW required.

Pool water heat demand (occupied)	48	kW
Pool water heat demand (unoccupied)	0	kW
Ventilation heat demand (occupied)	26.5	kW
Ventilation heat demand (unoccupied)	13.3	kW
Fabric heat demand	39.6	kW
DHW demand (occupied)	69	kW

The demand profile for the design day is shown below. This is a relatively consistent heating load during the opening hours with a peak 60kW.

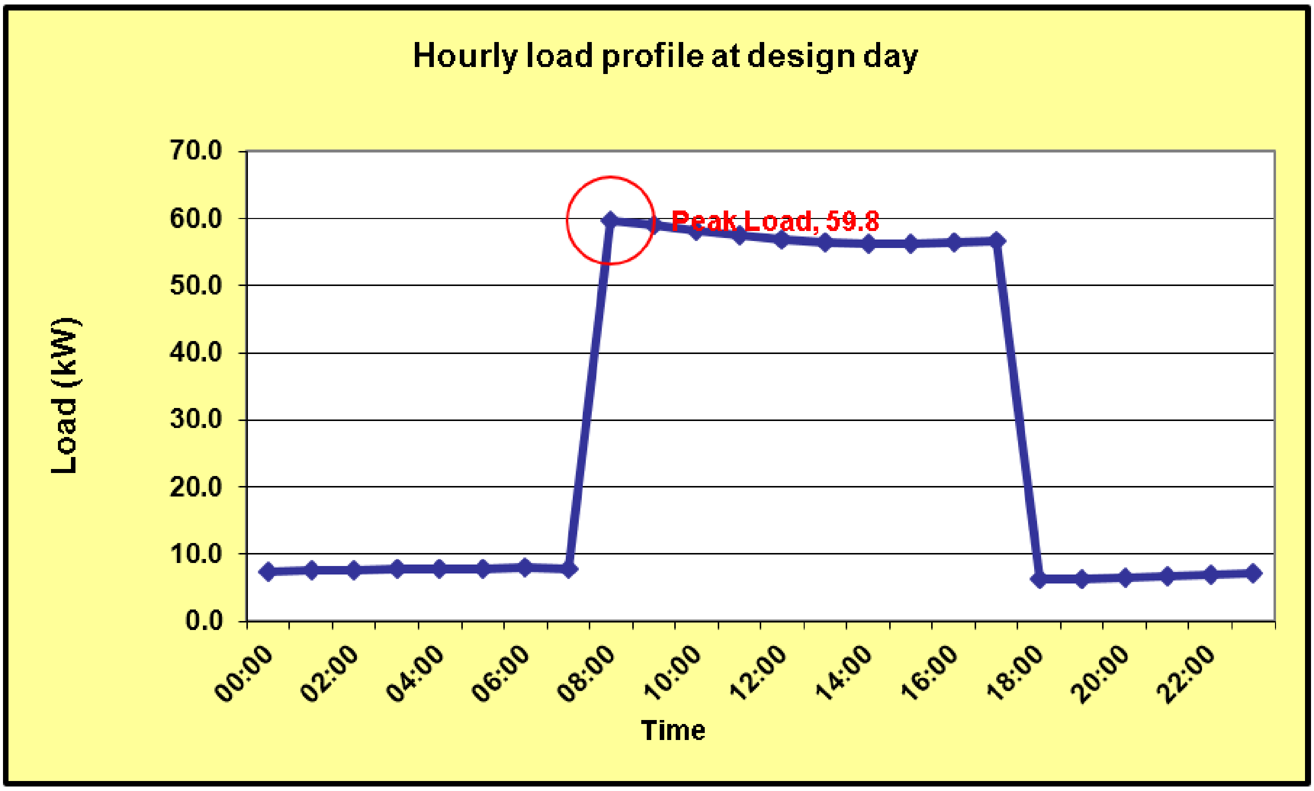


Figure 23-Thermal load of pool at design day

4.1.5 Final load and feasibility indicators

The final estimated heating load of Bowmore on the design day is shown in Figure 24. The design day is the coldest day of the year, requiring the maximum heating. Therefore, for the rest of the year the system will be working at below maximum capacity. One way of estimating the thermal loads for summer months is through the degree days method referred to in chapter 2.8. The degrees days method used in the study are embedded within the Biomass sizing tool. The distribution losses in the system were input as 20%. This is a high value for heat losses, however, a worst case approach is assumed.

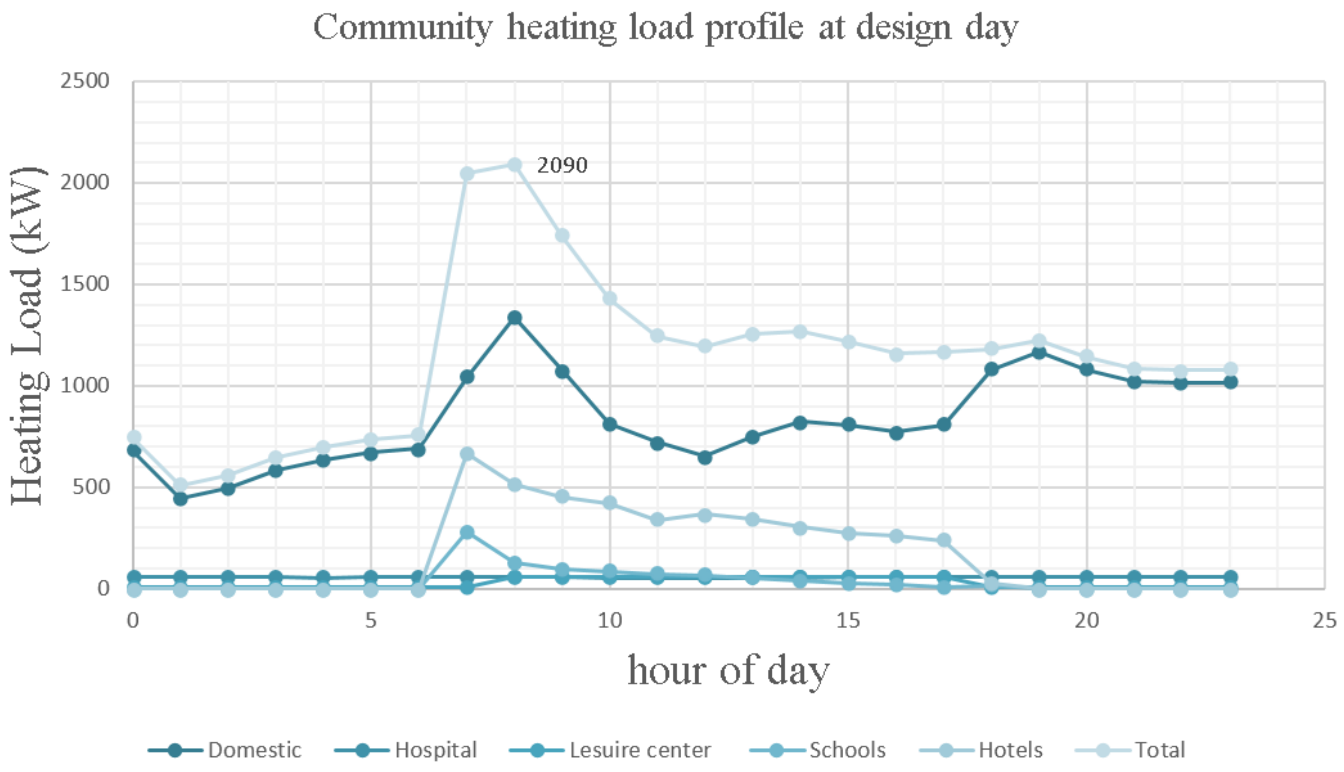


Figure 24-Community thermal load at design day

Total heating energy required:

Total heating energy required	
Average heat demand at design (kW)	1,388
Energy demand at design day (kWh)	33,308
Energy demand at summer day (kWh)	200
Annual energy demand (kWh)	9,155,149

The summer load of the system can be equated to the hot water demand, as little heat is required in summer months. The values for this are taken from the annual load duration curve which can be found in 4.2.5. The curve shows that the minimum hot water demand will be 20% of the boiler capacity- equating to 200kW.

The annual thermal load is 9.15GWhr

The annual consumption including losses is 9.67GWhr

From this data the following variables were calculated in order to aid the design process.

Load factor

The Peak heat demand at the supply point is related to the individual peak demands of local buildings by the diversity factor. The peak demand at the supply point should be significantly less than local buildings. The load factor is the fraction of annual heat demand to the heat generated by the network if it was run continuously at peak capacity.

$$Load\ Factor\ = \frac{annual\ heat\ consumption\ (MWh/yr)}{(peak\ heat\ demand\ (MW)\ x\ 8760)(h/a)}$$

Eq1

$$Load\ factor = \frac{9150\ (MWh)}{2.09(MWh) \times 8760}$$

$$Load\ factor = 0.49$$

The document [38] sets out bench marks for heat networks. It states the average load factor of networks to be 0.23 based on recorded data gathered from operating schemes in the UK. The paper [38] does not determine whether the 7 of the 14 schemes which returned data are well operated or well-designed systems . Furthermore 70% of the schemes involved in the study were built before 1990. The guide [6] states “DH will be more economical when supplying buildings with high load factors.” This load factor may be reasonable and advantageous to the scheme.

Diversity factor gives an indication of the variation in peak load that can be expected due to consumers not drawing hot water simultaneously [39] , differing thermal responses and alternating weather conditions [6],

$$Diversity\ factor = \frac{peak\ heat\ demand\ (PHD) at\ supply\ point\ (MW)}{sum\ of\ PHD\ of\ buildings\ connected\ (MW)}$$

$$Diversity\ factor = \frac{2000}{\sum(1336, 665, 227, 56, 60, 478.8)}$$

$$Diversity\ factor = 0.69$$

The large proportion of domestic loads increases this diversity factor, as the aggregate the demand to several peak times of day. As seen in Figure 24-Community thermal load at design day, the domestic load is significantly greater. The diversity factor of 0.69 means that only 69% of the peak load will be demanded at any given time, allowing a reduction in the size of the plant and heat network. The source [40] states a diversity factor of 0.7 for a ‘group of buildings, dissimilar users’, falling from a diversity factor of 1.0 for a single space. Acting as a viable cross reference for this result.

4.1.6 Validation of heat demand

The report generated by the Scottish heat map calculated the heating load of the study area to be 10GWh/yr compared with the 9.2GWh/yr. This report can be viewed in appendix 1. This provides a relatively strong correlation when the profile is considered over an entire year. The primary reason given for the discrepancy is the fact that the heating load of the distillery is not considered as part of the community heat demand. Taking this into account a second heat map report was generated only including the heating load of the distillery. This report can be viewed in appendix 2 and calculated the heating load of the distillery complex to be 355MW/hr. subtracting this from the 10GW/hr the correlation between the estimated results is strengthened.

The comments made regarding the accuracy of the heat map can be viewed in section 2.4. The fundamental errors which occur in approximating on the scale involved will result is variation in results.

4.2 Possible suitable low carbon heat sources

A major advantage to DH network is their compatibility with a range of heat sources. Bowmore is well endowed with sustainable, low carbon options. These are outlined and assessed as options in turn in the following sub chapters.

These include waste incineration, biogas turbines, and solar thermal. At an early stage a screening exercise was done with Argyle and Bute council looking at the most likely technologies to receive approval and those which were in line with council policy. Other factors in the screening process included ease of integration with district heating schemes and yearly supply dynamics. The technologies which were selected for further consideration are; wind to heat, solid biomass, water source heat pumps from waste water and waste industrial heat.

4.2.1 Wind Energy

In 2014 the Islay Energy trust installed an Enercon E33 turbine on the island in a community lead project. The Islay energy community benefit society raised £1.27million needed with the remaining £735000 being secured through a government loan. The turbine is a community owned endeavour and the scheme was oversubscribed by the local community.

The turbine is situated on land leased from Scottish natural heritage near to the airport, around 5 miles south of Bowmore. The turbine is built on one of the few available site on the Island due to the high concentration of SSSI's and other designated sites. Other factor influencing the site include the necessary approach to the airport. A wide range of approach routes are required given the volatile and variable wind Islay experiences.

The following raw data is supplied by Islay energy trust. It is displayed in order to give an indication of the amount of renewable energy wind which can be harvested on Islay.

Output

Table 5-Output data from wind turbine on Islay

Time period	Average Wind m/s	Exported kWh	Op Hours
Feb 12-28 -2015	10.9	34,505	242:23:00
Mar -2015	9.8	97,574	632:13:00
Apr -2015	7.3	58,395	404:52:00
May -2015	8.95	115,449	723:00:00
Jun -2015	7.4	84,075	646:00:00
July -2015	7.4	91,819	676:00:00
Aug -2015	6.8	56,689	495:00:00
Sep – 2015	7.6	95,432	635:00:00
Oct -2015	7.5	91,237	676:00:00

Nov -2015	10.2	144,563	680:00:00
Dec 1 - 2015	12.3	156,317	614:00:00
Jan -16	11	154,266	715:00:00
Feb-16	9.9	123,983	636:00:00
Mar-16	7.1	86,873	659:00:00
Apr-16	8.7	73,540	498:00:00
May-16	8.1	91,270	602:00:00

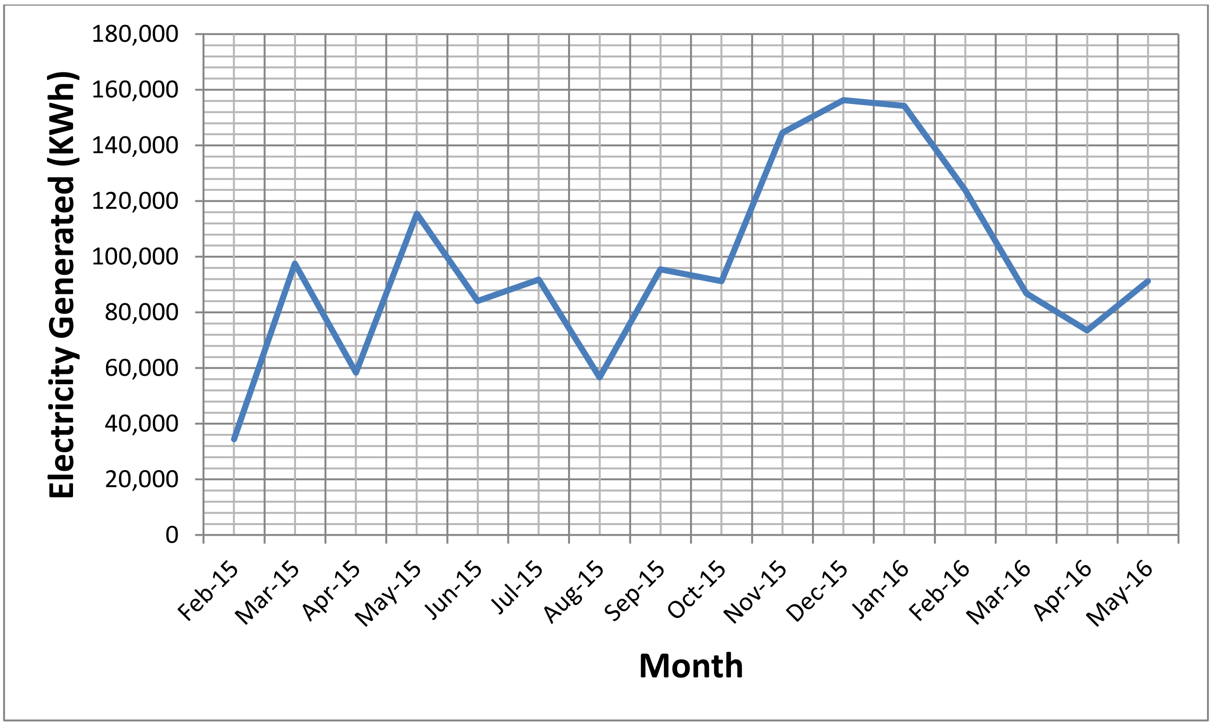
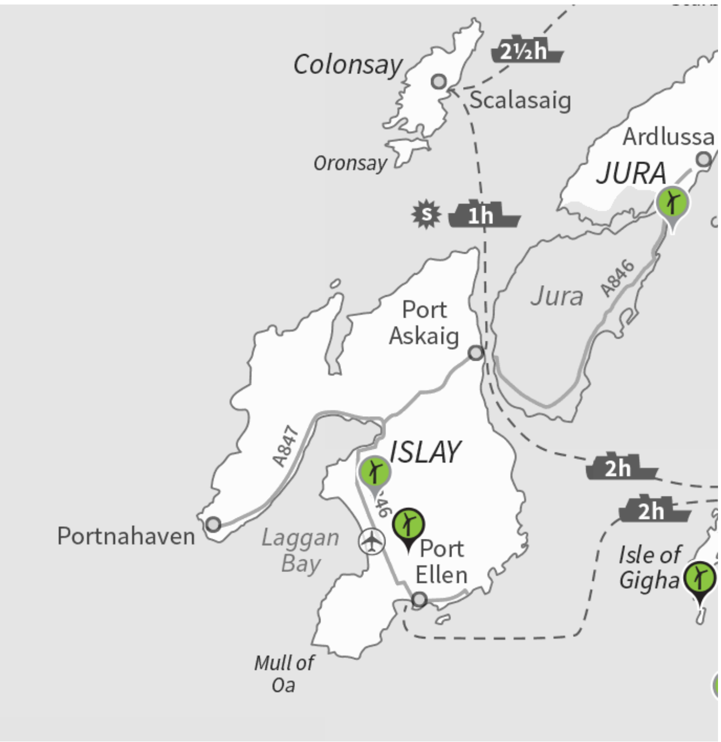


Figure 25-16 month wind turbine generation data

The Scottish heat map identifies the existing site of the wind turbine on Islay in addition to a second potential site. This is shown in

Figure *26*.

The current turbine produces a total of 1.25GWh/yr.



Key: Actual: Potential:

Figure 26-Actual potential wind turbine sites on Islay

Power to heat solutions

Wind turbines produce electricity which can be converted into low grade heat energy. Wind energy is both non dispatchable and variable.

The paper [41] describes the transients produced when large quantities of non-dispatchable renewable power is incorporated into an energy mix in relation to district heating. Here this study will outline the available technologies for converting electricity to heat.

Electric boilers - Large electric boilers driven by wind energy are a potential low carbon source for any district heating scheme. The boiler would be used in conjunction with a thermal store in order to allow matching between available wind power and heating demand. Studies of Danish systems show electric boilers to be a cost effective method for utilising energy [42]. The theoretical amount of heat which a direct electric heating powered by a second turbine could add to a thermal store is 1.25GWh per year minus transmission losses. This would account for 16% of Bowmore’s DH demand.

Heat Pumps - Heat pumps operate best when working continuously. Repeated start up and shut down cause mechanical wear and tear on heat pumps. This is a disadvantage when running from an unpredictable source. Further information on heat pumps can be viewed in section 2.1.4 including sources of heat available around Bowmore. Assuming a coefficient of performance (COP) of 3.25 [43], heat pumps could therefore theoretically deliver 4.1GWh to Bowmore's heating demand. This could account for 44% of the DH heating load assuming unlimited energy in sewage, 100% efficiencies and 100% utilisation rate.

4.2.2 Biomass

Biomass already provides 72.2% of the UKs renewable energy with 14.9% of this made up buy wood chip or wood pellets [44]. There are several key advantages to using biomass systems;

- Biomass boilers work well as a centralised plant removing the need for individual boilers in homes.
- Wood chip and wood pellets can be a profitable industry with socio-economic benefits for local communities rather than external fossil fuel suppliers.
- Qualifies for Renewable Heat Incentive [15]
- Biomass is a dispatchable power source, capable of being regulated to meet demand.

Is biomass a carbon neutral source of energy?

The burning of biomass releases carbon into the atmosphere which forms CO^2. If the carbon is fully combusted, then the carbon realised is equal to the carbon absorbed during the growth of the matter. Therefore, if biomaterial is planted at the same rate at which it is burnt then a 'closed loop' is formed which results in no net increase in atmospheric CO^2 [45].

Despite its apparent carbon neutrality, the use of biomass as a fuel source cannot be said to be nutrient neutral or harmless to the environment [45]. The growth of biomass is land and water intensive; it leads to a loss of biodiversity resulting in habitat loss and ultimately land degradation. The main criticisms of biomass as a fuel source is the life cycle of CO^2 emissions released in transportation from the production site to the point of use.

Is biomass feasible on Islay?

There are several estates on Islay which currently have large biomass stocks in the form of soft wood forests. These forests are a largely untapped resource despite the islands apparently prime environment for the growing of biomass, having fertile soil and a wet climate. The reason for the under use of the wood stock is transportation costs. With Islay being so remote, the cost of transportation by road and the essential ferry crossing render the currently fuel un-economically viable for use the mainland. The CO^2 emitted during transportation is kept to a minimum when produced locally to the point of use.

The Dunlossit estate on the island currently supplies wood chip, produced on the island, to the biomass burners which heat the school and hospital. During interviews with a representative of the estate it was made clear that there is significant scope to increase the amount of wood chip supplied sustainably and creating a market for said wood chip would be welcomed.

The implementation of a biomass scheme on Islay would have several key benefits;

- Creating a local value for a locally produced product.
- Increase in islands local economic productivity, leading to socio-economic benefits such as an increase in the number of jobs.
- Very low transportation cost and CO^2 emissions adding to the sustainability of the scheme.

Biomass energy plant

A biomass plant has four main components; biomass boiler, auxiliary boiler, buffer vessel and thermal store. The role of the buffer vessel is to protect the boiler. It offers an outlet for unwanted heat stopping the excess damaging the boiler.

Biomass in the form of wood chip or pellets is most efficiently burnt in a biomass boiler converting directly to heat energy. A choice between boiler types is usually based on cost, level of automation required and the type of fuel used. Biomass combustion equipment is governed by BS EN 303-5:1999. This covers properties such as performance, efficiency, emissions, thermal output, pressure testing, safety measures and testing. The type of boiler is determined by the grate used.

Moving grate systems – Boiler type with the greatest flexibility and ability to burn wood chip up to 50% moisture content but with the lowest response times. Lower response times are caused by greater levels of refractory lining. This a versatile design which can also be used to burn wood pellets if needed [6]- [46]. The configuration of a moving grate system is shown in Figure 27.

Stoker-burner systems- A more simple design means lower cost and upper limit of moisture content of 30-35%, in this case there will be moderate refractory lining to increase response times. This design features a small grate attached to the end of the auger feed. This design gives a high chance of burn back along the auger. If this happens the boiler must be turned off and emptied, reducing the working hours and increasing use of back up boilers, reducing the profitability of the system. A diagram of this system is shown in Figure 27 [6, 46].

Underfed stoker boilers- The burning fuel is fed from beneath the burning chamber. This system will typically burn up to 30% moisture content and is limited in the size of wood chip it can accept. Under fed systems will have both primary and secondary fans. This allows control of the rate of combustion at both the grate and in the final combustion zone. This design is shown in Figure 27 [46].

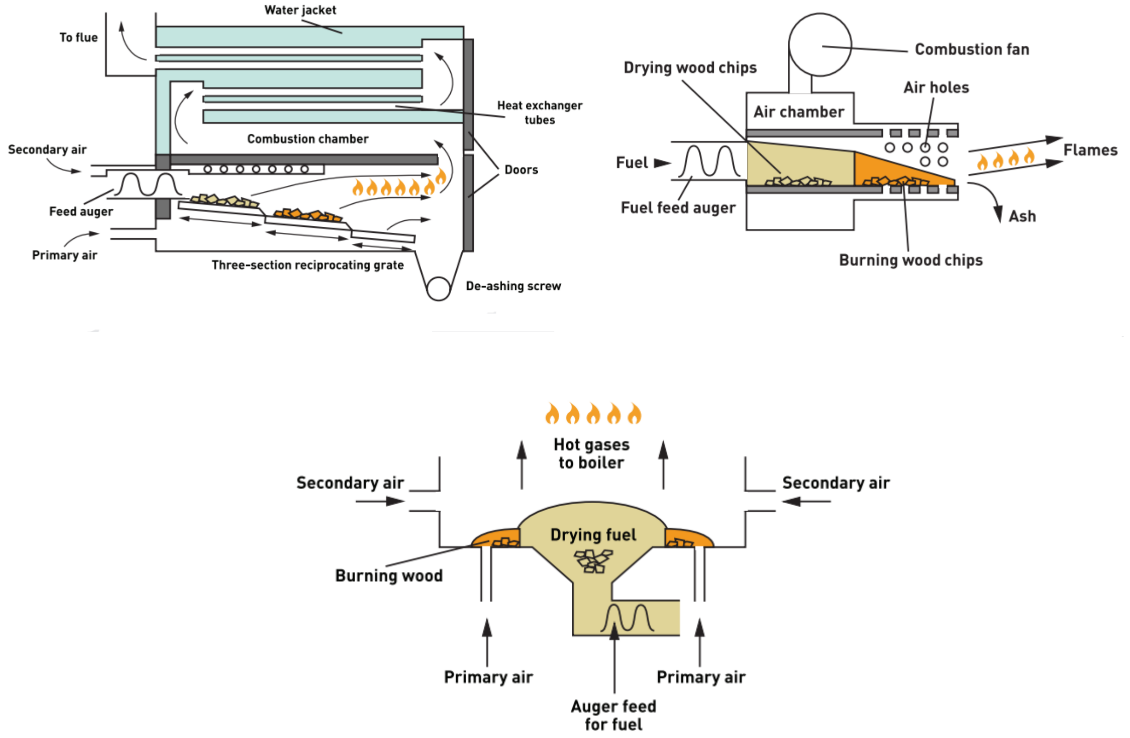


Figure 27-TL- Moving grate configuration TR- Stoke burner systems BL- Underfed stoker boiler [46].

Plant optimisation

The ideal operation of a biomass boiler is to run at a consistent level. This means that they very rarely match the instantaneous demand. The matching of demand is achieved by the thermal store and auxiliary boiler. When the boilers output is greater than the demand, the energy is used to charge the thermal store and in times of deficit the store discharges heat. If this heat is not sufficient then the auxiliary boiler augments it. These additions mean that the boiler does not have to be sized to meet the peak demand. Typically a boiler will be sized to one third of this maximum demand value. The thermal store allows the boiler to run at a continuous rate independent of the heat demand using surplus energy to recharge the store. This balance between the three heat sources is key to an efficient and economic biomass system.

If a biomass boiler is over sized they become unsuitable and uneconomical for summer time operation. Due to limits in turn down ration it is very uneconomical to run a biomass boiler for small loads.

The annual load curve represents the frequency distribution of the thermal load. This indicates the number of hours in a year when the load will be at a particular percentage of its maximum value. The boiler's rating and minimum output are also shown. The boiler's suitability for summer operation is determined by the minimum boiler output. If it is much greater than the fractional heating load then this will result in frequent on/off operation, reducing efficiency and wear on the boiler.

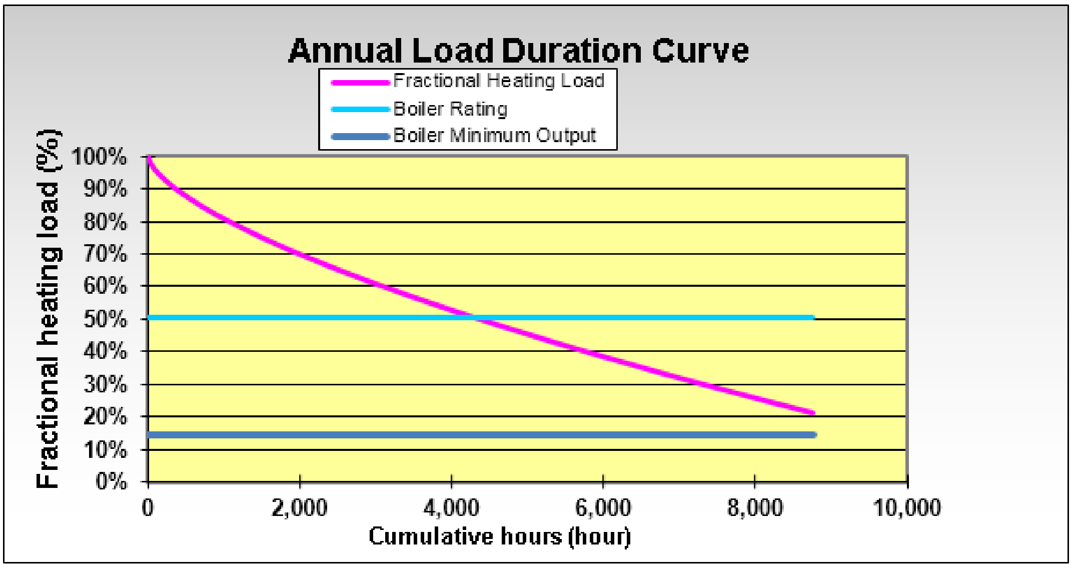


Figure 28-Example annual load duration curve

The annual load distribution curve is governed by the equation;

$$Heat\ load\ in\ exceeded\ for\ T\ hours\ annualy = 1\ - (1 - \beta \mathrm{min}) \times T^{\frac{\beta m - \beta min}{1 - \beta m}}$$

βmin= ratio of minimum load (DHW + district heat losses) to the peak load

βm = average load as fraction of maximum load (utilisation factor)

The graph shown in Figure 28 represents a boiler sized to 50% of the heating load. It gives an indication of how well the boiler will perform during periods of reduced load. This graph shows a good sizing match with the boiler being able to meet summer loads without frequent on/off operation, as it should never have to be turned off.

4.2.2.4 Heat Pumps

Compression heat pumps have several benefits to 4th generation integrated renewable energy systems; they can utilise excess electrical energy produced by non-dispatchable sources to produce heat that can be stored in thermal storage until the heat it requires, balancing the system [47], they perform at their highest efficiency when the temperature difference is lowest suiting low temperature systems. Compression heat pumps are also capable of cooling cycles. The performance of heat pumps is determined by the co-efficient of performance (COP). The workings of heat pumps and the effect of environmental factors on COP is well documented in literature [48] . The use of heat pumps is a location specific technology. Low temperature heat provided by wastewater may not be hot enough for high- moderate temperature DH so may need axillary heating.

The water treatment works outside Bowmore is a potential source of heat. The site is 350m from the distal point of the network. The paper [47] deems heat sources to be relevant if they are within 500m of the DH network, the water treatment works are within this boundary. The incorporation of heat pumps into District heating is covered [49].

Studies carried out into heat recovery from sewers include [47, 50-52]. Water treatment is a process with relatively constant annual flow and volume profiles, the temperature of the water will vary throughout the year with fluctuations in temperature of the environment. Despite this, temperatures of sewage in Denmark rarely drop below 9°C in the winter [47].

There are several technical problems with this technology, namely the soiling of the heat exchanger surface and inconsistent levels of sewage water reducing COP dramatically. The paper [53] cites COP of between 3.25 and 3.5 for heat pumps running from wastewater at temperatures of around 10°C , increasing by 0.3 with a 2°C increase in temperature.

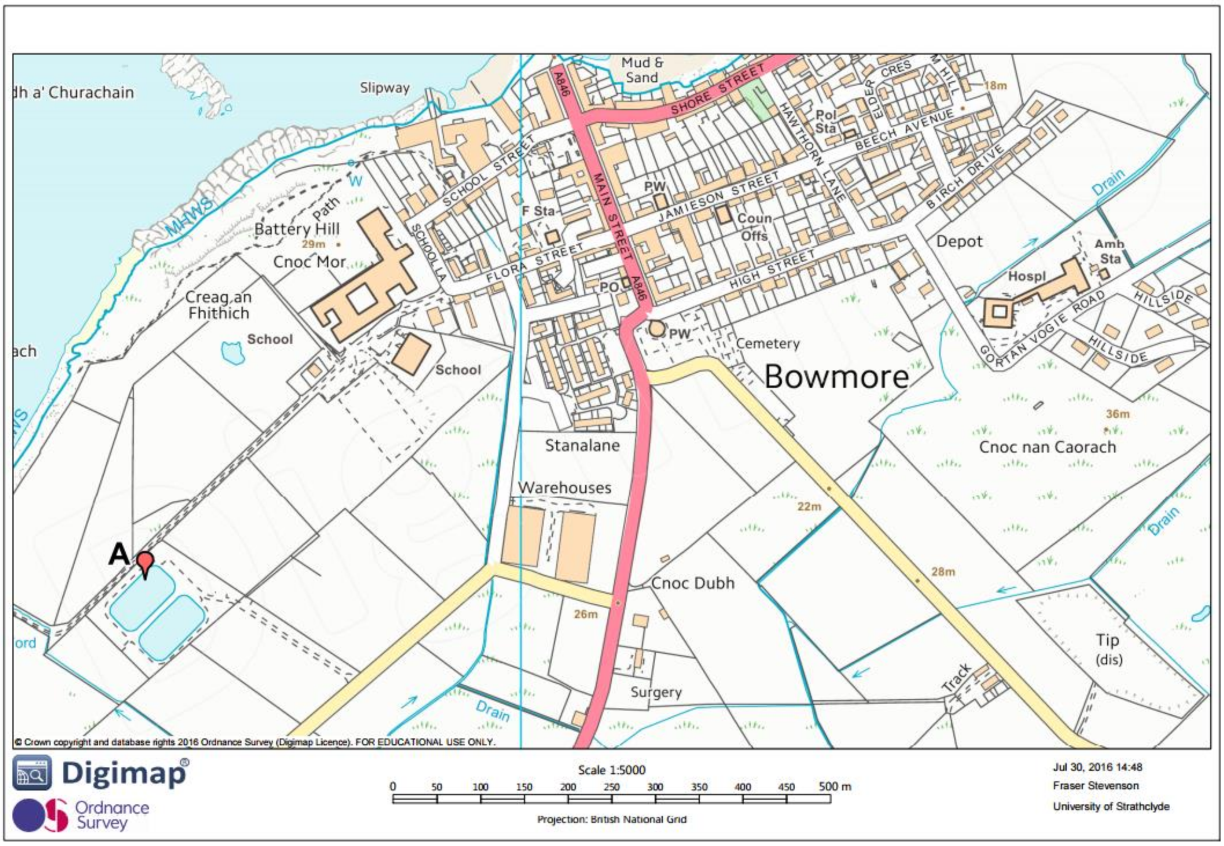


Figure 29-Location of water treatment works

4.2.2.5 Industrial waste heat

There is a general consensus that the drive for energy efficiency seen in domestic sector is not seen to the same extent in the industrial sector [54]. [55] estimates that 20-50% of all industrial heat in the US is dumped into the environment. However, some industries, such as the Scots whisky industry are committed to making there industrial processes more environmentally friendly [56].

Several studies [54, 57, 58] have been conducted into the use of industrial heat. [58] Finds that the economic case for using waste heat is much stronger at smaller to medium scale projects.

If the temperature of the waste heat is high enough it may be used directly in the DH network. If not a heat pump is required. The temperature needed will depend on the supply/return temperature of the DH network.

The Bowmore distillery is a prominent feature of the town and distilleries are known to produce large amounts of heat. This heat can be recycled through heat exchangers. This is currently the case in Bowmore with recycled being used to meet some of the heating demand of the pool. The quantity of this heat is unknown due to contacts not being able to provide the relevant data. The scope for increasing heat recovery is also unknown along with the distribution profile of the heat which would be available.

The lack of available information and lack of cooperation from the Bowmore distillery and the leisure centre curtails the analysis of the waste industrial heat for a DH scheme in Bowmore.

4.2.3 Location of Plant

Two possible sites are selected for the biomass plant based on their suitability.

The first site selected is by the school as this is the sight of the existing biomass boilers, marked as shown in Figure 30. The effect on air quality at this site is assumed to be acceptable as it is the existing site.

The second is in a council run storage yard on the intersection of Birth Road and Gortan Vogie Road marked as (B) in Figure 30 . This site has the advantage of being close to the hospital, central and is already used for industrial activity so reduces he likely hood of complaints by residents. Both sights are marked in Figure 30.

Non-technical factors to consider when choosing the site are;

- Easy of delivery
- Planning permission
- Public objections

For the purpose of the feasibility study site B is selected. Due to a more favourable central location and air quality considerations due to site A’s proximity to two schools. Site B is currently used to store aggregate and other road materials and gritting lorries so there are no concerns over the access to the site.

Figure 30- Possible locations for biomass plant

4.2.4 Options Appraisal of Low carbon heat sources;

Biomass is chosen as the primary heat source for the project. This is due to the apparent socio-economic benefits of creating a biomass industry on Islay, existing working relationships between supplier and operators of biomass schemes on the island and benefits of being a tried and tested technology. The feasibility of implementing any novel technologies in Bowmore given the current lack of funding available for such schemes is low. Only tried tested and proven technologies are likely to receive backing.

The limited information available regarding the water treatment facility ultimately limits its possible input into this study. The use of the heat source has been highlighted and researched as a potential means to reduce the cost of the heat supplied and make the scheme more sustainable. Before any detailed design takes place this should be investigated fully to give accurate estimations of the energy available. Its inclusion should not be over looked.

The use o wind energy is a feasible option. Calculations have shown based on current site data that a second turbine could produce theoretically 1.25GWh of the required heat demand. The turbine is subject to strict planning regulations and its approval cannot be guaranteed.

Industrial waste heat is a heat sources cited as having major advantages of a DH scheme. Despite being a very attractive heat source and the potential to be an exemplar case for such integration. The lack of available information means its potential benefits cannot be understood. This however, should be a corner stone of the detailed design phase.

4.2.5 Biomass plant sizing and optimisation

With biomass being identified as the most suitable heat source a plant sizing exercise is conducted to estimates costs of a 100 % biomass system and to allow a financial analysis.

The biomass sizing tool is used to estimate the optimal sizing of the thermal store, auxiliary boiler and biomass boiler. The following graph Figure 31 displays the possible boiler sizes as a percentage of the peak load, size of thermal store and % of energy derived from biomass for the heat demand of Bowmore.

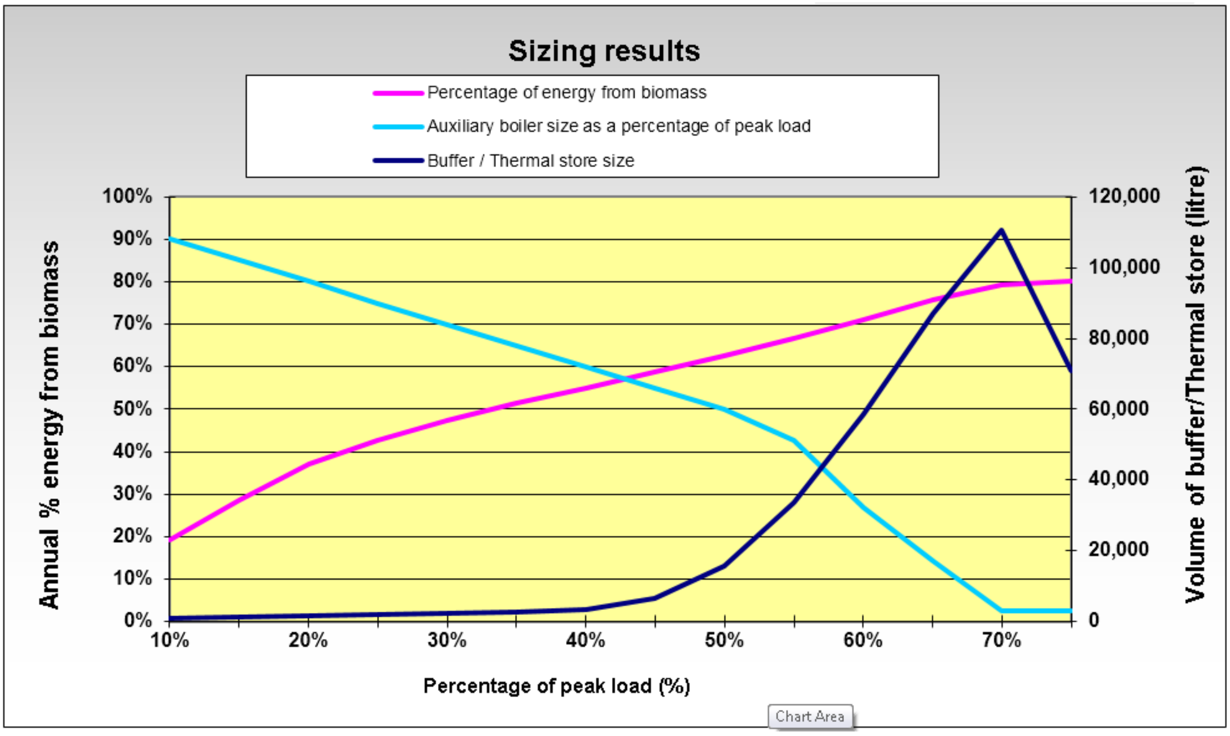


Figure 31-Sizing results from biomass sizing tool

For each size of boiler the corresponding size is thermal store is calculated. The point at which there is no benefit to increasing the thermal store size in this case is 70%. From this graph three possible size configurations are selected to investigate the optimal sizing of the system. The results for a biomass system sized to 50, 55 and 60% of the peak load are displayed in table (6).

Table 6-Plant sizing results part 1

		Option 1	Option 2	Option 3
Percentage of peak load	(%)	50	55	60
Biomass boiler capacity	(kW)	1,005	1,101	1,201
Minimum buffer vessel size	(litre)	6,900	7,500	5,100
Thermal store size	(litre)	27,300	54,800	61,100
Percentage of energy from biomass	(%)	62.8	66.8	71.6
Auxiliary boiler size (kW)	(kW)	993	844	525
Total system cost	(£)	1,769,500	1,824,500	1,855,000
Annual fuel cost from biomass	(£)	229,770	244,413	262,000
Annual fuel cost if use conventional sources	(£)	424,903	424,903	424,903
Annual cost saving	(£)	182,901	183,306	183,906
Simple payback	(years)	9.7	10	10.1
20year NPV	(£)	4,101,000	4,099,819	4,143,000
Estimated RHI payment (1st year)	(£)	127,835	127,835	127,835

The key performance indicators were selected as total system cost, payback period and renewable heat incentive (RHI) payments. These financial performance indicators are considered the most critical, as these will ultimately govern the feasibility of the scheme in real world applications.

Parameter	50% of peak load	60% of peak load	70% of peak load
Total system cost £	£1,769,000	£1,825,000	1,855,000
Payback period (years)	9.7	10	10.1

RHI payments £	127,835	127,835	127,835

The system sized to 50% of the peak load was selected as the most financially viable and therefore used in subsequent calculations. A boiler sized to 50% of the peak demand requires an auxiliary boiler sized 993kW.

Next the boilers suitability to meet the summer load needs to be assessed. This is done by considering the annual load curve.

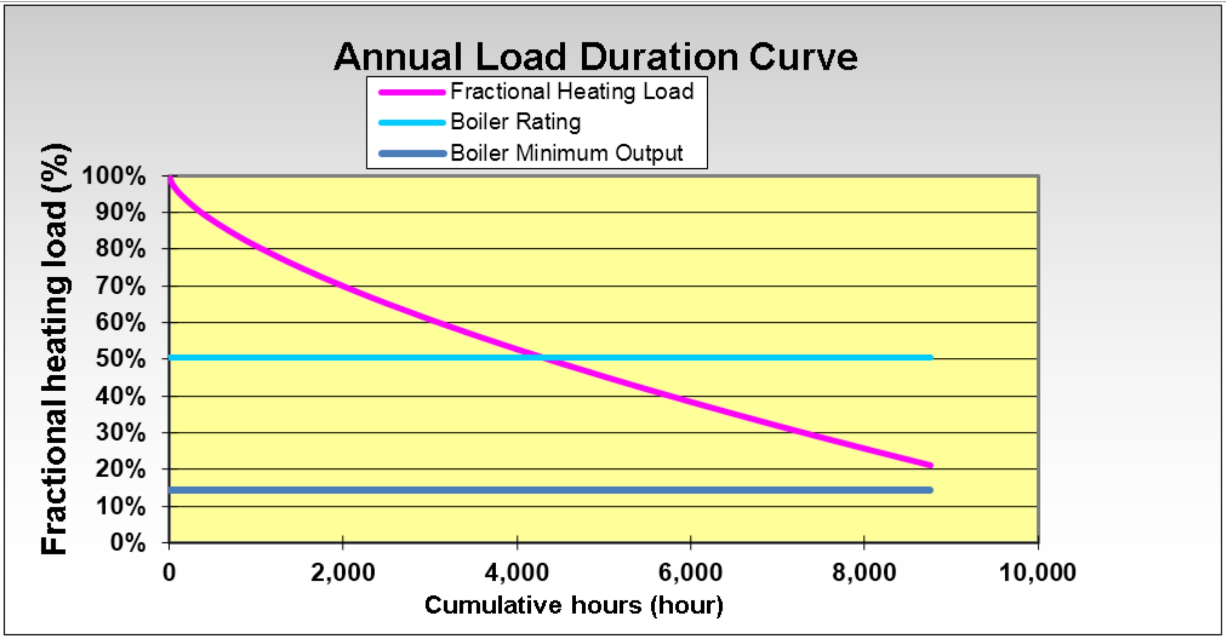


Figure 32- Annual load duration curve for 50% of peak load

It can be seen that the selected 50% boiler is sufficiently sized to meet summer load conditions using its turn down feature. The next step in the biomass sizing tool is sizing of the thermal store.

Thermal store sizing

After sizing the boiler the thermal store can designed to the correct size to balance the system. Figure 31 shows the relationship between boiler size and thermal storage volume graphically.

One consideration at this stage is the available space for large quantities of storage. As two large sites have been selected for the plant there are no real storage constraints in this design case.

The following variables are used in the calculation.

Location	Outdoor
Position	Vertical
Length (l)	3m
Outer diameter of vessel (b_0)	2.75m
Insulation thickness (α)	13mm [59]
Insulation type	Polyurethane

The assumptions give the Giving a tank with a volume of 17332 litres with a design day heat loss of 73kWh. The results in this case show that inclusion of a thermal store is beneficial for the overall system performance.

The final financial analysis of the system is contained in chapter 4.8.

4.3 Existing Low carbon infrastructure and location of back up boiler

4.3.1 Existing Infrastructure

Bowmore already has two existing Biomass boilers. The location of these is displayed in Figure 33, one serving the heating needs of the primary and high school, the other serving the hospital and residential care home.

The high school in Bowmore runs are 360kW wood chip boiler. This is a moving grate style boiler which runs on wood chip fuel manufactured by Schmid- energy.

The hospital features a ETA 200kW Hack burning chip boiler. The cumulative output of this boiler can be seen in Figure 20.

If a DH scheme was to be implemented in Bowmore then the heating demand of the schools and hospital should be included to act as anchor loads. This would mean either including the existing biomass boilers or disconnecting them. Disconnecting the boilers makes little economic sense. Including the boilers as a secondary heat source in the network is feasible, however the details of such a design should be covered in the detailed design phase as this adds layers of complexity in maintaining system pressure and temperature out width the scope of this study.

The inclusion of the school’s biomass system may increase its performance. The system would supply; a larger a heating load, be used more hours of the day and be used through the school holidays. These changes would increase the diversity factor for the boiler supply. This improves performance and financial viability of the existing scheme.

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Figure 33-Sites of existing low carbon infrastructure

4.3.2 Location of back up boiler

The site selected for the primary energy plant is sufficient in size to also contain the backup boiler. The same assumptions for the location of the primary source are held for the backup.

4.4 Optimising system temperatures

Temperature

The design parameters for selecting the design temperatures of a DH network according to [6] are;

- The flow and return temperatures must be compatible with existing heating systems in full and part load conditions.
- External design temperature. Through this study this is assumed to be -3 °C.
- The level of control given to consumers through the two-port control valves.
- The minimum temperature need for the consumer at the most radial point of the network (furthers from plant).
- The effect of external air temperature on the temperature curve of the system.
- Be within material properties for the piping used.

If the current heating systems found in homes are kept, avoiding extensive retrofitting work, upheaval and significant cost then the DH scheme should be designed to use comparable temperatures to the existing heating systems.

Traditional two pipe radiator systems in the UK are designed to work at supply temperatures of 82 °C and return temperatures of 71 °C [6] . High temperatures are used to reduce the surface area required for radiators. If retaining existing heating devices the accepted practise is to use a 85°C/65°C supply/return balance. Achieving this drop in temperature through the radiator requires limiting of the flow rates through radiators.

Fundamentally the trade of comes between using lower temperatures, reducing system losses and higher temperatures ease of use and economic feasibility. The CIBSE guide [4] states that if using existing radiators temperatures of 80/60 can be achieved due to the oversizing of most conventional radiators and highlights that in reality a scheme would be conducted in conjunction with demand reduction measures, allowing for lower temperatures.

A supply temperature of 80°C and return of 60°C are used for subsequent calculations.

The paper [60] outlines a novel technique using plate radiators connected to double string heating circuits demonstrating that integrating lower temperatures into exists ting radiators is possible . However this is not recommended as being out width the scope of this report.

4.5 Distribution Grid

Network transmission and distribution heat loss is a factor that it is critical to optimise when designing a DH system. The detailed design of the distribution network is a complex task done using advanced optimisation software. For the purpose of this feasibility study a simple representative design is used in order to estimate design parameters.

The main factor influencing heat loss and therefore distribution efficiency is network leakages. The most common reason for leakages are; ‘micro damages’ in the pipe lines, leakages at heat distribution units or leakages of working fluid caused by a repairs.

The average rate of heat loss in DH systems lies within the range of 7.6% - 27.8% [61]. Designing a system to minimise these losses will reduce the primary energy demand, however may increase the capital investment required [9]. Pre insulated pipes are the most common due to performance and ease of installation. Reinsulated pipes are governed by seven European standards [62-68]. The paper [69] identifies four categories which affect the heat losses of a pipe under normal working conditions; Operational data, thermal conductivity, geometry of pipes and pipe arrangement.

There are several pipe configurations available, flexible pre insulated pipes (symmetrical and asymmetrical), double pipes and triple pipes.

There are three fundamental equations which govern the distribution network. The first is the first law of thermodynamics:

$$Q = \dot{m} \times \ c_p \times \Delta T$$

Where Q heat measured in watts, $\dot{m}$ is the mass flow rate, c_p is the specific heat capacity of water in kilojoule per kilogram per kelvin and ΔT is the temperature difference between feed and return lines in kelvin.

The second can be approximated to the fundamental equation governing heat exchangers:

$$Q = U \times A \times \Delta T_{ml}$$

Where U is defined as the overall heat transfer coefficient measured in watts per square meter per kelvin), A is the heat transfer surface area in square meters and T_{ml} is the log-mean temperature difference measured in k. The log mean temperature difference is the temperature drop between primary and secondary flow circuits in the heat exchanger.

The third equation relates to the friction losses in the system and flow rate constraints. The pressure lossess can be estimated by the sum of two terms in turbulent flow.

$$\Delta P = \Delta P_c + \Delta P_d$$

Where ΔP_c is the localised pressure loss and ΔP_d is the distributed pressure loss. Both ΔP_c and ΔP_d are composed of an empirical co-efficient K, which is derived from the characteristics of each individual pipes giving the equation:

$$\Delta P = K_1 \times \dot{m}^2 + K_2 \times \dot{m}^{1.87}$$

The temperature and pressure of the distribution system decrease as the fluid moves as from the plant. Meaning the most radial point will have the minimum temperature and pressure and correspondingly the point nearest to the plant will have the highest temperature and pressure.

4.5.1 Network Layout

Several provisional layouts are designed in order to allow estimation of cost and network losses. Three possible routes are designed and then one selected to be used in subsequent calculations.

There exists a profound gap in the literature and in industrial knowledge regarding the layout of DH heating networks. Current standards feature an iterative trial and error layout method attempting to minimise piping length. Other factors which determine the route include; desire to minimize disruption caused by installation, minimise cost by routing through soft standing ground i.e, avoiding digging up roads and allowing ease of access.

As any such project enters the detailed design stage modelling programs such as NETSIM [26] or Termis [26] would be used to optimise the lay out, location of pumps, expansion values and other components to maintain working temperature and pressure.

4.5.1.1 Potential Network layout 1

Layout 1 is displayed in Figure 34. Where the solid black lines represent the DH pipes. The schematic for the system can be viewed in Figure 35. Using the block diagram format used in [70].

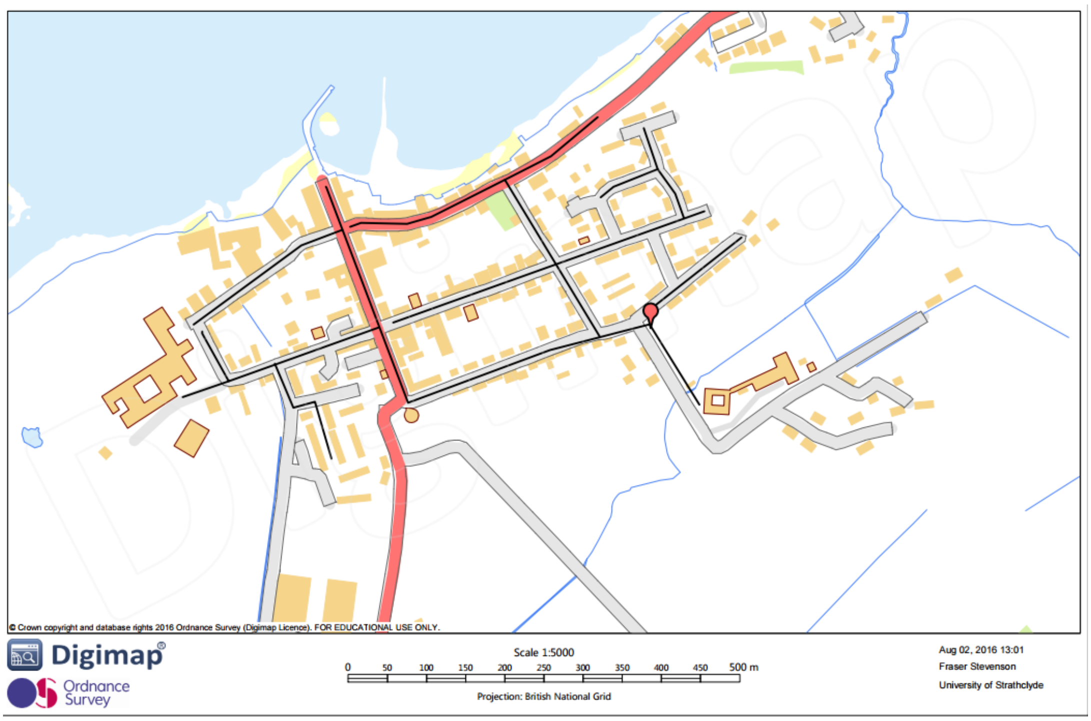


Figure 34-Layout option 1

The pentagon in the following diagram represents the plant, squares represent existing non domestic customers and green blocks representing the potential sources of renewable heat inputs and blue existing low carbon infrastructure.

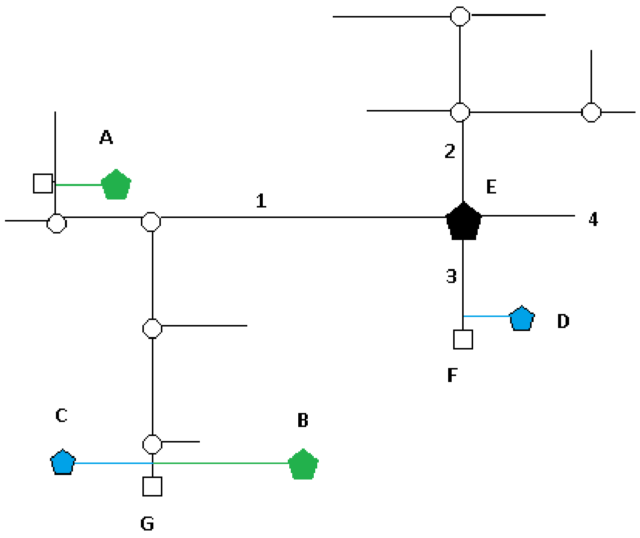


Figure 35- Lay out option1 – schematic

KEY

- A- Waste industrial heat from distillery
- B- Water source heat pump from water treatment plant
- C- Biomass boiler at school
- D- Biomass boiler at hospital
- E- Proposed plant centre
- F- Hospital
- G- Schools

The approximate length of each branch rounded to nearest 50m is given below.

Branch length

1- 1350m
2- 1300m
3- 150m
4- 150m

Total length- 2950m

This network is composed of three primary branches. Branches 1 and 2 are approximately the same length so are assumed to have similar domestic supply demands. Branch 1 does supply two non-domestic buildings and has two potential renewable energy sources.

4.5.1.2 Network Layout 2

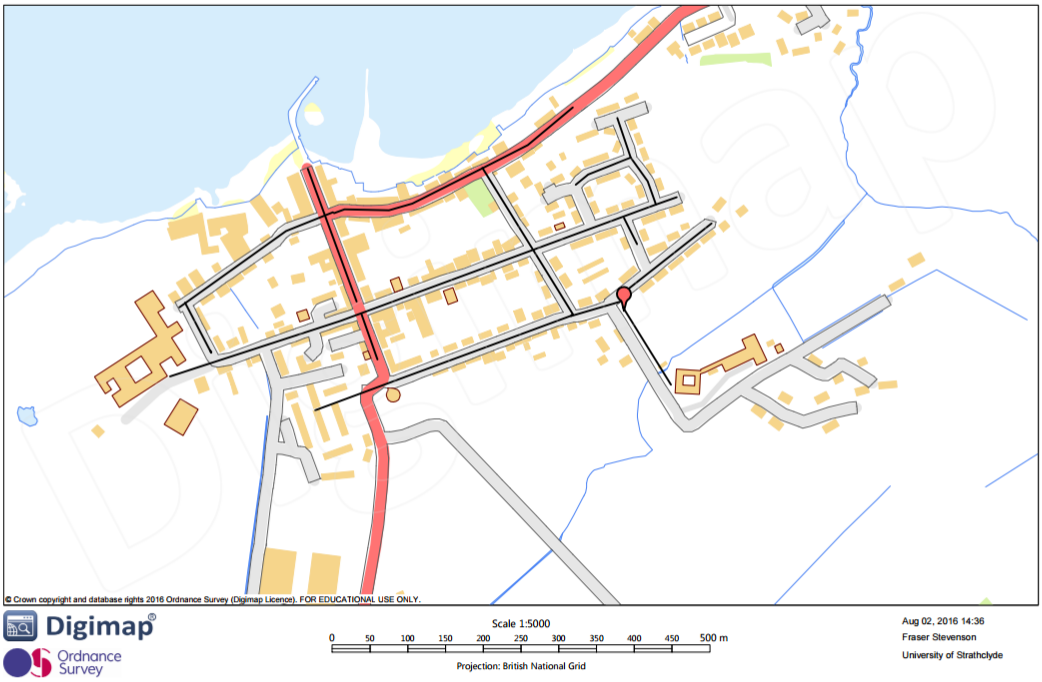


Figure 36-Layout option 2

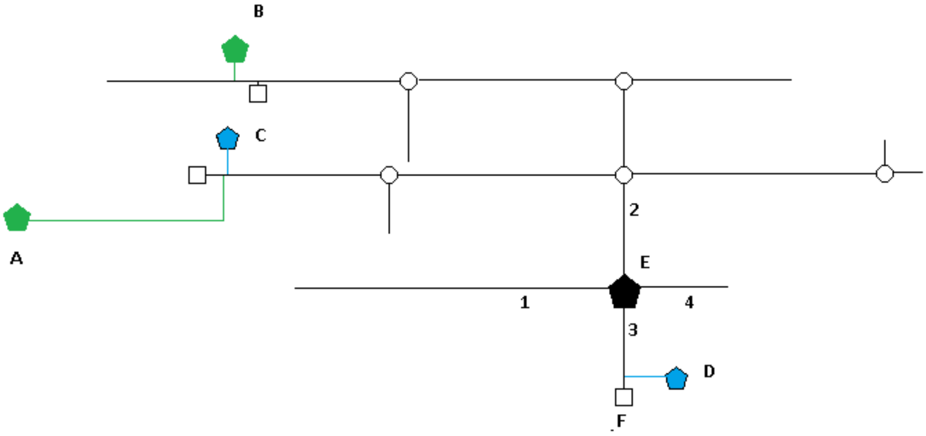


Figure 37-Lay out option2 – schematic

KEY

H- Waste industrial heat from distillery
I- Water source heat pump from water treatment plant
J- Biomass boiler at school
K- Biomass boiler at hospital
L- Proposed plant centre
M- Hospital
N- Schools

Branch length

1- 400m
2- 2100m
3- 150m
4- 150M

Total length- 2800m

The second layout options features one main branch, branch 2 that is far more substantial than the other branches, serving the vast majority of the heating demand, both industrial loads, both possible renewable energy sources and the schools biomass system. This means that this branch, particularly the early nodes, will carry more heat, increased pipe dimensions and therefore cost.

4.5.1.3 Network Layout 3

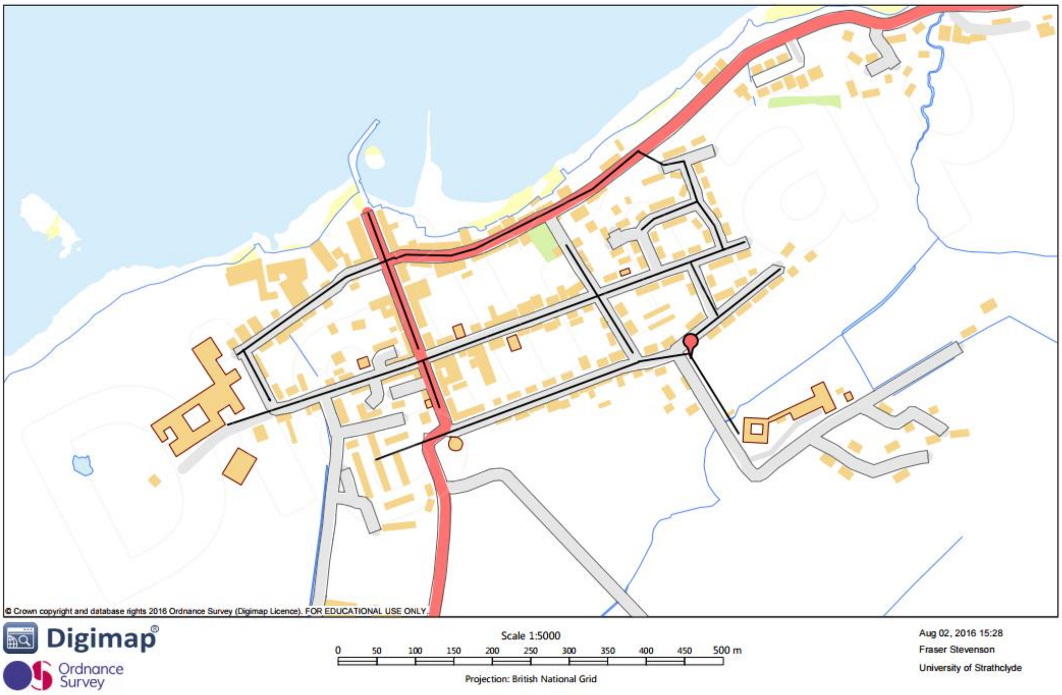


Figure 38-Layout option 3

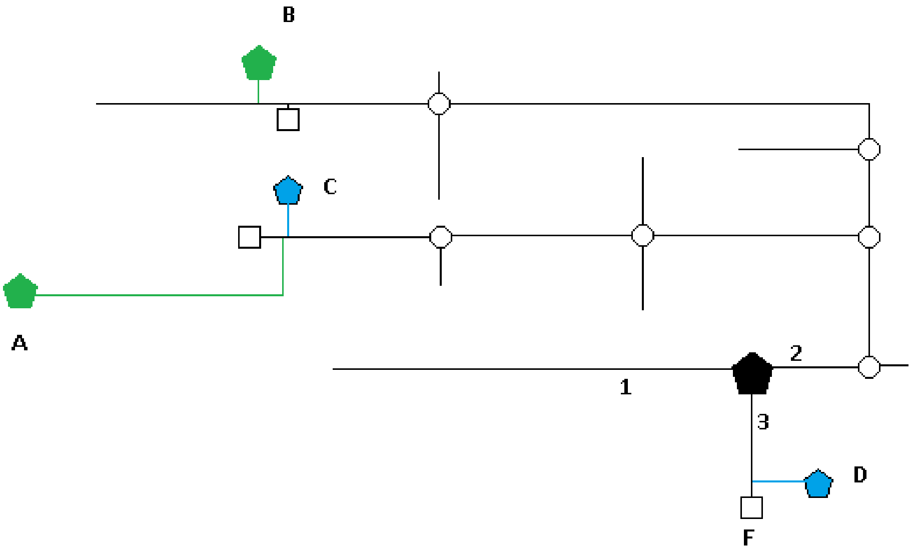


Figure 39-Lay out option3 – schematic

KEY

- O- Waste industrial heat from distillery
- P- Water source heat pump from water treatment plant
- Q- Biomass boiler at school
- R- Biomass boiler at hospital
- S- Proposed plant centre
- T- Hospital
- U- Schools

Branch length

5- 400m
6- 2100m
7- 150m
8- 150M

Total length – 2800m

4.5.1.4 Linear heat density

As the shortest trench length is 2.8km this is selected as the routing length for subsequent calculations allowing the linear heat density can now be calculated for the above design options.

Annual heat demand= 9,155,149 kWhr

Pipe length = 2800m

$$Linear\ heat\ density = \frac{Annual\ energy\ demand\ (MWhr)}{length\ (m)}$$

$$Linear\ heat\ density = \frac{9{,}155\ (MWhr)}{2800(m)}$$

$$Linear\ heat\ density = 3.27$$

This linear heat density is now compared to the % of annual losses recorded in study [23] to give an estimation of the system losses that could be expected.

Using the results from the Austrian study heat losses of 9.1% can be expected. The results from Denmark show around 11% and the Finish results 8.6%. The average of these is taken to be 9.7%.

4.5.1.5 Pipe sizing

Each pipe must have the capacity to accommodate the hot water required to meet all loads down stream of it in the network. The method of calculating the max hot water demand requires calculation of the coincidence factor [71]. The coincidence factor is a measure of how likely it is that the maximum hot water demand for each dwelling will be drawn at the same time. The factor of confidence is given below [71].

$$FC = \frac{DFR}{MFR}$$

Where DFR = design flow rate for downs stream hot water outlets (l/s) and MFR = maximum possible flow rate for downstream hot water outlets. The diversity factor recommended by CIBSE AM12:2013 [71] for use with multiple dwellings is shown in Figure 40.

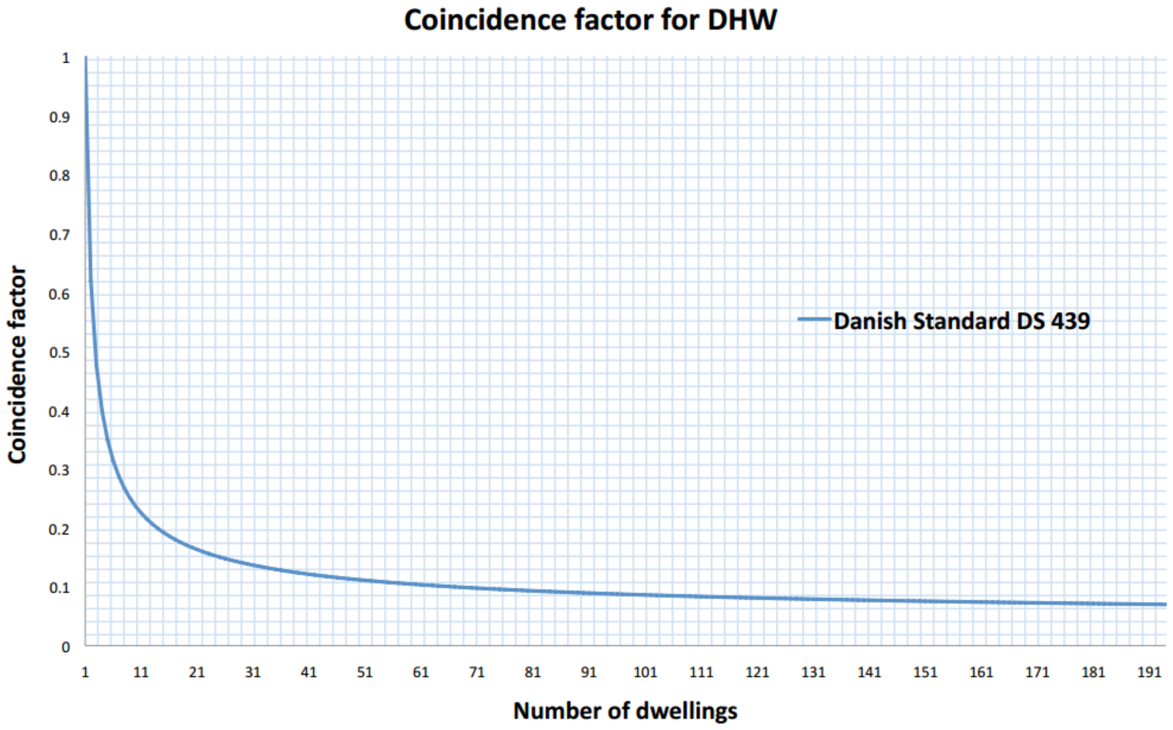


Figure 40-Diversity factor for multiple dwellings given by CIBSE AM12:2013

The gold standard for diversity factor calculation for DHW is the Danish standard DS 439 calculation method. The equation used is [4];

$$P_{max} = 1.19 \times N + 18.8\, N^{0.5} + 17.6$$

Where P_{max}=total rate heat required for dwellings in kW and N is the number of buildings defined as ‘normal’. In DS 439 a normal dwelling is defined as having 3.5 residents, with a bathroom containing either a bath or shower. The number of ‘normal’ dwellings can be calculated from a number of real dwellings. The calculation of N requires building survey results beyond the scope of the project. However, according to [4] residential buildings with more than 200 average sized dwellings is found to be less than 3kW for space heating and 2kW for hot water.

Flow rates for pipe sizing

Using a methodology set out it [71]the maximum design flow rate for the system is estimated. The flow rate at any given section will have to be sufficient to meet all subsequent heating and hot water demands. Thus the overall flow rate in district (Q_T) in l/s will be given by;

$$Q_T = (FQ_{DHW}) + (Q_{HTG})$$

A coincidence factor F of 0.55 is assumed from Figure 40. QDHW is the heating water flow rate required to meet peak domestic hot water demand (l/s) and QHTG is the heating water flow rate required to meet peak heating demand (l/s). These two terms are calculated as follows;

$$Q_{DHW} = \frac{P_{DHW}}{4.2 \times \Delta T_{\gamma}}$$

And

$$Q_{HTG} = \frac{P_{HTG}}{4.2 \times \Delta T_{\beta}}$$

PDHW is the power requirement (kW) for all downstream hot water heaters and where T_{γ} = design temperature drop across the district heating side of the heat exchanger during hot water production (see section 4.5 for details). PHTG is the power required (kW) for heating downstream loads, taken as the peak design day load and ΔT_{β} is the temperature drop across heat exchangers.

$$Q_{DHW} = \frac{176}{4.2 \times 20}$$

$$Q_{DHW} = 2.095$$

$$Q_{HTG} = \frac{2090}{4.2 \times 20}$$

$$Q_{HTG} = 24.9$$

$$Q_T = (FQ_{DHW}) + (Q_{HTG})$$

$$Q_T = (0.55 \times 2.095) + (24.9)$$

$$Q_T = 26(l/s)$$

4.6 Domestic Connections and metering

4.6.1 Connections and Substation design

The most common method of connecting district heating into a home is by replacing the existing boiler with a heat exchanger unit. Existing radiator systems need not be replaced if suitable supply and return temperatures are used. The pumps fitted to the system for circulation are designed for the pressure loss across conventional boiler plant. The heat exchanger is designed with a lower pressure drop so existing pumps do not need replacement [5]. Double piped radiators will rarely need replaced. Single pipe radiator systems offer greater challenge as they are designed to ensure higher return temperatures. In this case, conversation to double piped radiators should be considered.

Here there is a trade-off between the principles of fourth generation district heating and cost. The choice is between ensuring the lowest possible supply return temperatures and reducing the extent of retro fitting required. To utilise low supply temperatures under floor heating or another heating technologies with a very large surface area is required while high supply temperatures allow the use of existing radiators but increase system losses.

There are two types of connection method direct and indirect. The direct connection method involves no hydraulic separation between DH network and customer’s network. This is the cheapest option however limits the max flow temperature. The indirect method is more expensive as there is hydraulic separation, this allows a variation is supply temperature to meet demand and reduce risk of contamination of DH water and means the responsibility for supply inside the dwellings lies with the customer [6].

The following section outlines several variations of indirect connection methods. There are several designs of substation possible for district heating and district hot water heating.

The paper [72] investigates several of these solutions and their performance through real world results. Five possible substation set ups are investigated. These studies were conducted into low temperature water systems. In these systems water is not hot enough some applications namely water used for washing dishes or in some causes to prevent the growth of legionella [73]. Where this is the case direct electric heating is used to provide the extra heat required.

Here the effect of using a hot water tank and direct electric heating is evaluated between fourth generation DH substation designs.

Substation 1 features a storage tank and the DHW from the tank is used directly through a plate heat exchanger. When using a hot water tank it is important to ensure sufficient temperatures to avoid the growth of legionella[73]. A diagram displaying option 1 is shown in Figure 41.

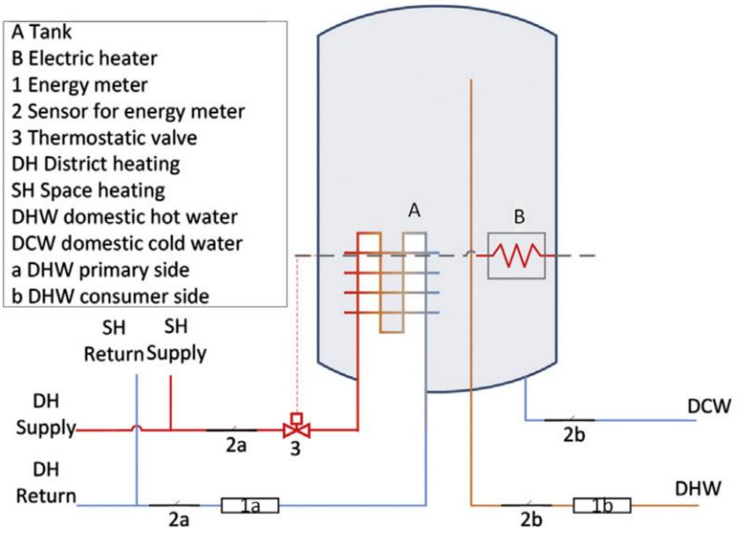


Figure 41-Substation design 1

Substation 2 is similar in design to S1 however it features a heat exchanger on the consumer side of the storage tank. Heated water is stored in the tank. Allowing the instantaneous heating of hot water reduces the risk of Legionella.

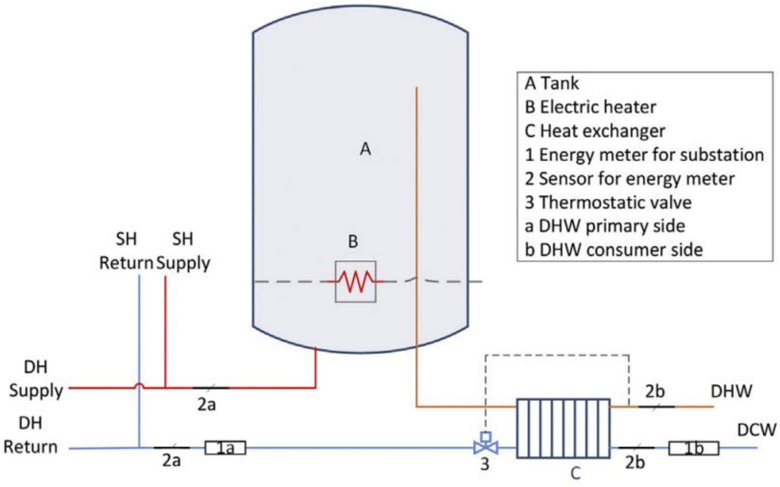


Figure 42-Substation design 2

Substation 3 uses a micro heat pump and storage tank before the heat exchanger. In this configuration the DHW is used as a source for the heat pump.

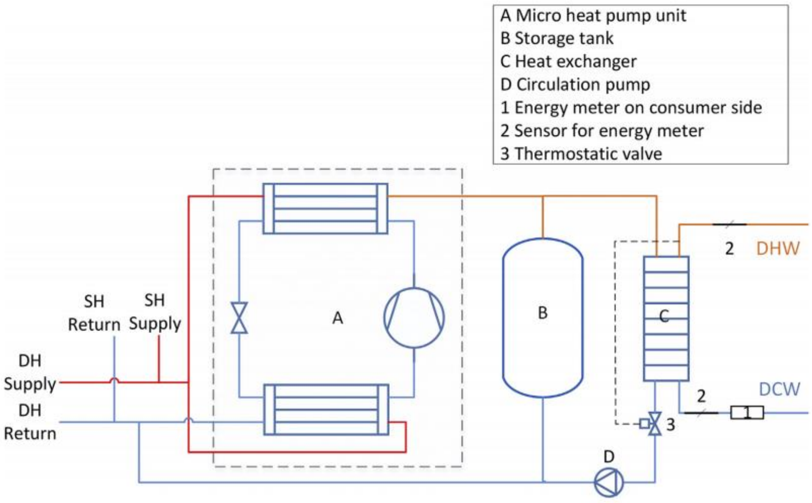


Figure 43-Substation design 3

Substation 4 does not use a hot water storage tank. A plate heat exchanger sits between the DH supply and the DHW. This has the benefit of saving space in homes. In places where hotter water is required such as hotter water taps a direct electric heater is installed.

Substation 5 also does not feature a storage tank but instead an electric heater is used to heat the total DHW flow. There is a plate exchanger between DH supply and DHW

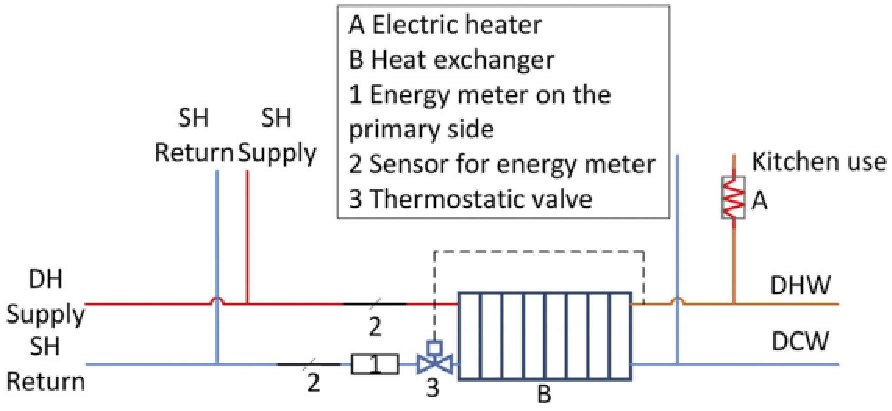


Figure 44-Substation design 4

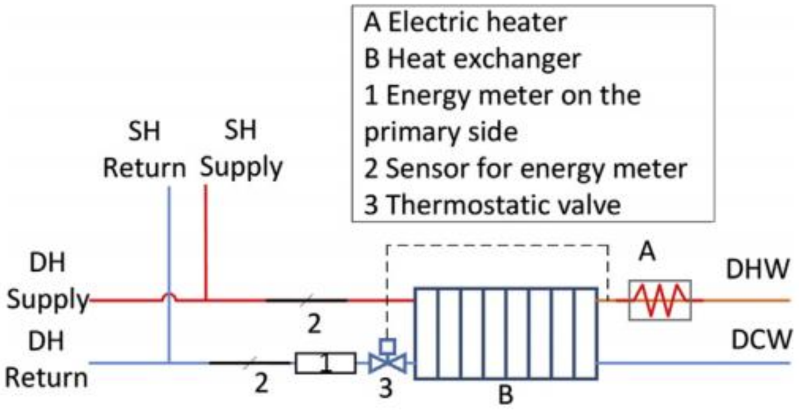


Figure 45-substation design 5

Results

The results from the testing of substation design is outlined below.

The use of a water tank causes a trade of between two factors. The tank can act a buffer and help to shave off peak demand, however, storing the water leads to heat losses reducing the efficiency of the system.

The findings of the study were that substations 1,2,3 and 5 all had higher costs than standard third generation designs. It found that due to more efficient use of heat by reducing losses through the system designs 4 and 5 can reduce the integrated energy cost by 33-50% compared to systems with storage tanks. These results are shown in Figure 46.

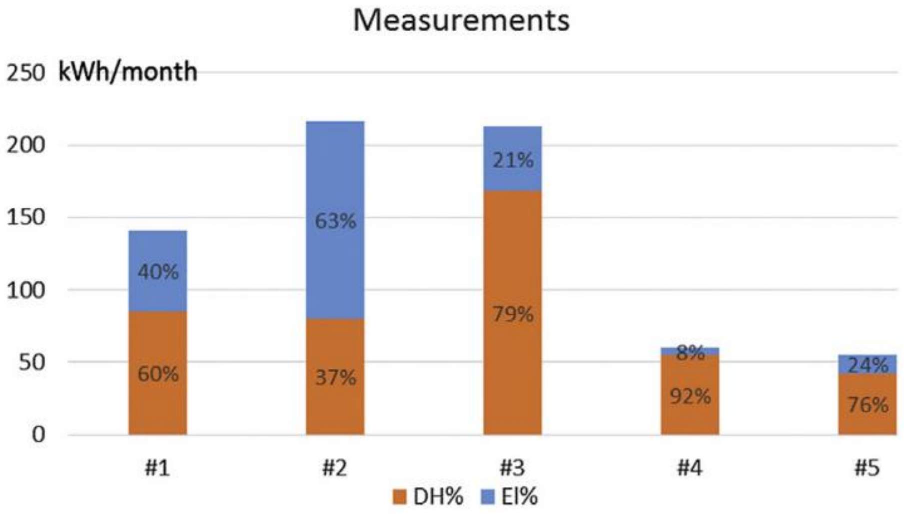


Figure 46-Measured heat and electricity delivered for DHW preparation in the five substations for May

The costs associated with each substation are shown below in table (7)

Table 7-Substation cost - [70]

		S1	S2	S3	S4	S5
Capital Investment	£/home	1320	1650	4400	1210	1760
Operation and maintance	£/home/year	26.4	33	88	24.2	35.2
Integrated energy price	£/Kwh	0.176	0.165	0.253	0.088	0.11
Standardised cost	£/kWh	0.242	0.253	0.484	0.154	0.209

These results show that substation designs 4 and 5 have the lowest standardised cost. These costs however are based on idealised circulations, real world results may differ.

The best performing substation design was substation design was S4. The connection type is also the cheapest costing on average £1210 per home. This figure is used in the subsequent financial analysis. He S4 design also has the lowest operation and maintenance cost at £6 per quarter.

4.6.2 Heat Metering

The metering point is usually placed at the customer connection as the location of the metering point will determine the financial responsibility for heat and heat losses.

The common components for heat metering are; a flow meter, temperature sensors and heat calculator. The general arrangement of these components can be viewed in Figure 47. These meters are owned, maintained and installed with capital from the heat supplier. The method of transmitting the recorded data will depend on the quantities of heat supplied. There are three main types of meter, manual reading, automated reading and smart meters.

Automated meter reading- Meters which can communicate wirelessly with the central data base through mobile signal or optical cable. AMR avoid the expenses of having to manual take readings and give detailed usage and demand profiles use full for future modelling and understanding demand on consumption profiles.

Smart meters- Are the next generation of automated readings offering very high spatial and temporal energy readings. They allow very accurate modelling of demand data and usage profiles, down to the particular individual consumer level.

Smart meters are recommended for use in this DH network. Smart meters are on route to becoming the new standard metering equipment. As they offer greater temporal resolution and real-time feedback of heat consumption data. This data can be used for billing purposes and to help improve the quality of the supply and operation of the system. An in depth review of the benefits of smart meters can be viewed [74, 75] .

Smart meters are not without their draw backs. The real time availability of energy consumption data remotely indicates if a house is occupied, if appliances are in use and occupancy patterns. The availability of such data means that the security of the network may be considered as a main concern [76].

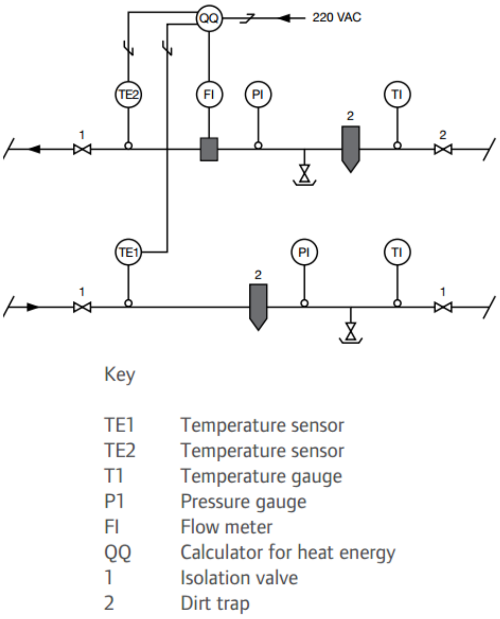


Figure 47-Configuration of heat meter

The document [77] sets out estimations for the pricing of metering of DH equipment. These can be viewed in table (8) and are used in subsequent financial analysis.

Table 8-Cost estimates for metering [75]

Cost description	Cost per Dwelling
Capital cost of heat meter	£212
Capital cost of installation of heat meters	£80
Capital cost of data gathering system	£62
Capital cost of installation of data gathering system	£93
Running costs	£81

4.7 Minimise negative effects of phasing developments

The phasing of building a new district heating network in Bowmore is simplified due to several factors;

- No new builds are currently being planned. New housing associations buildings are currently being built to the south east of Bowemore. These however are fitted with air source heat pumps.
- Heat demands are already established so there would be no significant build up in demand or agreements as when to connect and build plant.
- There are little limits to the selected plant site in terms of expansion.

4.8 Financial analysis for biomass system

A full table containing the financial results for the 100% biomass system can be viewed in Figure 48. The results of using a 1,000kW boiler sized to 50% of the load are shown. The results from the biomass sizing tools built in financial analysis take account of the returns available from renewable heat incentive (RHI) payments, fuel cost saving and internal rate of return.

The indicative total capital cost of the system is was calculated to be £1,952,000. This is a combination of user defined inputs and standardised inputs from within the biomass sizing tool where these variables were unknown. An annual consumption of 9.7GWh takes into account the distribution losses of a DH network. There is scope for this to be reduced as distribution losses were modelled on a worst case scenario. Within the financial modelling the GBP to EUR exchange rate was set to 1.17 (this is important as a large proportion of the service and equipment for DH is manufactured and purchased from Europe). The RPI inflation rate is set to 1.1%.

The annual cost including RHI payments is found to be of £195,909. This is an average cost of £578 per building connected. The 50% sizing option uses £326,374 wood of wood chip per year and £70,827 worth of kerosene in this case.

The source [78] states that the average heating bill for a 3 bedroom home using LPG is between £1800-£2200 per year. The proposed scheme in would offer substantial bill savings to an area with high levels of fuel poverty.

There is uncertainty of sustaining levels of RHI payments. If the RHI payments were to be stopped then the price would increase by £127,835 per annum. This would lead to a yearly increase in house hold bills of £376 to£955.

To assess to effect of increased price of fuel the model was repeated with fuel priced increased by 10%. This would increase the monthly fuel bill to £818.

The payback period for the scheme would be 9.7 years. This is a relatively long payback period if the project were done on a purely economic basis. As previously discussed the scheme offers benefits beyond economic. This also assumes there are no grants given. The help of financial grants could greatly reduce this figure, making it a more attractive proposition.

Limitations to financial model

These results show a strong financial case for a biomass scheme. There several limitations which must be stated regarding these results;

Recommendations regarding heat input from renewable sources mentioned in section 4.3 are not included in this financial model. The inputs form these technologies will reduce the over size of the boiler, reduce the required quantities of biomass fuel and kerosene but increase the capital cost. The inclusions of such technologies will therefore alter much of these financial assumptions.

The UK government seems committed to reducing RHI payments. Figures used in this calculation were correct at the time of calculating them however the most recent update states *"DECC has announced there will be a 15% reduction to the biomethane for injection tariff, a 15% reduction to the small, medium and large biogas tariffs and a 10% reduction to the small commercial biomass tariff, effective from 1 July 2016*."[79]. Although not directly relevant to this project the future RHI incentives available for such schemes cannot be guaranteed, particular if the time scale for reaching accreditation is unknown.

	Biomass boiler	Auxiliary boiler	Overall system
Heating Fuel	Wood chip	Kerosene	
Price per kWh (pence per kWh)	3.66	4.09	
Annual demand (kWh)	9,173,091	9,173,091	9,173,091
Annual consumption (kWh)	6,202,737	3,466,573	9,669,310
Annual cost (£)	227,020	141,725	368,745
CO2 factor (tonnes C02/kWh)	0.00001579	0.000292470	
Annual CO2 emitted (tonnes)	98	1,014	1,112
Electricity			
Price per KWh (pence per kWh)	13.5	13.5	
Annual consumption (kWh)	40,585	14755	55,341
Annual cost (£)	5,479	1992	7.471
CO2 factor (tonnes C02/kWh)	0.0000517	0.000517	
Annual CO2 emitted (tonnes)	21	7.6	28.6
Totals			
Annual consumption (kWh)	6,243,322	3,481,329	9,724,651
Annual cost including RHI	52,193	143,717	195,909
Annual CO2 emitted (tonnes)	118.9	1021.5	1140.4

Figure 48-Financial analysis part 2

4.9 Risk assessment and sensitivity analysis

The paper [80] identifies the following main project risks.

- A fundamental lack of experience and knowledge of UK based customers and suppliers of DH schemes.
- Problems with the logistics of managing the simultaneous development of heat sources plants (or connections to existing sources), building of distribution networks and fitment end user connections
- Significant revenue variability because of lack of understanding of tariffing options, tariffing policy or the exposure to take up risk if long term contracts have not been agreed.
- Concern over the potential for the network to lose its economic viability in the long term if alternate technologies become financially competitive
- Take up risk

Take up risk

The greatest potential risk to any investor or financial stakeholder (sponsor or local authority) is the risk of poor scheme take up. The modelling carried out in this project and financial analysis assumes 100% take up. The paper [80] states that an up take of rate up at least 40% is required for a project to make a return.

The most effective solution for reducing the uptake risk is to ensure a long term contract agreement with anchor loads. The most effective way of ensuring uptake is by offering attractive heat prices and approaching coordinated groups namely;

- new developments,
- housing association
- Large scale commercial buildings.

Other factors which reduce the risk involved for the developer include;

- Availability of waste heat
- Accessibility to low cost sources of heat
- High heat demands

- Electrically heated dwellings or dwellings heated by other more expensive means

With these factors in mind a risk register has been created for Bowmore in line with best practise procedures. This can be viewed in appendix 4.

4.10 Environmental impact

Incorporating low carbon sources of heat should reduce the CO2 emission resulting from the heat used in Bowmore. This is an obviously beneficial environmental impact. However, there are wider environmental impacts to consider. These include local noise pollution, air quality pollution and ecological factors such as the increased wood chip production leading to mono-cropping and loss of habitat and in the case of wind turbines there could be concerns raised over the islands wild bird population. As shown in Figure 49 Islay is covered in a large number of SSSI's (special sites of scientific interest) and special areas of conservation giving the area an important ecological status.

Compared to the reference electric boiler the entirely biomass scheme would result in saving 2373 tonnes of CO2 compared to a reference boiler. Included in this calculation is the electricity used for pumping and heat losses. Not included are the life cycle CO2 emissions of component manufacturing and infrastructure development. This could be increased if a more expensive but more sustainable balance was struck between woodchip fuel and the auxiliary boiler.

The burning of biomass releases small amounts of particulates into the atmosphere- namely SOx and NOx resulting from complete and incomplete combustion respectively. In urban environments the concentrations of these particulates are regulated. The release of the particulates can be curtailed through a series of measures within the combustion process or treatment of flue gasses. The paper [81]explains such processes and methods of predicting there effect.

There are also environmental effects which occur during the harvesting of the crop. These include; Despite carbon neutrality biomass burning is not nutrient neutral, removing nutrients from the soil and ecosystems in which it grows, excessive harvesting can lead to soil erosion and water runoff, a loss of natural habitat and flora leading to losses in biodiversity [82] . The methods of production and the scale at which this would take place on Islay are not deemed to be significant. The current supplies use responsible and sustainable practises raising no concerns over the impact of increasing production.

The locality of the proposed production means minimal transportation avoiding the main criticisms of biomass as a fuel source [83].

Noise and visual impacts are minimised by using existing waste or industrial group for the energy centre, however further research is required into dispersion models, acoustic surveys and planning permission requests during the detailed design phase.

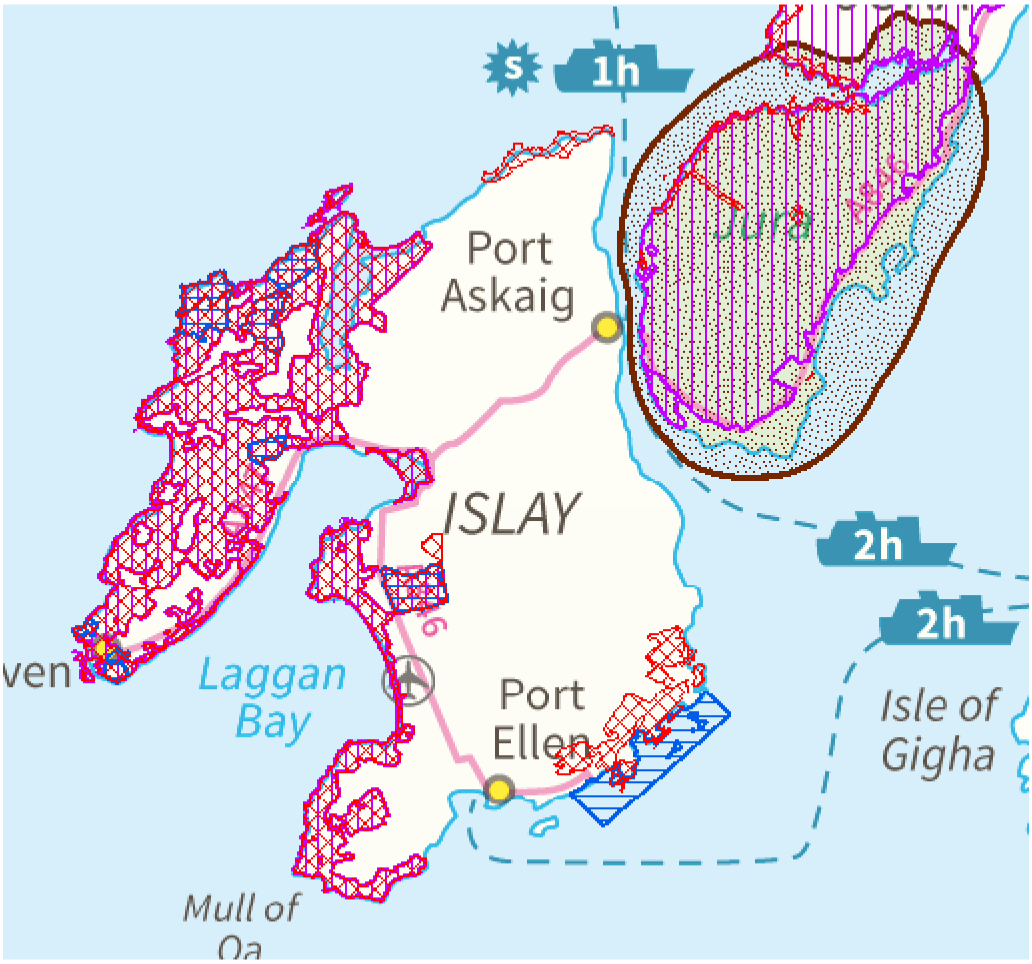


Figure 49-Designated sites on Isaly [84]

4.11 Business and Contractual structures

Any change to the energy network on either a large or small scale will cause economic redistribution of assets and effect local economic and social factors. This reorganisation will both benefit some and hinder others meaning effective planning and legislative measures must be put in place.

As with other renewable energy technologies DH is rarely economically viable without government incentives. Investments into such schemes are capital intense dissuading initial investment without guarantees of security or high returns.

The main challenge for policy makers and investors- private and public- are summarised by [7].

“The first is to decide where to have district heating and where not to have it; the second is to decide to which extent heat should be produced versus the implementation of energy conservation; the third is how to motivate a suitable integration of fluctuating RES including the integration with other parts of the overall energy system.”

The success of district heating in the majority of cases is based upon attractive policy and subsidies. This means that much of the DH market is removed from the normal forces of competition which effect natural markets [85]. Here possible business for DH heating schemes will be discussed. Taking examples from the mature and developed Swedish market where 50% of heat is derived from district heating.

Research [86] has shown that capital investment is the single biggest limiting factor to DH Schemes. In mature markets incoming cash flow can reduce this effect, however in emerging markets such as Scotland subsidies from local and national government much provide help.

In the absence of these types of support there exists four types of ownership: municipally owned, privately owned, private and public partnership and stake holder owned [24].

Increasingly the societal and environment credentials of DH schemes has made them attractive investment for financial actors namely pension funds, social capitalists and impact investors. DH heating schemes typically offer long term secure investments with sustainability profiles.

The fourth generation of district heating principles change these market energy barriers. By reducing the demand through energy saving buildings the potential revenue derived from a system. In doing so it reduces the peak demand, limiting initial investment costs. The inclusion of other actors such as waste heat from industrial processes further reduces initial capital cost and the running costs of the system instead shifting a price risk onto customers [86]. DH schemes can be particularly successful in projects where there is a shared interest, with cooperation in creating a shared value economy [87].

The contracts required for a district Heat scheme fall into three categories [88]

Works Elements	Service Elements	Property agreements
Design	Energy purchase	Sale or lease of operational land and buildings
Construction and connection to premises	Generation of heat and electricity	Easements, rights of way and access arrangements
Financing	Operation and maintenance	Street work licence
	Metering and billing	
	Connection of new customers	
	Supply of heat and electricity to connected customers	
	Customer services	

Here four possible structures are explained in detail.

Energy supply (ESCo)

An energy supply company (ESCo) who is responsible for supplying heat to customers builds and operates a system to that means. The ESCo may be responsible for a defined area, region or group of buildings.

This type of contract must be a long term master or concession contract in order to ensure the repayment of initial investments. Concession contracts should be used if the future demand is uncertain in order reduce risk. This type of contract shifts risk between ESCo and project sponsor. In cases of new builds the connection cost and work can be agreed between ESCo, developer and sponsor. In the case of a retro fit the ESCo can offer its own terms to the relevant public or local authority.

Supply agreements would be put in place between ESCo's and customers. These would set boundaries for price, complains procedure and penalties for failure to meet standards. Multiple types of customer contracts may exist, usually separate for residential and commercial customers.

Service level agreements (SLA) exist between ESCo, sponsors, customers and developers. This contract has four levels, each between one shareholders and provides a set of standards to which the operation of the system can be held accounted to. This contract and the master agreement define the rights of the shareholders and the step-in rights given a failure of the ESCo to meet its standards.

Wholesale heat supply (DBO)

In design build and operate contracts the project sponsor appoints a single contractor to design build and operate the scheme which provides whole scale electricity. This electricity is then sold by the sponsor to the customer. This contract type is favourable to project sponsors as it shifts all risk -except the credit and demand risk- to the contractor.

The most important features of the contract are the price of heat, the required availability and standards of performance. In this way the contract structure is similar to a PFI contract. Another similarity is the possible need for alternative financing agreements.

DBO contract will typical be long term in order to allow the initial investment to be repaid. DBO contracts have the advantage of ensuring reliability of supply as the contractor will receive penalties for failure to meet agreements. However, the incentive for the contractor to minimise cost only exist at the contract tenure stage. After this point the contractor would benefit from any increases in cost. In DBO operate contracts the sponsor retains the relationship with the supplier, despite not being responsible for reducing the heat.

Network delivery and operation (NDO)

A sponsor appoints contractors to design, operate and build the scheme while retaining the responsibility and risk involved. This involves separate design and build, operate and maintenance contracts.

This type of contract is beneficial in the case of having few, defined types of customer. IN this type of contract the sponsor retains ownership of the assets, customer relations and responsibility for pricing. Here the sponsor holds all risk. NDO does have the benefit of allowing the sponsor to have ease of access to low cost finance and low cost heat sources. NDO contracts should be tighter and more defined than other contract types as the risk remains with the sponsor post construction and throughout the life cycle.

The operating contractor should work with the building contract in order to approve the design of the plant they will be running and work with sponsor to ensure the correct guarantees from the build contractors.

Operation and Maintenance (OM)

OM contracts are typically implemented for retrofitting, upgrading or expansion or a scheme by a developer. These schemes are typically shorter contracts with all risk lying with the sponsor. A contractor is unlikely to accept a contract with performance penalties as the value of these contracts to the contractor are not worthy of the risk leaving shortcomings in performance likely causes of disputes.

Contracts for Metering and billing

In the case of small district heating schemes it is usually beneficial to contract a metering and billing company to carrying out this service. Specialist companies have the facilities, including credit, to carry out these tasks more efficiently unless the economies of scale for much larger schemes mean that setting up services to conduct these tasks becomes viable.

Contract recommendation

A DBO operate style contract is recommended for any project of this kind. This is based on the theoretical assumptions that; DBO operate contract offer the greatest security of supply and financial stability for the sponsor. This conclusion was echoed during interviews with representatives from Argyle and Bute council the operators of the current biomass systems on the island.

5 Results, conclusions and suggestions for further work

5.1 Results

The results have shown district heating in Bowmore to be a viable option. Several important design parameters of the scheme have been calculated namely heat density and linear heat density. Both of these indicators of feasibility are well above the prescribed levels found in literature.

There is a large scope for inclusion of various renewable energy sources to supplement to proposed biomass scheme. Identified in this paper are electricity generated by wind turbines powering either a direct electric boiler to a storage vessel or powering a waste water heat pump. Identified but not fully considered due to lacking accessible data and time constraints include waste industrial heat from the Bowmore distillery and using the waste products from the distillery to form a biogas fuel.

As with the literature review done for this study the relevant results for each step of the feasibility for each section are included within the respective sections. The final recommendations made by this report to be taken into the detailed design phase are summarised below in table (9).

Table 9-Final Recommendations of feasibility study

Design parameter	Chapter	Recommendation /Result
Overall heating load	4.1.5	9.15GWh
Possible renewable heat sources	4.2.4	Wind, Biomass, Heat from waste water, industrial waste heat
Size of Biomass plant scaled to meet 50% of load	4.2.5	1005kW
Simple payback period	4.2.5	7.6years
Carbon emitted	4.10	2373
Optimal system temperature	4.4	80/60°C
Approximate length of network	4.5.1.2	2800m
Connection method	4.6.1	No individual storage tanks, indirect connection with additional direct electric heating. Estimated cost per dwelling £1210
Financial analysis	4.8	Fuel costs-£195,909 Initial capital cost- £1952000 RHI revenue per year -£127,835
Risk analysis	4.9	Risk register can be seen in Appendix 4
Environmental impact	4.10	Positive environmental impact with correct design considerations
Contractual structure	4.11	Design build operate contractual agreement

5.2 Conclusions

This report allows several conclusions to be draw regarding a DH network in Bowmore, the selected approach methodology and the CIBSE guide.

The first conclusion is that Bowmore is dense enough, spatial and linearly for a DH scheme. Therefore despite initial preconceptions this should not consider as a barrier to its implementation.

Secondly Bowmore is sufficiently well endowed with renewable sources of heat to meet a significant part of its heating demand through sustainable technologies. This report due to time constraints has not analysis these source in depth, however heavily recommends a thorough assessment to be conducted. This report has assumed that all of the heating load will be met by biomass, which is feasible using locally sourced wood chip.

Geographically Bowmore is well suited to a DH scheme, it futures densely packed terraced housing, wide streets and is off the gas grid. There are several disadvantages though; primarily the lack of new builds and aged housing stock. New builds are much easier to incorporate low temperature heating systems in to while incorporate low temperature heating schemes into existing, particularly aging housing stock can be very disruptive and technically challenging. Inversely the aged nature of Bowmore s housing stock and the fuel poverty levels of the area my mean that this is an upgrade worth the disruption. In reality thermal efficiencies measures should be implemented before any DH scheme. This is discussed [89].

5.3 Critical evaluation of 'CIBSE guide A'

Only section 2 'feasibility study' of the guide will be evaluated.

The CIBSE guides aim is to set minimum and best practise standards throughout the industry. This aim is well intended as the industry is developing and still immature. The code of practise is written to –'improve the quality of feasibility studies'. The extent to which it achieves this aim can be questioned.

The code sets out a series of minim standard requirements for each stage of the feasibility study. The minimum standard requirements are at times basic and will only raise the standards of the work of someone with very limited knowledge of DH schemes. If this is the case then the guide lacks sufficient depth or referencing to allow the engineer or layman to make a well informed and objective decision. Minimum requirements such as; *'Consideration shall be given to the principles of hydraulic control to be employed to ensure that use of the low carbon heat supply source is maximised, especially where multiple heat generation sources and distributed boilers are used.'* give an example of this as no further information is given. Recommendations are made regarding the design of the system without giving a methodology for meeting these goals.

The code offers no method of tailoring its guidelines to each individual proposed network. It leaves the role of assessing which factors- from an extensive list- are the most relevant to the designing engineer. Moreover, it does not provide guidance on whether or not an objective has been fully defined to a high enough standard. There is no governing or authoritative text to assess how thoroughly the guidelines have been implemented.

This limits the codes usefulness as a legislative text. In its current form it may not be designed as such, however, the political and regulatory frame work needed to drive the implementation of district heating networks require by definition a legislative structure. In failing to perform in such a way it may have little effect in improving standards in heat networks very far.

The code does not give guidance of the most effective methodology for addressing the feasibility section of the report. For example the objective 'Identification of low carbon eat sources' precedes analysis of existing infrastructure. The logical progression would be to fully understand existing demand along with the existing supply before considering possible low carbon sources. As in the case of Bowmore, the existing biomass boilers were selected due to advantageous local conditions.

In essence the document lacks teeth. In order to truly improve the standards of DH CIBSE and the relevant bodies should be given an authoritative role with reports such as this carrying the necessary legislative power.

One major flaw in the feasibility section of the report is that it does not consider the social aspects of a DH heating scheme. As previously discussed these are critically important to a schemes success. A brief summary of the type of consideration what is lacking in terms of social considerations is set out below.

5.3 Unaddressed social implications of DH schemes

Despite the environmental and cost benefits offered by district heating there are social implications to the infrastructure required in such a scheme. A fundamental criticism of DH planning models is that they do not include these social factors at the design stage. The study [87] looks at social aspects concerning one variable-the choice of fuel- but there has been little work done into public opinion of DH networks.

The study [87]sites the ultimately decisive factor as cost. The studies summary of the attitudes towards different factors are outlined below. In this study people were not given any prior knowledge about district heating schemes.

Cost: There was variance in public's perception of cost. Some expected much higher cost for green technologies while others thought they would be low relative to other non-renewable alternatives. Uncertainty also existed over the level or existence of government subside, a decisive factor. Despite initial investment costs most people thought the cost of fuel and energy would be lower.

Ecology; Participants agreed with the environmental aspects and benefits of district heating schemes. Green credentials are sought after by many communities and community groups.

Network design: The building of the energy centre and laying of the piping network are concerns, like any large scale infrastructure project for those effected. The issue of where the pipes would be laid and through whose properties can lead to social tensions. The paper [87] sates that the restoration of land used in building is a prerequisite. Studies conducted into heat loss from pipes can be found [90-92].

Bowmore is has several features which make the layout of a DH network easier, reducing the disruption during construction and maintenance;

There are no major barriers to be crossed such as major roads, railways, rivers or canals.. Care would have to be taken not to block the A864, the primary road through the town which links either end to the rest of the island. The grid style layout witch the town follows means that with the correct phasing of works this should not be an issue.

Bowmore is set out with wide streets and wide pavements in the majority of cases. Despite being hard standing pavements offer several advantages to roads for running pipe work under. There should be no need to lay pipes under any building, existing or planned. Detailed drawings of existing utilities were not available given time and resource constraints, however should be assessed for the detailed design phase.

5.4 Suggestions for further work

This report has begun to assess a DH scheme for Bowmore. Further work should be conducted into each of the 11 sub chapters of the feasibility study. The most pressing areas of study would be to fully analyse the renewable sustainable heating resource available and how these would be connected to the DH network, maintaining supply and return temperatures of the network if they are located at radial points.

The renewable sources investigated are not an exhaustive list. The technologies invested were dictated by a screening study bone with Argyle and Bute council. This was based on council policy and political landscape at the time of study. This does not mean that the most effective technologies were considered, solar thermal heating, bio-gas production from distillery waste are two technologies which should be looked into closely.

Waste heat from the distillery was deemed to be key to the success of the DH scheme. Given the cooperation of the distillery and leisure centre an analysis in to the available would valuable to any future scheme.

A detailed lay out of the distribution network is not conducted here. This is a substantial area of study in its own right. The modelling packages for such a study are listed in 4.5.1.

To fully assess the CIBSE guidelines the project would have to continue to fruition using the objectives of the code. This would allow any short comings or benefits of using the guides to come to light.

6 Appendices

Appendix 1 – Scottish heat map report for Bowmore

Scotland Heatmap

Heat Demand

Total Heat Demand: 10 GWh/yr
Public Heat Demand: 2 GWh/yr
Energy Supply: 1

Summary Information

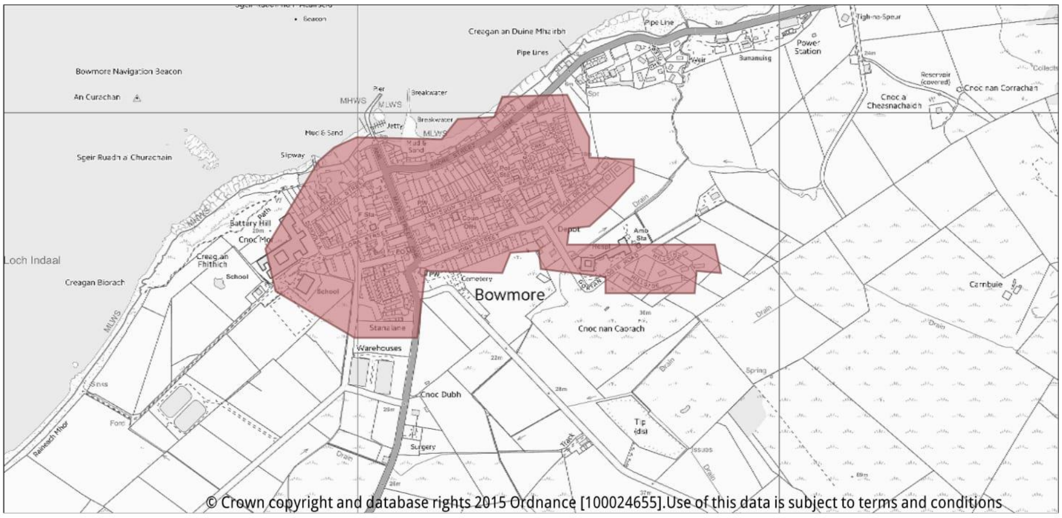
Area: 0.329 km2
Report Centre: X: 659756 | Y: 131321

Additional Information

Local Authorites Covered:
Argyll and Bute

Data Zones Covered:
S01007326, S01007327

Reporting Area



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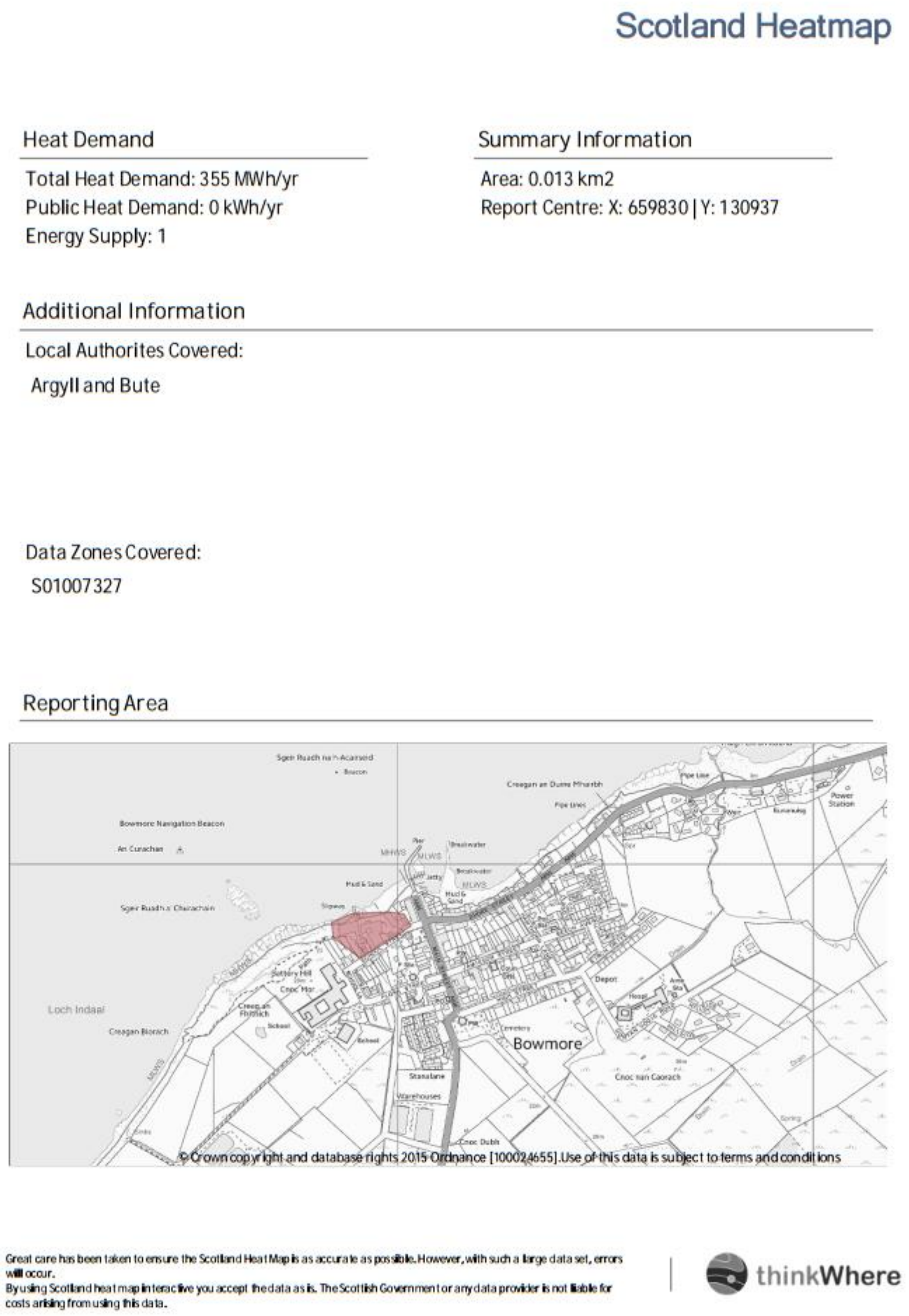
Appendix 2 - Scottish heat map report for Bowmore distillery



Scotland Heatmap

Heat Demand

Total Heat Demand: 355 MWh/yr
Public Heat Demand: 0 kWh/yr
Energy Supply: 1

Summary Information

Area: 0.013 km2
Report Centre: X: 659830 | Y: 130937

Additional Information

Local Authorities Covered:
Argyll and Bute

Data Zones Covered:
S01007327

Reporting Area

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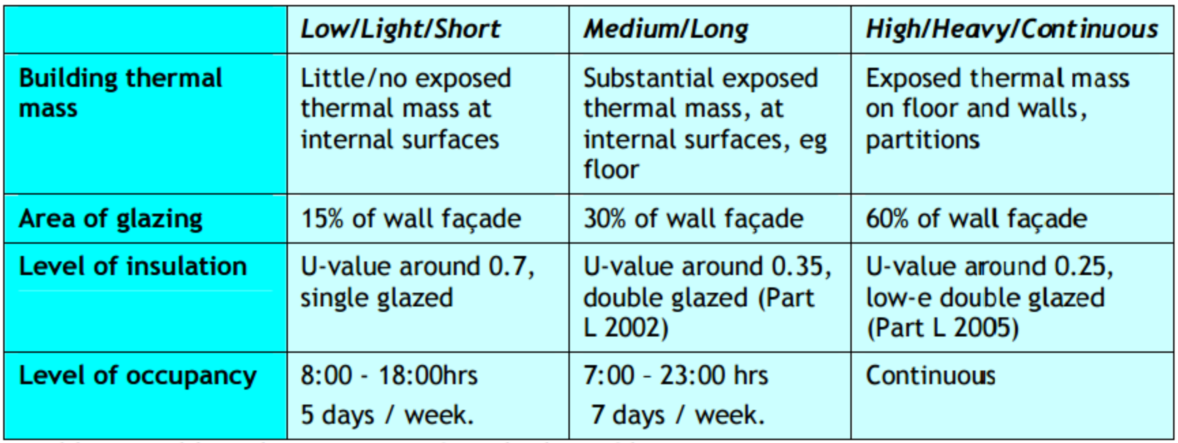
thinkWhere

Appendix 3- Definitions for biomass sizing tool



	Low/Light/Short	*Medium/Long*	*High/Heavy/Continuous*
Building thermal mass	Little/no exposed thermal mass at internal surfaces	Substantial exposed thermal mass, at internal surfaces, eg floor	Exposed thermal mass on floor and walls, partitions
Area of glazing	15% of wall façade	30% of wall façade	60% of wall façade
Level of insulation	U-value around 0.7, single glazed	U-value around 0.35, double glazed (Part L 2002)	U-value around 0.25, low-e double glazed (Part L 2005)
Level of occupancy	8:00 - 18:00hrs 5 days / week.	7:00 - 23:00 hrs 7 days / week.	Continuous

Table 1: Building characteristics for inbuilt profile generation.

Appendix 4- Risk register

Likelihood	Impact	Risk score	Risk level	Comment
1	4	4	low	Air quality control measures will be impended to reduce impact.
3	2	6	med	The remoteness of the project adds risk. Construction cost effect capital investment but have small effect over project life time
1	3	3	low	Good existing relationship with supplier, however, two suppliers have monopoly over local wood chip supply.
2	3	6	med	Bowmore is off mains gas grid leaving it more susceptible to price Fluctuations in imported fuel. This price could fall making project Less viable, however it is more likely to rise. Uncertainty of future Levels of government funding and subsidies.
1	3	3	low	Local authority is projects prosperity and planning authority.

				Planning may be an issue if wind turbines are included.
2	2	4	low	Large proportion of load is domestic, privately owned properties, however, strong sense of community and recent over Subscription to wind turbine project.
2	2	4	low	Local authority already operates similar schemes in the area and it wou

7 References

1. IEA, *Energy Technology Perspectives 2012- Pathways to a Clean Energy System.* https://www.iea.org/publications/freepublications/publication/ETP2012_free.pdf, 2012.

2. change, D.o.E.c., *The Future ofHeating: Meeting the challenge*, H.S. Team, Editor. 213: London.

3. DECC, *Delivering UK Energy Investment*. 2014, HM Government

4. CIBSE, *Heat networks:Code of Practice for the UK*, T.A.f.E. CIBSE, Editor. 2015: London.

5. Bard Skagestad, P.M., District Heating and Cooling Connection Handbook, Programme of Research, Development and Demonstration on District Heating and Cooling. IEA.

6. BRE, *A technical guide to district heating*. 2014, IHS BRE Press: Watford

7. Henrik Lund , S.W., Robin Wiltshire , Svend Svendsen , Jan Eric Thorsen ,Frede Hvelplund , Brian Vad Mathiesen, *4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainabl energy systems.* Energy, 2014.

8. D. Connollya, H.L., B.V. Mathiesena, Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renewable and Sustainable Energy Reviews, 2016. **60**: p. 1634–1653.

9. B.V. Mathiesena, e.a., Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy, 2015. **145**: p. 139–154.

10. Lund., H., Renewable Energy Systems-A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. Second Edition 2014: Academic Press.

11. al, H.L.e., *Heat saving strategies in sustainable smart energy systems.* International journal of sustainable energy planning and management 2014. **4**: p. 3-16.

12. X.S. Jianga, Z.X.J., Y.Z. Lia, Q.H. Wua, W.H. Tanga, Modelling and operation optimization of an integrated energy based direct district water-heating system. Energy, 2014. **64**(1): p. 375-388.

13. D. Connolly, H.L.B.V.M.S.W., B. Möller , U. Persson ,T. Boermans , D. Trier , P.A. Østergaard , S. Nielsen *Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system.* Energy Policy, 2014(65): p. 475-489.

14. al., X.C.e., Energy saving and emission reduction of China's urban district heating. Energy Policy, 2013. **55**: p. 677-682.

15. Boyle, K. DISTRICT HEATING & HEAT NETWORK DESIGN.

16. Engineers, M.F.C., A case against the widespread use of district heating and CHP in the UK 2010(3).

17. Energy, A., Scottish Heat Mapping Project – companion report 2007, EST

18. C. Loredo, N.R., A. Ordóñez, *Modelling flow and heat transfer in flooded mines for geothermal energy use: A review.* International Journal of Coal Geology, 2016(IN PRESS).

19. Niu, Y., Research on Thermal Energy Recycling Utilization in High Temperature Mines. Procedia Engineering, 2015. **121**: p. 389-395.

20. al., G.F.e., Low enthalpy heat recovery potential from coal mine discharges in the South Wales Coalfield. International Journal of Coal Geology, 2016(IN PRESS).

21. Nielsen, S., A geographic method for high resolution spatial heat planning. Energy, 2014(67).

22. Power, P., Powering Edinburgh into the 21st century. 2006.

23. Thomas Nussbaumer, S.T., *Status Report on District HeatingSystems in IEA Countries*. 2014, IEA Bioenergy Task 32, Swiss Federal Office of Energy, and Verenum, Zürich 2014.

24. M, K., *Community Energy: Planing, Development and Delivery* 2012: INTERNATIONAL DISTRIC ENERGY ASSOCIATION

25. Deborah Roberts, E.V.-T., Euan Phimister, *Fuel poverty in the UK: Is there a difference between rural and urban areas?* Energy Policy, 2015. **87**: p. 216-223.

26. ; Available from: http://www.schneider-electric.com/en/product-range/61418-termis-software/.

27. Census, S., 2011.

28. CIBSE, CIBSE Gide A: Environmental design CIBSE, Editor. 2006.

29. Mattia De Rosa, V.B., Federico Scarpa, Luca A. Tagliafico, *Historical trends and current state of heating and cooling degree days in Italy.* Energy Conversion and Management, 2015. **90**: p. 323-335.

30. Underground, W. 25/07/2016]; Available from: https://www.wunderground.com/q/zmw:00000.4.03102?sp=EGPI.

31. professionals, D.D.W.d.f.e.; Available from: http://www.degreedays.net/.

32. strathclyde, U.o., Heating Demand profile generator (H.D.p). 2007, ESRU.

33. Strathclyde, U.o., CASE STUDY Riverside Community, Stirling.

34. Scotland, N.R.o., Argyll & Bute Council Area - Demographic Factsheet. 2015.

35. Scotland, E.

36. Trust, C., Biomass Boiler System Sizing Tool, User Manual. . 2013.

37. Scotland, E. 26/07/2016]; Available from: http://www.educationscotland.gov.uk/parentzone/myschool/findaschool/schools/islayhighschoolargyllbute.asp.

38. DECC, Assessment of the Costs,Performance, and Characteristics of UK Heat Networks. 2015: Kew, London

39. MOSELEY, M., *BEST PRACTICE IN DISTRICT HEATING NETWORK DESIGN*, R.u.p. solutions, Editor. 2014.

40. solutions, R.-U.p. *DISTRICT HEATING & HEAT NETWORK DESIGN PRESENTATION BY KENNY BOYLE*. 2015; Available from: http://www.usewoodfuel.co.uk/media/411085/k._boyle-district_heating_and_heat_network_design_bridge_of_allan_11_mar_2014.pdf.

41. H. Averfalk, P.I., U. Persson, S. Werner, *ON THE USE OF SURPLUS ELECTRICITY IN DISTRICT HEATING SYSTEMS.* The 14th International Symposium on District Heating and Cooling,, 2014.

42. Simon Gill, M.J.D., Damien Frame, Graham W. Ault, *THE ROLE OF ELECTRIC HEATING AND DISTRICT HEATING NETWORKS IN THE INTEGRATION OF WIND ENERGY TO ISLAND NETWORKS.* International Journal of Distributed Energy Resources, 2010. **7**(3): p. 245-263.

43. Yaxiu, G., Huqiu, D., Yu, G., Huanjuan, Z, *The potential of urban wastewater heat: The feasibility analysis of using wastewater source heat pump.* Water Resource and Environmental Protection, 2003: p. 1481-1484.

44. Change, D.o.E.C., Renewable sources of energy: Chapter 6, Digest of United Kingdom Energy Statistics (DUKES). 2015: London.

45. R. Saidur , E.A.A., A. Demirbas, M.S. Hossaina, S. Mekhilef, *A review on biomass as a fuel for boilers.* Renewable and Sustainable Energy Reviews, 2011. **15**: p. 2262–2289.

46. Palmer, D., Tubby, I., Hogan, G. and Rolls,W., *Biomass heating: a guide to medium scale wood chip and wood pellet systems*. 2011, Biomass Energy Centre, Forest Research, Farnham.

47. Rasmus Lund , U.P., Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy, 2016. **Article in press**: p. 1-10.

48. Cordin Arpagaus, F.B., Jürg Schiffmann,Stefan S. Bertsch, *Multi-temperature heat pumps:A literature review.* International journal of refrigeration, 2016. **69**: p. 437-465.

49. DECC, Heat Pumps in District Heating. 2016.

50. David J. Durrenmatt, O.W., A mathematical model to predict the effect of heat recovery on the wastewater temperature in sewers. . Water Research 2014. **48**: p. 548-558.

51. Florian Kretschmer , L.S., Thomas Ertl, Analysing wastewater temperature development in a sewer system as a basis for the evaluation of wastewater heat recovery potentials. Energy and Buildings, 2016. **128**: p. 639-648.

52. Oguzhan Culhaa, H.G., Emrah Biyikc, Orhan Ekrend, Arif Hepbasli, *Heat exchanger applications in wastewater source heat pumps for buildings: A key review.* Energy and Buildings, 2015. **104**: p. 215-232

53. Sara Simona Cipolla, M.M., Heat recovery from urban wastewater: Analysis of the variability of flow rate and temperature. Energy and Buildings, 2014. **69**: p. 122-130.

54. Fang, e.a., Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy 2015. **86**: p. 589-602.

55. BCS, Waste Heat Recovery: Technology Opportunities in the US Industry.Waste Heat Recovery: Technology Opportunities in the US Industry, 1–112. 2008.

56. Association, T.S.W., Scotch Whisky Industry Environmental Strategy Report. 2015: Edinburgh.

57. Tingting Fang, R.L., Genetic optimization of multi-plant heat production in district heating networks. Applied Energy, 2015. **159**: p. 610-619.

58. Inger-Lise Svensson, J.J., Thore Berntsson, Bahram Moshfegh Excess heat from kraft pulp mills: Trade-offs between internal and external use in the case of Sweden—Part 1: Methodology. Energy Policy, 2008. **36**: p. 4178-4185.

59. Adams, A., *Bringing thermal energy store vessels to life.* Renewable Energy Focus, 2016. **17**: p. 121-123.

60. Michele Tunzi , D.S.Ø., Svend Svendsen, Rabah Boukhanouf , Edward Cooper, Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings. Energy, 2016. **113**: p. 413-421.

61. J. Danielewicz , B.S., M.A. Sayegh , N. Fidorow, H. Jouhara, Three-dimensional numerical model of heat losses from district heating network pre-insulated pipes buried in the ground. Energy, 2015. **Article in press** p. 1-13.

62. (CEN), E.C.f.S., Preinsulated bonded pipe systems for underground hot water networks – Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene. EN 253:2009. 2009, CEN: Brussels

63. (CEN), E.C.f.S., Preinsulated bonded pipe systems for underground hot water networks – Fitting assemblies of steel service pipes, polyurethane thermal insulation and outer casing of polyethylene. EN 448:2009. 2009, CEN: Brussels.

64. (CEN), E.C.f.S., Preinsulated bonded pipe systems for underground hot water networks – Steel valve assembly for steel service pipes, polyurethane thermal insulation and outer casing of polyethylene. EN 488:2011. . 2011, CEN: Brussels.

65. (CEN), E.C.f.S., Preinsulated bonded pipe systems for underground hot water networks – Joint assembly for steel service pipes, polyurethane thermal insulation and outer casing of polyethylene. . 2009, CEN: Brussels.

66. BSI, District heating pipes – Preinsulated bonded pipe systems for directly buried hot water networks – Surveillance systems. BS EN 14419:2009. 2009, BSI: London.

67. BSI, District heating pipes – Preinsulated bonded twin pipe systems for directly buried hot water networks – Twin pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene. BS EN 15698-1:2009. 2009, BSI: London.

68. BSI, Design and installation of preinsulated bonded pipe systemsfor district heating. , in BS EN 13941:2009. 2009: London.

69. A. Dalla Rosa, H.L., S. Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on heat losses. Energy 2011. **36**(5): p. 2407-2418.

70. Chiara Bordina, A.G., Daniele Vigo. , *An optimization approach for district heating strategic network design.* European Journal of Operational Research, 2016. **252** (1): p. 296-307.

71. FlatStations, D., *FLATSTATION DESIGN GUIDE*. 2015.

72. Xiaochen Yang, H.L., Svend Svendsen, Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating. Energy, 2016. **109**: p. 248-259.

73. DS/CEN/TR16355, Recommendations for prevention of Legionella growth in installations inside buildings conveying water for human consumption CEN, 2012

74. Pepermans, G., *Valuing smart meters.* Energy Economics, 2014. **45**: p. 280-294.

75. R. Pereira, J.F., R. Melicioa, V.M.F. Mendes, J. Martinsc, J.C. Quadradod, *Consumer energy management system with integration of smart meters.* Energy Reports, 2015. **1**: p. 22-29.

76. McHenry, M.P., Technical and governance considerations for advanced metering infrastructure/smart meters: Technology, security, uncertainty, costs, benefits, and risks. Energy Policy, 2013. **59**: p. 834-842.

77. DECC, The metering and billing of district heating, district cooling, and communal heating and hot water systems. 2014: London

78. trading, O.o.f., *Off-grid energy- An oft market study* OFT, Editor. 2011: Fleetbank house, London.

79. OFGEM. Available from: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-non-domestic-rhi.

80. POYRY, The potential and costs of district heating networks. A report to the department of energy and climate change. 2009, Poyry Energy Oxford

81. K. Sartor, Y.R., P. Ngendakumana , P. Dewallef., *Prediction of SOx and NOx emissions from a medium size biomass boiler.* Biomass and Bioenergy, 2014. **65**: p. 91-100.

82. R. Saidura, E.A.A., A. Demirbasb, M.S. Hossaina, S. Mekhilefc, *A review on biomass as a fuel for boilers.* Renewable and Sustainable Energy Reviews, 2011. **15**(5): p. 2262-2289.

83. Md.S. Roni, S.D.E., Erin Searcyb, Jacob J. Jacobson, *Estimating the variable cost for high-volume and long-haul transportation of densified biomass and biofuel.* Transportation Research Part D: Transport and Environment, 2014. **29**: p. 40-55.

84. SNH. *SNHi service* 2016 24/08/2016]; Available from: https://gateway.snh.gov.uk/sitelink/searchmap.jsp.

85. S. Frederiksen, S.W., *District Heating and Cooling*. 2013: Studentlitteratur AB.

86. A. Sandoff, J.W., *Advanced District Heating and Cooling (DHC) Systems* Woodhead Publishing, 2016: p. 293–317.

87. Barbara S. Zaunbrecher, K.A., Tobias Falke, Martina Zieflea., *No pipes in my backyard? Preferences for local district heating network design in Germany.* Energy Research & Social Science, 2016. **14**: p. 90-101.

88. london, M.o., District heating manual for London. 2013.

89. Mattias Gustafssona, M.R., Louise Tryggd, Björn Karlssonb, CO2 emission evaluation of energy conserving measures in buildings connected to a district heating system – Case study of a multi-dwelling building in Sweden. Energy, 2016. **111**(15): p. 341-350.

90. Jean Duquette, A.R., Peter Wild, Thermal performance of a steady state physical pipe model for simulating district heating grids with variable flow. Applied Energy, 2016. **178**: p. 383-393.

91. Tymofii Tereshchenko, N.N., *Importance of Increased Knowledge on Reliability of District Heating Pipes.* Procedia Engineering 2016. **146**: p. 415-423.

92. Rasmus Lund , S.M., Choice of insulation standard for pipe networks in 4th generation district heating systems. Applied Thermal Engineering, 2016. **98**: p. 256-264.