Department of Mechanical and Aerospace Engineering

Community Biomass Heating Networks: Modelling and Evaluation of Future Potential

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Signed: Graeme Flett Date: 6th September 2013

Abstract

Reducing carbon dioxide emissions and fuel poverty are both important goals for the Scottish and UK Governments. Identifying energy solutions that lower both factors is a significant challenge. Community heating networks with a biomass heat source are a potential solution for areas with a suitable demand profile. Although the requirement for guaranteed demand and low investment returns are likely to restrict the use of heat networks to social projects on a non-profit basis.

Increasingly strict Building Regulations are enforcing building fabric improvements and additional renewable microgeneration, to reduce heat demand and the overall carbon footprint. The EU has mandated that by 2020 all new buildings should be 'zero carbon' in-use for heating, water and lighting. As a capital intensive solution, the reduction in demand has the potential to render heat networks uneconomic for new-build projects. Heat networks can also be used as a retro-fit option on existing buildings. In these cases, a higher demand is offset by increased integration costs.

No modelling tools exists that allow small-to-medium scale heat networks to be analysed in detail. An Excel-based tool has therefore been developed based around the SAP 2012 model to allow demand and financial analysis of networks under a wide variety of demand conditions.

The reducing demand was shown to have a significant impact on the unit heat costs of all viable heating systems. Considering total heating system costs, networks were shown to get marginally less competitive in comparison with other sources. However, there remains a range of new-build developments where heat networks remain cost competitive at all expected demands levels.

Biomass heating networks were shown to be significantly more beneficial when all heat related costs, including incremental building fabric and renewable microgeneration costs to meet CO_2 targets, are included. Biomass supplied housing can typically meet targets with the minimum stipulated fabric requirements, while all other alternatives require a significantly higher level of building performance. This additional cost can be of the same order as the heat network cost.

For social housing, where the ongoing use of the network can be mandated, a more integrated approach to building fabric requirements, rent and heat charging, and how emissions targets are achieved could potentially allow the emissions and fuel poverty goals to be achieved.

For retro-fit projects, heat networks benefits were shown to be marginal for the three case studies reviewed. The economics are highly sensitive to the integration cost estimate. Only for areas where 'ECO' grant funding is available would heat networks be clearly viable. Replacement of electric or solid fuel heating systems should be the priority, with limited benefits from replacing gas heating.

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Abbreviations

ASHP – Air Source Heat Pump

BDST – Biomass Decision Support Tool

BR – Building Regulations

BRE – Building Research Establishment

BREDEM – Building Research Establishment Domestic Energy Model

CHN – Community Heating Network

CHP – Combined Heat and Power

EST – Energy Savings Trust

HA – Housing Association

HIU – Heat Interface Unit (Consumer Unit)

HLP – Heat Loss Parameter

MAT – Mean Ambient Temperature

MIT – Mean Internal Temperature

MLRT – Mean Living Room Temperature

MVHR – Mechanical Ventilation with Heat Recovery

O&M – Operation and Maintenance

OAP – (Old Age) Pensioner

PEX – Cross-linked Polyethylene

PUR – Polyurethane

PV – Photovoltaics (solar panels)

RHI – Renewable Heat Incentive (scheme)

ROC – Renewable Obligation Certificate

SAP – Standard Assessment Procedure

SIMD – Scottish Index of Multiple Deprivation

UFH – Underfloor Heating

WHHA – West Highland Housing Association

ZCH – Zero Carbon House (or Zero Carbon Hub if a reference source)

1. Introduction

1.1 Overview

Almost half of all energy use in Scotland is related to heating (and cooling) (ScotGov, 2013a). Reducing the carbon dioxide (CO_2) impact of the heating supply is therefore a key factor in achieving the targeted 42% CO_2 emissions reduction compared to 1990 levels by 2020 (ScotGov, 2013b). In addition, 27.9% of Scottish households in 2010 were classified as being in fuel poverty (ScotGov, 2012a), and the Scottish Government plans to reduce this "as far as practicable" by 2016 (ScotGov, 2013c). Community heating networks have been identified as one of the potential solutions required to meet both the emissions and poverty targets (ScotGov, 2013a).

(Note: The networks described in this study are known variously as 'community heating', 'district heating', 'heat networks', and other combinations of these terms. In the UK, 'community heating' is often used. For this study 'community heating' and 'heat networks' are used, and are interchangeable. 'CHN' is used as an abbreviation for both terms.)

Community heating networks use a centralised source of hot water and a piping distribution network to replace individual building heating units (gas boilers, electric storage units etc.). There are several types of centralised sources that can be used, but typically biomass boiler, gas or biomass CHP (Combined Heat and Power), or waste heat are used for new systems to meet emissions requirements.

Networks can vary in scale from small developments for rural estates, through larger standalone developments for individual housing schemes and non-domestic users, to large district-wide networks encompassing large numbers of private and public consumers. In several European countries, they are used to supply large proportions of the total demand for heat and hot water. In Denmark, for example, the proportion is 61%. Several large European cities, such as Vienna, are supplied by city-wide networks. (Lukosevicius and Werring, 2011).

As a common heating solution globally, the technology associated with community heating is relatively mature. Recent improvements in the piping design, particularly twin cross-linked polyethylene (PEX) piping, has significantly reduced the associated heat loss. Current research focus is on the use of lower temperature networks to further reduce this loss, although this impacts building heating system design as temperature differentials are reduced.

Community heating currently accounts for <2% of the UK heating demand (Poyry, 2009). Barriers to further development and the ultimate UK potential are widely debated (DECC, 2013a; ScotGov, 2013a; Watts et al, 2010), but Poyry (2009) considers that systems will be largely restricted to social housing and community buildings. However, this could still result in up to a 7-fold increase in network capacity depending on market and policy evolution.

The primary reasons for the limited potential uptake of community heating are financial risk, demand variability, consumer expectations, and contractor experience. Community heating requires a large upfront capital investment with limited potential for significant returns (Poyry, 2009), which limits private investment. System income is typically directly linked to demand, and the impacts of consumer behaviour and climate can lead to significant income variability from system to system and year to year. A deregulated energy market means that UK consumers, particularly private-owners, expect to have a choice of energy supplier. Finally, with limited contractor experience, build costs in the UK are higher than more experienced countries (GLA, 2013).

Network business models generally require a guaranteed (anchor) demand over the lifetime of the scheme (up to 40 years for the piping system). For this reason, almost all existing UK schemes are focused on government-funded, non-domestic consumers (schools, hospitals etc.), and social housing. None of the current policy instruments either impel or encourage private home owners to switch to community heating, and extending schemes into mainly private housing developments is rare (e.g. the Lerwick waste energy scheme (Sheap, 2013)).

Heat networks are a potential solution for both new and existing buildings. Each type of project has associated benefits and risks. New-build projects are typically on greenfield or cleared brownfield land which makes pipe installation easier, but the heat demand density is lower. New-build developments can also be designed for efficient pipe routing, with the buildings designed for network connection. For retrofit projects the opposite is true, laying pipes through an existing development and buildings is significantly harder, but demand density is higher in older buildings.

For new-build projects, increasingly strict material, insulation, and emissions requirements in current and forthcoming Building Regulations has and will continue to reduce heat and hot water demand per-consumer. This demand reduction has a direct impact on heat network economics.

The Scottish Government published a roadmap for Building Regulations in 2007, using the 2007 update as a baseline (SBSA, 2007). Successive improvements in energy performance were set for planned Regulations updates in 2010, 2013 and 2016. The 2016 Regulations would require zero net carbon emissions (i.e. in use). Planning regulations will require a 50% building renewable energy supply by 2020, and by 2030 it is expected all new Scottish buildings will be life-cycle carbon neutral (i.e. including all material, construction, and removal related emissions). (SBSA, 2007)

1.2 Project Aim

The primary aim of this study is to determine if community heating networks are currently, and will continue to be, economically viable under Scottish conditions. The modelling need is significantly greater for domestic networks, which have significantly more users and longer piping networks. The analysis focuses on small-to-medium size housing developments (50-300 houses) and, where applicable, adjacent non-domestic consumers. The viability for new-build developments under increasing stringent energy performance requirements, of retro-fitting heat networks to older buildings, and comparative performance against alternative heat sources, are considered.

Community heating is a capital intensive solution, therefore it needs to be determined if financial incentives, potential economies of scale, and appropriate business models exist to maintain an acceptable level of economic risk and return. Existing networks in Scotland have been hampered by both poor design and demand estimation (McIllwraith, 2011). It is therefore critical to determine if existing tools and evaluation methods are suitable given the different business model and risks associated with community heating compared to utility-supplied, individual heating systems.

Biomass boiler heating units are currently the primary heat source for this scale of system, and are used as the basis for this study. Small-scale (<1 MW) biomass CHP (Combined Heat and Power) systems were reviewed but found to be uneconomic, and they currently have reliability concerns, therefore they were not included. Above 1 MW, gas or biomass CHP systems need to be considered.

Biomass heating can significantly lower the rated carbon emissions from a development where sustainable fuel sources are used, and is eligible for associated incentive payments. Thermal storage and hydrocarbon-based back-up boilers are also utilised to allow the most efficient sizing and operation of the biomass boiler for annual load variations.

The main focus for the analysis is developments with a maximum peak load of less than 1 MW, which corresponds to the limit of the 'Medium Biomass' band of the Renewable Heat Incentive (RHI) Scheme ('Small' is up to 200 kW). Currently this corresponds to a development of approximately 300-400 houses or demand for 2-3 schools.

While much larger networks are currently being considered, this scale of system remains the most likely to move forward in significant numbers in the short term. A larger 2-3 MW scheme appropriate for biomass CHP in Glasgow was also considered for comparative analysis, and to determine if the same modelling approach was practical for larger scale projects.

Based on the need for a significant guaranteed consumer base, the most likely source of domestic networks with be social housing. The study, therefore, focuses on Housing Association developments, or areas with a significant proportion of Housing Association properties. (All social housing in Scotland is managed by Housing Associations). The project will aim to show if community heating can reduce social housing energy costs and be used as a means to tackle associated fuel poverty.

Case studies were selected from suitable developments and areas in Glasgow, and Argyll and Bute. A range of locations are considered from city areas on the gas-grid, to rural, off-grid locations. The focus of the project is on the potential for networks in Scotland, and considers typical Scottish housing types, energy sources, and specific policy instruments. It is, however, assumed that the analysis will be largely applicable to similar locations throughout the UK.

If future projects are largely restricted to community buildings and social housing, the result is that the average network consumer will be significantly different from the national average consumer used by most existing demand models. Using a recently developed model for heating demand based on socio-economic factors (Kelly et at, 2012), and actual housing design information rather than national average assumptions. The importance of accurate housing and occupancy data, and therefore models that can usefully use this information, is also considered.

The economic evaluation basis for a community heating network is different from individual heating systems. For individual systems, the internal heating equipment (boiler, radiators, tank etc.) are typically considered to be part of the house and viewed as an associated fixed cost. The apparent unit cost is therefore only the delivered fuel or power cost. For community heating, the whole network is typically owned and operated by a single entity, with all costs covered by a single unit charge. Using the selected case studies, how the economics of networks and individual systems should be compared is reviewed to ensure that all associated costs are considered fairly.

For Housing Association projects it can be considered that the Association is the developer, building owner, and heat network owner. This allows and also requires that the overall housing development costs for each heating option are evaluated. The selection criteria being that funding for housing and associated heat supply is used as effectively as possible to reduce heat costs and CO_2 emissions. Therefore as an extension of the economic analysis, the financial impact of meeting emissions targets and minimum building fabric levels, are also reviewed.

As a significantly lower CO_2 rated fuel than all other viable alternatives (BRE, 2013), the difference in overall building costs to achieve emissions targets can be significant. Beyond the mandatory minimum building fabric baseline, additional required improvements can therefore be evaluated as a heat-related cost, and included in the heating cost analysis for each option considered.

This additional cost per unit of CO_2 saved can also used to evaluate building improvements, and the alternative use of additional renewable microgeneration (such as solar panels), to determine if the policy mechanisms currently in place promote cost effective heat supply and CO_2 reductions, and allow biomass community heating to be evaluated fairly.

Finally, as a significant heating supply option globally, the technology used for community heating systems is relatively mature. However, there are several areas that are being evaluated for potential performance gains, particularly for future lower demand networks. Improved piping design, piping insulation, and the use of lower temperature networks to reduce heat loss, are also reviewed.

1.3 Project Methodology

No commercial or freely available models exist that allow demand and community heating system costs to be determined within a single package. The first task was to therefore develop a suitable demand estimation and financial model, that also allowed sensitivity to building fabric and socio-economic factors to be incorporated as outlined in 1.2.

A community heating evaluation model requires modules for heat demand estimation, pipe system design, boiler and auxiliary equipment sizing, and financial evaluation. Although an overall community heating model does not exist, modelling approaches for each individual module are well understood. The developed model therefore combined standard existing methods, where possible.

Once developed and validated with existing data, the model was used to analyse a variety of potential current and future project case studies. Three new-build and three existing building developments were selected for comparison. For the new-build projects sensitivity to each step change in Building Regulations, including predicted future updates, was considered. For retrofits, sensitivity to future improvements, grant availability, and construction costs were reviewed.

The financial evaluation of community heating against alternative individual heating systems is not straightforward. Each has a different balance of ownership, equipment lifetime, and running costs. A timescale of 40 years was chosen for the evaluation, based on a 20 year lifetime for boilers and other generating units (therefore requiring one replacement after 20 years), and a limit of 50 years for a community heating pipe system using a 70°C supply temperature. A 40 year basis therefore gives a fair comparison against alternative heating system if reinvestment timings are considered.

Over the 40 year period, total costs for equipment, fuel, and maintenance were calculated and converted to net present value. From this total an effective cost per kWh over the 40-year period is determined, allowing for any incentive payments or grants available. This allows a direct comparison of all heating options using a familiar heat charge unit basis.

2. Background

2.1 Community Heating Overview

A community heating network typically has three main components as shown in Figure 1: (1) a central heat plant and fuel storage, located in an 'Energy Centre', (2) the piping network, typically underground, and (3) the Heat Interface Unit (HIU), a heat exchanger and metering module between primary and secondary networks, located at each consumer or small group of users.

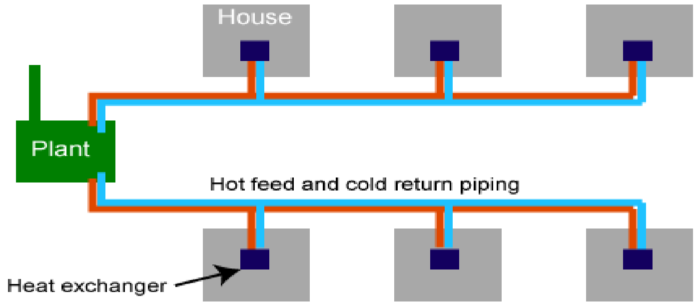


Figure 1: Community Heating Network Schematic (Greenspec, 2013)

A main primary heat network, with a separate secondary circuit for heating and hot water at each consumer, known as an 'indirect' system, is assumed. Heat can be supplied directly to the house network, either only for heating, or less frequently for both heating and hot water. This has the benefit of reducing system cost and temperature differentials as no exchanger is required between circuits. However, system reliability is reduced as all users are connected to the same circuit, and direct supply also places limits on system temperature and pressure (Frederikson, Wollerstrand and Ljunggren, 2008). This type of system is typically not recommended or used in the UK (Gagliardi La Gala, 2013), and is not considered for this study.

The Energy Centre comprises the boiler(s), fuel storage, thermal storage (if used), the network controls, and the waste gas exhaust. Additional auxiliary boilers can be specified as back-up for the biomass unit or for peak demand periods. Typically this would be a gas, oil, or LPG boiler. Thermal storage is usually a hot water tank connected to both supply and return circuits. It is used to provide a buffer for short periods of high demand, allowing the boiler size to be reduced. It also allows the network return water to be reheated prior to the biomass boiler, which has a higher inlet water temperature requirement than fossil fuel boilers to prevent excessive fouling (Palmer et al, 2011).

From the Energy Centre, an insulated underground pipe network carries hot water to the individual consumers. It is a closed loop with both supply and return pipes following the same route.

The HIU at each consumer comprises separate heat exchangers for hot water (connected to incoming cold water supply) and heating (connected to closed heating circuit), and usage metering.

2.2 Community Heating System Design

The critical aspects of system design are boiler sizing and fuel selection, pipe sizing and routing, pipe material selection, and operating temperature. Each aspect is detailed below.

Networks can also be defined by a variety of different general factors related to the energy demand and layout, such as area heat density, which can be used to analyse potential network viability. These factors are given in each case study description, and used in the discussion of a simplified area selection method in 6.2. Several relevant factors are defined in 2.2.4.

2.2.1 Boiler Design

Boiler selection and sizing is a complex decision process and is not covered in detail within this investigation. Boiler sizing requires a detailed estimate of peak loads at small time resolutions, and an estimation of load diversity across a number of consumers. The Biomass Decision Support Tool (Carbon Trust, 2013) is the primary source of boiler sizing but is not currently set up for the current and future Building Regulations that are required for this study. A simplified method was therefore included in the model to allow boiler size and cost to be estimated. This is done using standard diversity correlations, piping heat loss estimation, and peak heating and hot water load calculations based on the SAP (Standard Assessment Procedure) 2012 methodology (BRE, 2013).

Biomass boilers of the capacity reviewed have two fuel options, wood pellets and wood chips. Wood pellets have a higher energy density and are easier to handle, but are generally more expensive. Wood chips have a higher moisture content and lower density, but are lower cost and suitable for automatic feeding systems. Costs for both options are included in the case studies.

As heat demand varies over time, the turndown ratio of the boiler is an important factor. Biomass boilers have much smaller effective turndown ratio than fossil fuel boilers. Pellet units typically have a better turndown ratio of 4:1, compared to 3:1 for woodchip units. Sizing of a biomass boiler to ensure that the system remains within its efficient operating range for as much of the year as possible is critical. To achieve this it is recommended to size the primary boiler for less than 100% of the peak load, and to use thermal energy storage and auxiliary fossil fuel boilers to meet short duration peak demands. (Palmer et al, 2011). (The basis for the developed model is discussed further in A.1)

2.2.2 Piping Network Design

Typical Piping Configuration

In recent years there have been significant improvements in community heating pipework. For the small-to-medium sized networks considered, individual steel supply and return pipes have been generally replaced by cross-linked polyethylene (PEX) pipes. For smaller diameters (up to 63mm), twin PEX pipes can be used that house both supply and return pipes in the same insulated casing.

Several studies have shown that twin piping is more cost effective than single pipes. Zinko et al (2008) states a c.10% overall cost saving for a typical network, and Kristjansson and Bohm (2006) a 27% reduction in heat loss and 23% reduction in capital costs for a 25mm pipe size. SFAB (2007) has estimated that the installed cost of a twin pipe is 10% lower than the equivalent separate single pipe installation due to the narrower trench.

The conclusion is therefore that PEX twin pipes, which are widely available, are more effective than single pipes, and their use is assumed as the standard basis. Single PEX pipes are used for sizes greater than 63mm. Beyond 160mm diameter steel piping is required but none of the case studies evaluated require this size of piping.

Future Piping Configuration

Further analysis by Zinko et al (2008) and Kristjansson and Bohm (2006) has concluded that similarly constructed triple pipe systems with two supply pipes and one return pipe could be even more effective than twin pipes. The second supply pipe is only used during peak use periods (typically one-hour per day on average (Zinko et al (2008)). Both supply pipes are smaller than the equivalent single pipe and therefore heat loss is reduced during the periods of one supply pipe use. Zinko et al (2008) estimates that the overall system lifetime cost saving is c. 8%, including the increased controls required. Calculations by Kristjansson and Bohm (2006) determined that the heat loss saving was approximately 25% over a twin pipe with equivalent capacity. Triple pipes are not currently commercially available.

Another potentially lower cost pipe installation method is 'EPSPEX'. This is commercially available in Scandinavia and involves placing the bare PEX water pipes inside solid rectangular blocks of standard polystyrene material. The increased structural integrity of this construction allows the pipe to be placed in narrow block-width trenches (Frederikson et al (2006)). The polystyrene is, however, susceptible to water damage and needs to be protected and installed above the water table.

Limited data is available for 'EPSPEX' system performance but Zinko et al (2008) determined approximate factors of 0.85 for installation costs and 0.65 for heat loss compared to twin pipes.

Testing showed that the insulation performance loss of the standard 'EPSPEX' pipe with no further protection was 40% after four immersions, improving to 20% after one month of drying. Mechanical strength was maintained and standard PEX pipe lifetime was not changed (Sallberg, Nilsson and Bergstrom, 2004).

For both the triple pipe and the 'EPSPEX' systems, there is little experimental, modelling or cost data available. The model allows each to be selected for comparison purposes, using the piping capital and heat loss factors given above, but the results should be considered an approximation. These options have not been included in the main analysis as neither has been used extensively. Their potential influence on future network viability will be marginal, but could result in c.3-5% project cost reductions.

Typical Pipe Insulation

Polyurethane (PUR) is the current preferred piping insulation material based on cost, performance and susceptibility to moisture ingress.

Many vendors provide multiple insulation thicknesses for the same water pipe sizes. These are typically defined as 'standard' or 'Series 1', 'plus' or 'Series 2', and, if available, 'plus-plus' or 'Series 3'. Overall pipe dimensions are generally consistent across a range, therefore the 'plus' size is typically the next standard casing size up from the 'standard' design.

Unless otherwise stated, 'standard' insulation thickness has been used as it can be shown to be the most cost effective overall. Further details are provided in Appendix E. 'Series 3' is not typically used, or commonly available, and therefore has not been defined in the model.

Future Pipe Insulation

Recent work has been done to identify if insulation performance could be improved significantly using newly developed or proposed insulation materials, such as Aerogel or Vacuum Insulated Panels (VIPs) (Berge, 2013). This analysis used an inner 10mm insulation core of these high performance, high cost materials, with an outer layer of standard PUR insulation to standard thickness. The Aerogel/PUR insulation reduced the heat loss by 13%, and the VIP/PUR by 23%. At current pricing levels payback was determined to be 29 and 11 years respectively. However, both are subject to performance deterioration from water ingress and loss of vacuum or encapsulated gases.

Frederikson, Wollerstrand and Ljunggren (2008) also discuss using vacuum 'super-insulation' materials that could potentially reduce heat losses by a factor of at least 10. However, these are not yet in wide commercial use, and performance in warm, wet environments is not proven.

As no improved insulation materials are near to being commercially available, or have a clear potential to be cost-effective or suitable for long-term use in underground piping, the current 100% PUR design is likely to be the most cost effective solution for some time. No other options are included in this study.

Pipe Sizing and Routing

Optimum pipe sizing requires pressure drop, velocity limits, and the costs associated with construction, pumping, and heat loss to be considered. For large networks, detailed software tools, such as Bentley 'sisHYD' and Fortrum 'Apros', are available. However, the process is somewhat simplified by the available discrete pipe sizes. Smaller networks can therefore be optimised for each individual section, and then reviewed against the overall network limit for pressure drop.

Efficient pipe routing is also important, as the per-metre installed cost is high. As will be discussed further, a development that is specifically designed to minimise pipe lengths can be viable whereas one with a similar demand density but a poorer pipe layout is not.

2.2.3 Operating Temperature

The network operating temperature is a key parameter for system design and costing. Reducing the average temperature reduces the heat loss from the pipe network. However, lower temperatures are generated in the heating and hot water systems, which can increase costs and Legionella risk.

It should be noted that this review uses a static model of the system with average temperatures on a monthly timescale. The dynamic variation of supply and return temperatures over time will have a significant impact of boiler performance and heat loss estimation. However, it is outside of the scope of this review to model how the system operates at this level of detail. Further work is required in this area as there are no existing, freely available tools for this type of analysis. Key parameters such as real time difference in supply and return temperature and heat exchanger delta-T are therefore not considered further but are important for network performance.

Current 'Gen 3' networks typically operate with a 80°C supply temperature and return at c.60°C. This allows use of 'standard' building heating systems and can generate hot water at 60°C. 'Gen 4' systems with a 50-60°C supply temperatures have been suggested as a means to lower costs in low demand networks (Wiltshire, 2012). However, generated consumer water temperatures are reduced by at least 10-15°C, even if more efficient heat exchangers are used.

Significant research and testing of lower temperature networks has already been undertaken (for example, Olsen et al (2008), Wiltshire (2012), Dalla Rosa and Christensen (2011)), particularly in Scandinavia. These generally show a reduction is system costs, but have not clearly considered the overall cost impact if dwelling heating system costs are also included.

The network operating temperature impacts the heating system design. Standard radiators, which would be expected for retrofit projects, are typically designed to BS EN 442 criteria (BSI, 2003) with a mean water temperature of 70°C, and a design room temperature of 20°C (a 50°C delta-T). This requires a 'Gen 3' temperature network.

Radiators can be specified for lower temperature differences, although there is an associated cost penalty for the increased heat exchange area required. Underfloor heating operates at lower temperatures than radiators, but is generally restricted to ground floors and difficult to retrofit.

For hot water, while the 45-50°C generated temperature typical for a 'Gen 4' system is acceptable for comfort and domestic uses, it is below the 60°C limit generally required to protect against Legionella (Mathys et al, 2008). However, German DVGW regulations for domestic water use (DVGW, 2004) have removed this requirement for systems of less than 3 litres, as the risk is related to the water residence time between generation and use.

As shown by Thorsen (2012), with a Heat Interface Unit (HIU) for each individual dwelling, no hot water storage tank, and a well designed piping system with an approximate volume of 0.1 litres/m, most dwellings would have a water system volume of less than 3 litres. While not yet acceptable in the UK, it is assumed that there is at least the potential for lower temperature networks to be acceptable in the future. This would only apply to domestic networks. 'Gen 3' systems would still be required for larger-scale consumers.

Lowering the temperature also increases the pipe lifetime and maximum operating pressure based on Miner's Rule (BSI, 2000), and the insulation also performs better (Olsen et al, 2008). Pipe lifetime for cross-linked polyethylene (PEX) is 25-30 years based on 80°C and 7.6 barg, 50 years at 70°C and 8.5 barg, and 50 years at 50°C and 10.6 barg (Brugg, 2013).

Biomass boilers require a minimum return temperature of 60-70°C due to tar condensation in the flue. This can be managed by generating water at c.30°C higher than the system requirement and using the thermal storage or a direct supply-to-return bypass to increase the return temperature by a similar degree (Palmer et al, 2011).

Detailed analysis of the cost impact of reducing operating temperature is in 6.1. The conclusion from the analysis was that a 70°C supply and 50°C return temperature was optimal. Below this temperature there is no additional pipe lifetime benefit, and the heat loss reduction is shown for viable networks to be a smaller benefit than the increased heating system costs. A 70°C/50°C basis has therefore been used as standard for all further analysis.

2.2.4 Network Demand and Design Factors

The following factors can be used to define networks generally, and provide a useful means for differentiating between areas and networks without detailed analysis. These factors are calculated by the developed model and several key factors for simple network analysis are discussed in 6.2.

Plot Ratio – Ratio of building floor area to land area. Without considering heat demand, this factor gives a simple definition of the building density of an area.

Area Heat Density – Annual heat demand in GJ per square metre of land area covered by the network. Provides a key definition of the heat demand within an area.

Pipe Heat Density – Annual heat demand in GJ per metre of piping. Provides a key definition of the suitability of the network layout. Areas of high relative area heat density but low pipe heat density suggest an area with an inefficient piping layout with an excess of smaller branch pipes or long individual consumer connections.

Pipe Length Per Connection – Another definition of the effectiveness of the piping layout. Combined with area heat density, this factor can give a determination of whether consumers in an area are concentrated enough for a heat network.

Occupant Density – Can be defined in terms of occupants per land or floor area to give further information on likely demand in conjunction with plot ratio and area heat density.

Pipe Heat Loss (%) - Pipe heat loss expressed as a percentage of total heat generated. Another factor defining the relative effectiveness of the piping network.

2.3 Heat Demand and Building Regulations

For housing built in the period after cavity walls generally replaced solid walls early in the 20th century and 1991, there is very little typical thermal performance difference where a minimum level of insulation improvements (cavity wall and roof insulation, double glazing) are also installed. However, since the 1992 Building Regulations update, the energy performance of new housing has improved significantly, driven by improved construction methods, a reaction to both rising energy costs and fuel poverty, and latterly climate change and CO_2 emissions concerns.

This thermal performance improvement is planned to continue over the next 10-20 years. With a final target that new-build housing achieves life cycle zero carbon performance by c.2030. Similar improvements are required for non-domestic buildings. (SBSA, 2007)

Since the 2002 Building Regulations release, and particularly for the 2007 and 2010 updates, CO_2 emissions reduction has been a key aim (ScotGov, 2013d). In 2007 a review panel instigated by the Scottish Government published the 'Sullivan Report' (SBSA, 2007). This set out a roadmap for Building Regulations updates in 2010, 2013 and 2016, using baselines set by the 2007 release for heating, water, ventilation and lighting energy use. CO_2 emissions targets were set at 70%, 40% and 0% of the 2007 benchmark house design for the subsequent updates. EU Regulations require that 'zero carbon in-use' housing, using the same basis, is implemented by 2020 (Heffernan et al, 2013).

The 2010 updates was published as planned with a 70% target, but the 2013 update has been delayed by one year with the target changed to 55% from 40% of the 2007 benchmark. It is therefore likely that economic realities will slow the roadmap schedule but the 2020 EU 'zero carbon' requirement remains a fixed goal.

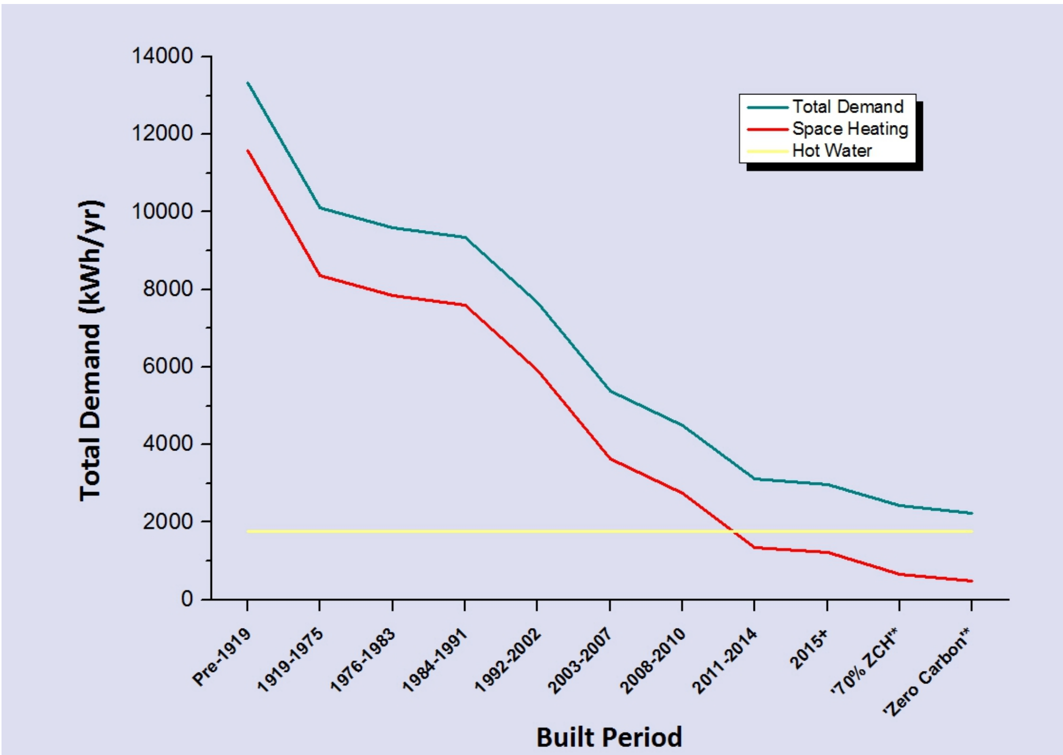
From the 2007 update, the Building Regulations process has been integrated with the SAP (Standard Assessment Procedure) method for calculating building energy and emission performance (ScotGov, 2013d). The SAP method has been developed by the BRE (Building Research Establishment) Trust for the UK Government, with the latest version released in 2012 (BRE, 2013).

Recent Building Regulations releases set a minimum (backstop) building fabric requirement (component U-values, air changes, thermal bridges) but further improvements (building fabric, low carbon microgeneration etc.) may be required to meet the dwelling-specific CO_2 target set against the 2007 baseline (ScotGov, 2013d).

A major factor in the CO_2 emission calculation is the method of heating to be used. The use of biomass-fueled community heating can make a significant difference to a dwelling's rating for a given design due to the relatively small CO_2 emission rating for biomass (see Table 3).

As reviewed in detail in 3.4 and Appendix C, few older houses are currently without further thermal improvements. In the majority of cases this is roof insulation, cavity wall insulation (where possible), and double glazing. Further insulation of solid wall properties is expensive and less common. In most cases, the implementation can either be assumed, or an average factor assigned based on the proportion with and without the improvement. Implementation is higher for Housing Association properties, as energy efficiency is a mandated requirement. This will continue to be the case with the recent Energy Efficiency Standard for Social Housing policy (SFHA, 2013a).

The result of these policy drivers has been a large reduction in heating and hot water energy demand per house. Figure 2 highlights the estimated reduction in heat and hot water demand for a typical 2-bed, 90 m^2 property based on build period. This has been calculated using the developed model (see Section 3), with the 'nominal' building fabric assumptions as detailed in 3.4, where applicable. Building completion dates are assumed to have a delay of one year from the relevant Building Regulations update. The results show that for the 20-year period from 1991 to 2011 there has been an estimated 60% reduction in overall heat demand, with further reductions becoming harder to achieve. Figure 2 also demonstrates that we have now reached a point where hot water is the primary demand.



* For 'Built Period' definitions see 3.4

Figure 2: Modelled heat demand of a typical 90 m^2 house for different construction periods

For heat network viability, the improvements in building energy performance, and associated demand reduction, are significant. This raises the following questions:

- Is there a point on the building thermal improvement roadmap where heat demand is too low to generate sufficient income for new-build heat networks?
- Can the significantly lower CO_2 per emission rating of biomass heat networks be used as further justification by considering the additional building fabric and microgeneration requirements associated with meeting CO_2 targets for other potential heating systems?
- How viable are heat network retro-fit projects, as standalone investments and in comparison to new-build projects, considering the increased cost and disruption of network construction against a higher expected heat demand?
- What is the most appropriate method to supply a very small heating demand and hot water? Is there a point where heat networks are no longer competing with central heating boilers and heat pumps?

2.4 Community Heating Economics

Economic analysis and risk for a community heating network differs significantly from standard individual heating units, even where, in both cases, the housing and network would be owned by the same organisation (e.g. a Housing Association). Where individual heating units are utilised, there is either a fixed cost for the homeowner, or a tenant is charged rent which includes the provision of a heating system. The income risk from variable or falling demand is borne by the separate utility supplier. This risk is generally spread over a very large population, with fixed standing charges used to provide income insurance.

For current UK projects, a single entity typically owns the community heating infrastructure (including the heat interface unit (HIU) within the customer premises), and charges a single unit cost for heating and hot water. Freely available charging information is scarce, but it would appear that standing charges are currently not the norm. With significant upfront capital investment (typically much higher than for individual heating systems (see Table 25)), and an income stream wholly dependent on demand, the financial risk for heat network owners is high. The demand is seasonal, there are year-to-year variations with the varying severities of the heating season (see 3.6.1), and there can be highly variable usage behaviour across the relatively small, homogeneous populations that are currently supplied (Kelly et al, 2012).

Specific areas that need to be considered for the economics of community heating developments are as follows:

- Heat Charge Basis
- Network business model
- New-build or existing housing
- Incentives and grants

2.4.1 Heat Charge Basis

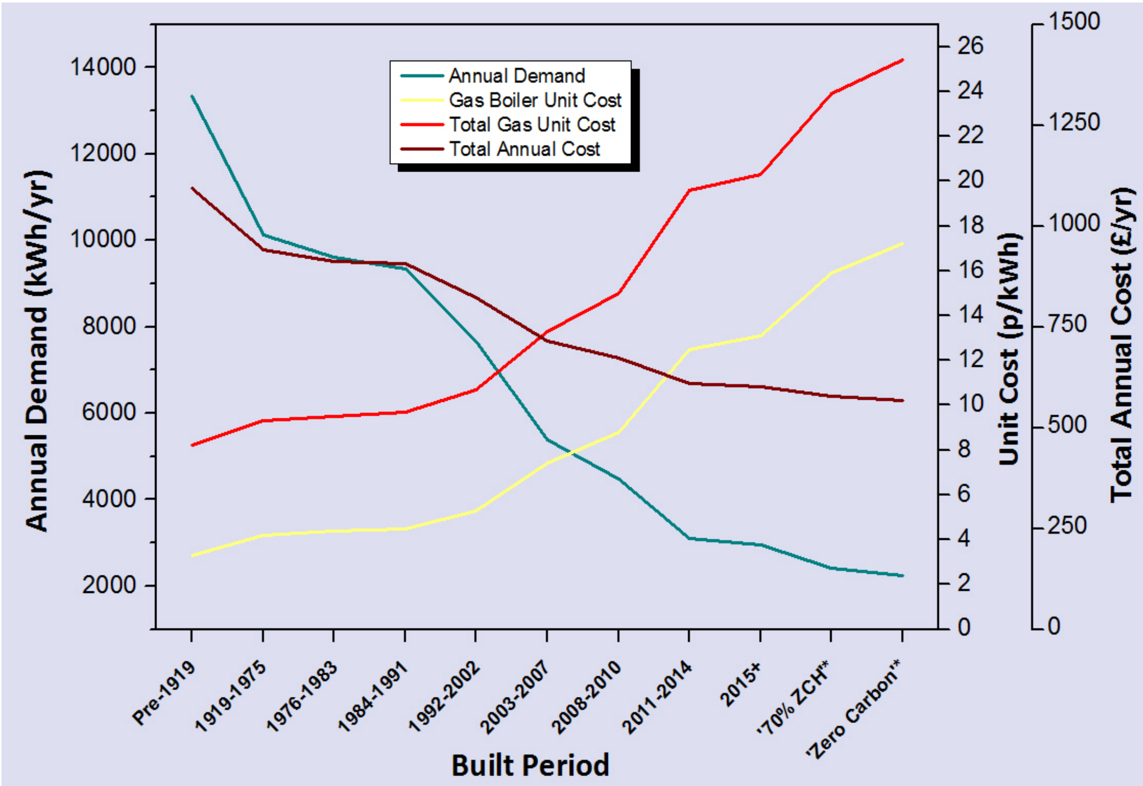
How costs are accounted and heat from the network is charged for compared to the available alternative heat sources is important. Consumers are unlikely to have a clear idea of the effective cost per kWh for individual heating systems if capital and maintenance (O&M) costs are included. As shown in Figure 3, the impact of these fixed costs become increasingly significant as demand reduces.

Charging a flat rate for heat from the network, may mean that the heat charge must be set at a much higher per-kWh rate than was paid to the utility company for fuel-only beforehand. While the overall cost to the consumer may be the same or lower, the expectation of a certain per-kWh cost for energy may cause problems.

For tenants, if the heat charge is decoupled from rent, they may have a similar concern even if the rent is reduced significantly to account for the removal of the individual heating system. For the fuel poor, very high unit charges may also discourage use to below minimum levels for well-being, despite an overall lower annual cost.

Figure 3 shows the per-kWh effective cost for a gas boiler and how this cost also increases significantly with the falling demand associated with the Building Regulations updates shown in 2.3. The basis is the same 90 m^2 house considered in 2.2.

As shown, the effective cost of the boiler and associated maintenance costs increases from c.40% of the total heat cost for a pre-1919 home to 68% for a 'zero carbon' home (see 3.4 for definition). The impact of both the fixed equipment cost, and standing charge for the gas supply, also increases the overall per-unit charge significantly for each subsequent update. Therefore the 'zero carbon' home has an overall per-unit charge for gas over three times that of a pre-1919 home. As a result of these fixed charges, although demand drops by 83%, total cost of supplied energy only drops by 48%.



* For 'Built Period' definitions see 3.4.

Figure 3: Gas boiler and total gas cost (inc. boiler) per kWh for different construction periods

There is another specific issue relating to community heating network implementation within an area with multiple existing heat sources. While community heating may reduce the average heat cost for the area, and allow some consumers with poor existing heating systems to reduce their fuel costs, it may only maintain, or even increase, costs for a sizeable minority. A common example would be an area with existing oil/LPG and electric heating, where the electric systems are likely to be significantly more expensive per-unit.

2.4.2 Network Business Model

One of the main barriers to heat network development is the level of upfront investment and the need for a minimum guaranteed long-term income to recover it. For this reason, current projects are primarily focused on community and social housing schemes, with the Housing Association or Local Council the non-profit network owner. For social housing, with no alternative systems available, consumer demand can be guaranteed and 'break-even' investment can be tolerated.

Poyry (2009) reviewed network potential against several discount rates (10%, 6% and 3.5%). Significant development was shown to be economic at the 3.5% level only, and then only for large-scale private housing integration using waste heat and natural gas CHP (Combined Heat and Power). This review was prior to the introduction of the Renewable Heat Incentive (RHI) scheme, so it is expected that smaller systems using biomass may also now be economic at c.3.5% and should be investigated. According to Poyry (2009), 3.5% represents the minimum that would be considered acceptable for a 'not-for-profit' scheme. Significant private investment in the short term is therefore considered unlikely without market or policy changes that markedly increase returns.

As outlined in Section 2.6, there are some larger networks under review but it is expected that the majority of near-future development will be focused on single housing estates and community buildings (e.g. schools, hospitals, community centres etc.). This review will therefore focus on social housing developments using biomass systems. Community buildings are difficult to model accurately and therefore only considered, where relevant, as single known heat loads. It is assumed that the networks will be owned by the Housing Association or co-owned with the Local Council.

The lifetime cost analysis of the model is based on neutral 'break-even' financial performance with a 'non-profit' discount rate of 3.5%. In reality a higher return is likely to be required for justification, but the actual return is determined by the heat charge set. How total heat charges should be set in comparison with other heat sources is outside the scope of this analysis, therefore this 'break-even' basis is used to give a fair comparison between options rather than actual financial performance.

2.4.3 New-build or Existing Housing

For new-build properties the analysis is straightforward. Community schemes can be compared directly against the available equivalent individual heating system options.

Retrofit projects are more difficult to analyse. An existing 'value' of the replaced heating equipment must be considered. Whether the house has an existing 'wet' heating system with radiators and/or underfloor heating pipes, or not, is also a factor. The additional cost of adding a 'wet' system to a property is estimated at between £2500 and £4500 (Poyry, 2009), depending on dwelling type.

Piping costs are also significantly higher for retrofit projects as pipe trench construction will be through existing infrastructure. The additional cost will depend on the housing density and type of area, with different installed costs being applicable for town centre, suburb and parkland/rural areas.

The cost of the piping hook-up within the buildings is also likely to vary considerably between types of housing. Piping either needs to be mounted externally, or routed through existing walls and floors. A generic hook-up cost of £1560 per flat, and £3120 per house is assumed based on Poyry (2009). However, in all retrofit cases the sensitivity to this assumption has been analysed.

2.4.4 Incentives and Grants

As low carbon energy solutions are currently, in general, more expensive than conventional sources, there are financial incentives available to support uptake. These are either ongoing demand based payments (the Renewable Heat Incentive (RHI) scheme), or upfront grants or low-cost loans against the initial capital cost. Where a fuel poverty reduction for existing housing can also be demonstrated, additional grants are available. The following sections detail current funding mechanisms.

Renewable Heat Incentive (RHI)

Community heating networks supplied from biomass systems are currently eligible for payments under the government non-domestic RHI subsidy scheme, which is applicable for shared multi-dwelling systems.

The current non-domestic RHI scheme guarantees payments for 20 years based on metered delivered energy. (This differs from the domestic RHI scheme that will pay incentives for only 7 years). There are three payment levels based on boiler size, 'small' below 200 kW, 'medium' between 200 kW and 1 MW, and 'large' above 1 MW.

Below 1 MW there are two tiers, with Tier 1 applicable for total metered annual energy up to the equivalent of running the system at 100% for 1314 hours (15%), and Tier 2 for subsequent eligible production. This is designed to prevent systems being run without demand for RHI income, with the Tier 2 payment set below the fuel cost. (EST, 2013a)

Table 1 shows the tariff levels for non-domestic biomass systems as of 1st July 2013. Tariffs are reviewed quarterly, and can change significantly between periods, usually lower to reflect increasing uptake and reducing costs.

Biomass RHI Tariff	Tier 1 (p/kWh)	Tier 2 (p/kWh)
'Small' (<200 kW)	8.6p	2.2p
'Medium' (200 kW to 1 MW)	5.0p	2.1p
'Large' (>1 MW)	1.0p	1.0p

Table 1: Non-domestic Biomass RHI tariffs as of 1st July 2013 (EST, 2013a)

Grants/Loans

Scotland does not have a standard capital grant mechanism for community heating schemes. However, the Scottish Government is currently investigating if further development funding is required as part of the 'Expert Commission on Community Heating' (ScotGov, 2013a).

Community Heating is not currently eligible for Green Deal financial support for individual households. This is principally due to the difficulty in accounting for system wide savings at the household level (DECC, 2012).

Community Heating will, however, be eligible for funding under all three types of 'ECO' funding provision. 'ECO' funding replaces existing schemes supporting energy improvement, CO_2 reduction and affordable heating improvements for deprived areas (lowest 15% by SIMD), rural areas (target for 20% of investment), and generally for hard-to-heat or off-grid housing (Ofgem, 2013). Specific levels of funding are not yet clear, but initial enquiries suggests that it may be in the region of 40-50% of energy-related initial investment (ACC, 2013; KSEP, 2013).

Of the case studies reviewed, the Govanhill and West Bowmore schemes would potentially be eligible for 'ECO' funding, based on housing, location and deprivation rules. The impact on feasibility of RHI payments only and RHI plus a 40% of initial capital grant are considered.

In Scotland, low-cost loans with an interest rate of 3.5% are available until 2017 to non-profit organisations through the Warm Homes Fund (EST, 2013b). This scheme has provided funding for the West Highland Housing Association (WHHA) Dunbeg project (see 4.2.2). However, as the financial model uses a simple discount factor and does not specifically consider cost of finance, this benefit is not reviewed in detail.

2.5 Alternative Heating Systems

The relative economic viability of a heat network is related to the availability of other heating options within the identified area, and, if applicable, what is already installed.

For future house designs, as the space heating requirement reduces to very low levels (c.20-30 $kWh/m^2/yr$), the challenge becomes finding an efficient means to supply heat and hot water in an economic and energy efficient package. Many of the potential solutions require a degree of user input and increased installed cost that is suitable only where the user has made the choice.

For wider use in housing developments, and for rental and social housing properties in particular, the heat and hot water system should have straightforward operation, and preferably be automated based on temperature and/or time. The source also needs to balance cost and energy saving, with the presumed goal being the lowest overall cost to both Housing Association and tenant that meets the minimum emissions requirement. The result is that the available solutions for general housing developments do not change as demand falls to the 'zero carbon' level.

The following are identified as viable alternative heat sources:

- Gas boiler (condensing type)
- Electric storage heating (high SAP CO_2 rating, may require rule change to reflect potential use of off-peak electricity to be viable)
- Solar thermal plus water storage with electric immersion back-up for low solar periods
- Air-source heat pump (ASHP); separate, or integrated with Mechanical Ventilation and Heat Recovery (MVHR) system for low infiltration housing

(Ground source heat pumps could also be considered but have not been included as they are more capital intensive than ASHPs (EST, 2013c), and more difficult to integrate within a development.)

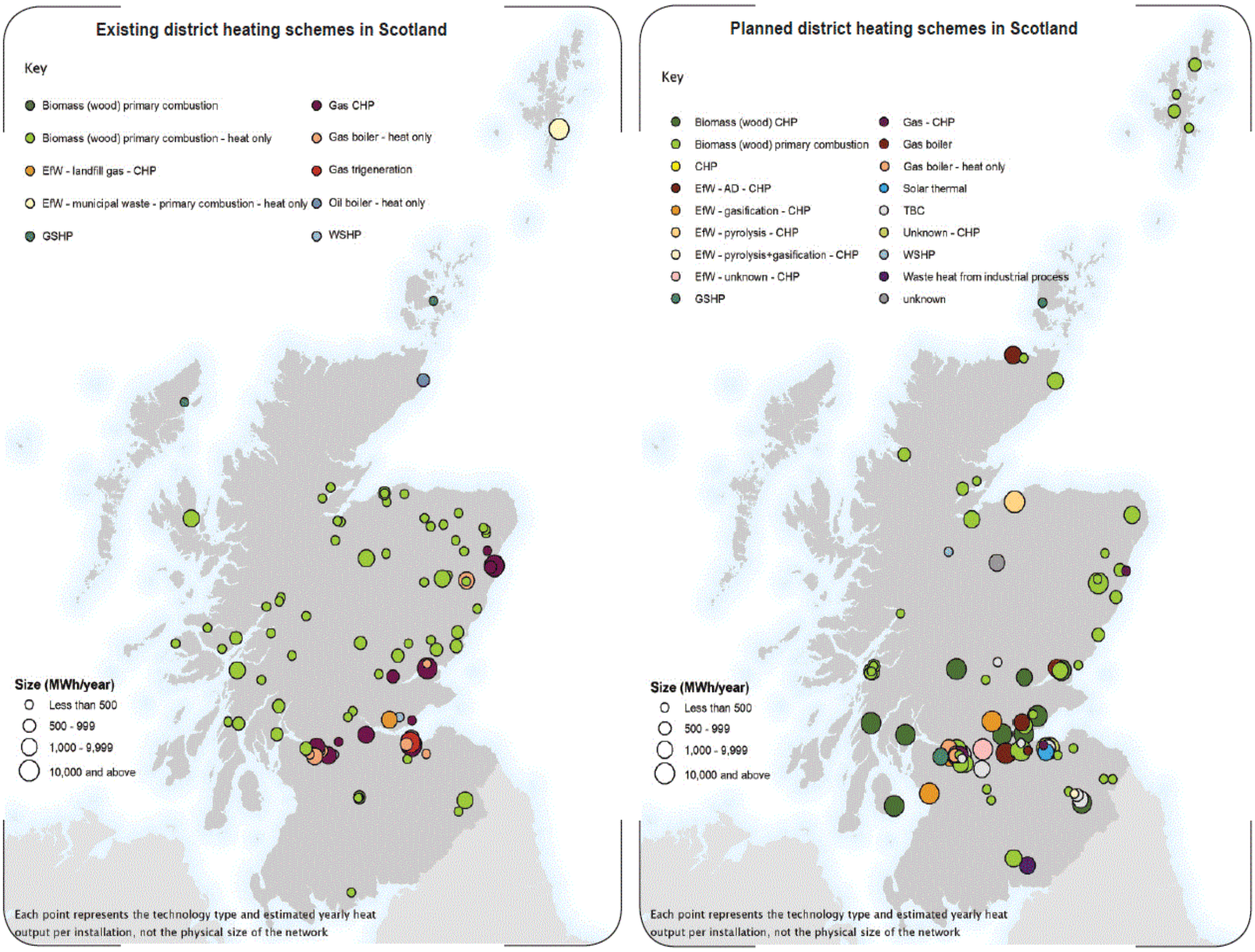
The following have been discounted for the reasons given:

- Electric boiler – discounted due to high cost and emissions rating. ASHP preferred.
- Oil/LPG boiler – Discounted due to fuel delivery costs, user input required, and safety requirements. Not typically used for social or rental housing.
- Individual biomass boiler – Requires a degree of user input that would not be practical where not specifically chosen by the user.
- Wood stove with back-boiler, water storage with immersion backup – Can provide a small amount of heat to main living space and water heating for radiators or MVHR air-water heat exchanger. Not considered due to degree of user input required.
- Electric panel heaters – low installed cost but very high fuel cost and prohibitive CO_2 rating.

For gas heating the standing charge is included in the heat cost as it is assumed that heating is the primary reason for the connection. For electrically-powered heating (storage, ASHP, Solar Thermal backup), the electricity standing charge is not included as there will be an electricity connection for general household use regardless of the heating system used. This is, therefore, not an additional cost associated primarily with heating provision.

2.6 Existing Scottish Community Heating Projects

The following two maps from the Scottish Government highlight the number and size of existing and planned schemes in Scotland.



Figures 4a and 4b: Map of existing and planned heat networks in Scotland (ScotGov, 2013e)

Schemes broadly fall into three categories, (1) large single non-domestic consumer (estate, hospital, school), (2) single housing developments (typically 50-300 houses), and (3) large multi-consumer area-wide developments.

Existing examples of the type (1) are Ninewells Hospital (Dundee) and Western General Hospital (Edinburgh). (DUKES, 2012)

For category (2), project sponsors West Highland Housing Association (WHHA), have one existing scheme of 89 houses at Glenshellach (Oban), and two proposed schemes in the Oban area (see Section 4). Other similar schemes include Home Farm (Portree) covering 132 new-build houses, and Cables Wynd House (Leith) covering a 212-property multi-storey block (Lovell, 2013).

There are currently few large scale developments of type (3). Wick has an existing scheme covering a distillery and c. 270 houses using biomass (Marshall, 2007). Lerwick has a 30km network covering over 1000 customers supplied by a waste-to-energy plant (Sheap, 2013).

The majority of existing large city schemes use Gas CHP (Combined Heat and Power) systems. Aberdeen has three schemes supplying 1200 houses and 8 public buildings. In Glasgow, the Cube estate in Maryhill with 3500 homes is connected to a single gas CHP system. (Croft, 2012).

The largest biomass project to date for Cardenden in Fife is currently under initial development (Mitie, 2011). If completed, three 1.5 MWe biomass CHP units could eventually supply all 2200 homes in the town. Initially, 1200 homes owned by the local Housing Association will be supplied. Cardenden has areas of high deprivation and fuel poverty and the scheme is eligible for 'ECO' funding.

An area currently under review for large-scale community heating is Dundee's Waterfront Area (biomass CHP, 6 phases, mixed users, up to 100 MWe capacity), as part of a general redevelopment project. Similar schemes for Grangemouth and Rosyth are also proposed. (Forth, 2010).

3. Community Heating Network Model Development

3.1 Model Overview

There is evidence that existing heat network schemes in Scotland, particularly those installed several years ago, have suffered from poor demand estimation (McIllwraith, 2011). For such a long-term investment, a conservative estimation of future demand is necessary. There are several factors that may contribute to this overestimation.

The mindset required to estimate peak demands for system sizing and long-term demand for income generation are different. Peak estimation requires a realistic assessment of demand extremes. Long-term demand estimation requires sensitivity analysis to improvements in fabric and behaviour, accurate assessments on demand restrictions such as empty houses and secondary heating systems, and an understanding of the potential natural variability for different house and occupancy types. The use of non-specific tools or data may therefore give rise to poor long-term estimation, particularly for smaller developments with a narrow range of houses, occupancy, and income levels.

As discussed in 3.2, no suitable existing model was found, therefore a new model was developed specifically for this study.

The developed model is not designed to estimate peak loading to design accuracy, only to give an approximation for project economic assessment. The Biomass Decision Support Tool (Carbon Trust, 2013) remains the core tool for peak load estimation, although an update is required for current and future conditions. The principle aim is to allow long-term demand and financial sensitivity to all key factors to be analysed.

The model includes the ability to set socio-economic factors to assess the potential impact of a relatively homogeneous set of occupants compared to national averages. For larger developments, and where consumer type is more difficult to assess, these factors can be set to an average value.

Demand can also be factored to allow for typical void rates for social housing, to account for any secondary heating sources, or to predict approximate numbers of empty or 2nd homes if planning to connect areas of private dwellings. Housing Association void property levels vary considerably, particularly between urban and rural areas, although are often <1% (SHR, 2012). Second homes can be at significant levels in rural Scotland (Bevan and Rhodes, 2005). For example, in south Islay the level was 6.1% in the 2001 census, which would potentially impact the West Bowmore case study conclusions (see 4.3.3).

3.2 Existing Modelling Methods

3.2.1 Existing Network Models

An extensive review of existing renewable energy integration modelling software was undertaken by Connolly et al (2008). The following tools were identified as having applicability to community heating system analysis; 'BCHP Screening Tool', RAMSES, COMPOSE, BALMOREL, HOMER, RETScreen, SIVAEL and TRNSYS16. (RAMSES and TRNSYS16 are commercial products and were not considered further).

Of the tools available, the 'BCHP Screening Tool' (ORNL, 2013) was the closest in application to the type of model required for community heating evaluation. Basic building and occupancy information is entered, a background calculation determines the demand profile, cost data and other factors, and an economic evaluation for CHP (Combined Heat and Power) is produced. However, the tool is specifically designed for CHP and commercial buildings, and cannot be easily modified. The remaining tools were reviewed and all found to be either more applicable to wider-scale energy matching (RETScreen, Homer, COMPOSE), or too detailed (BALMOREL).

ARUP have produced an Excel-based tool called DENet (ARUP, 2013) to allow the feasibility of retrofitting community heating in the UK to be determined. It is designed as a first pass feasibility tool once heat mapping has been completed. The inability to calculate demand directly and a focus on large-scale CHP networks meant that this tool was not directly suitable. It would be useful for less detailed modelling of large area-wide networks, where heat demand is already known.

Several commercial tools exist for hydraulic modelling of community heating networks. These include 'sisHYD' from Bentley and 'APROS' from Fortrum Power Solutions. These were considered to be most suitable for large, integrated network analysis and detailed design. Simpler network modelling would be possible for smaller-scale, feasibility studies.

The conclusion of the analysis is that there is no existing overarching tool that allows sensitivity to the specific parameters of interest to be investigated. A new tool was therefore required.

3.2.2 Existing Parameter Models

Community heating network analysis at the level of detail required, requires the following modules:

- Demand estimation from building design information and occupancy.
- Boiler and thermal store sizing using diversity factors.
- Piping network optimisation using pressure drop and heat loss calculation, and cost analysis.

Demand Estimation

The socio-economic and occupancy heating demand factors identified by Kelly et al (2012) and considered for use in the model (see 3.5), use the mean internal temperature (MIT) of a dwelling. Finding a suitable demand model that was also based around MIT was therefore preferred.

The SAP (Standard Assessment Procedure) methodology (BRE, 2013) uses this basis and is integrated with the Building Regulations process. SAP provides a methodology for estimating monthly space heating and hot water demand, and also the peak instantaeneous loads required for boiler sizing. Monthly estimates were deemed to be sufficiently accurate for feasibility analysis over a long time scale (typically 30-40 years).

Using the SAP method would also allow existing SAP calculation results, that are mandatory for all new buildings, to be used in place of estimated building fabric for more accurate results. It also involves a relatively straightforward calculation process that can be modelled in Excel. This is demonstrated by the BREDEM (Building Research Establishment Domestic Energy) model, also developed by BRE, from which the SAP process for single house evaluations was developed.

Despite some existing concern about the accuracy and resulting incentives of the SAP process (Kelly, Crawford-Brown and Pollitt, 2012), it was used as the basis for demand estimation due to its general applicability, ease of modelling, and relevance to the current planning process.

Boiler and Thermal Store Sizing

It is a well understood concept that equipment sizing for peak demand in multi-user, intermittent-use systems must have a diversity factor applied to the sum of individual peak loads. This accounts for the maximum number of users likely to be using this type of system at any specific time.

For space heating, equation (1) from Marks and Stockwell (1980) for the diversity factor for N users is used. This equation is also used by the Biomass Decision Support Tool (Carbon Trust, 2013).

$$D_{SH} = 0.67 + 0.33 \times \exp\left[\frac{(1-N)}{220}\right] \qquad (1)$$

For hot water, there are several diversity factor equations that can be used to ensure peak demand across a number of users can be estimated accurately. The equation from the Danish Standard DS439 was reviewed by Thorsen and Kristjansson (2006). It was found to match with actual measurements up to c.10 consumers but overestimated for larger populations. The British Standard BS6700 gives significantly higher values and is likely to overestimate usage (Galluzzi, 2011).

An equation provided by the Swedish Technical Regulations for community heating (SF, 2004) gives lower values. This equation slightly underestimates the actual measurements, but tracks the measured values significantly better for larger number of users than the DS439 equation.

Figure 5 compares the factors calculated by the Danish and Swedish models, and the measured apartment building usage results from Thorsen and Kristjansson (2006).

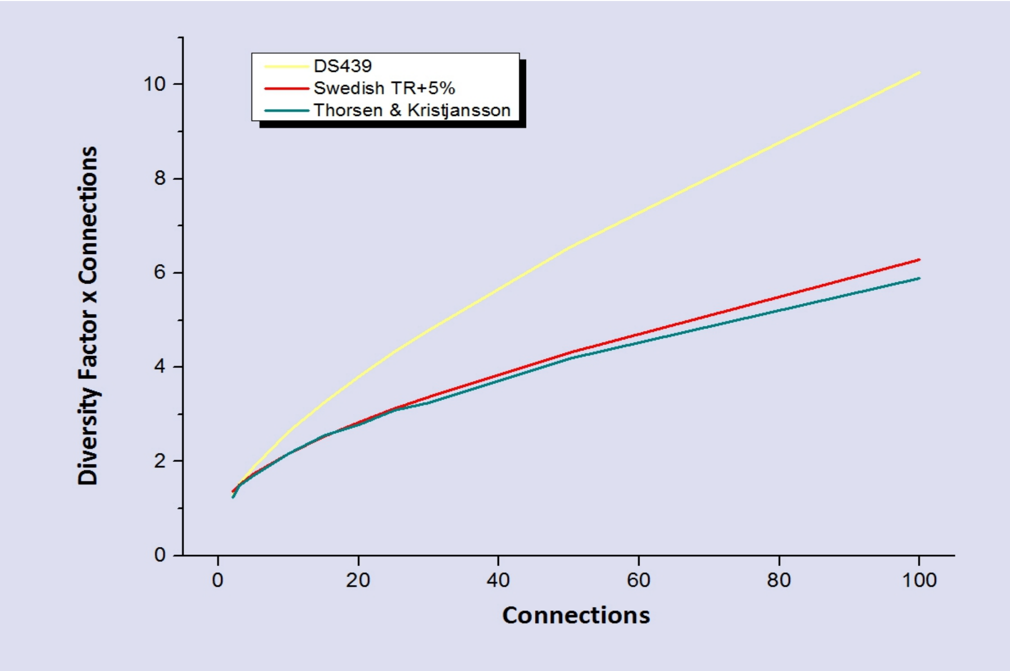


Figure 5: Comparison of Diversity Factors from standard Danish and Swedish models against measured data (Thorsen and Kristjansson, 2006)

Based on the above results, the Swedish Technical Regulations model equation will be used. A 5% safety margin has been added to account for the worst-case underestimation of the Swedish model up to c.100 users compared to the measured data. The equation is as follows:

$$D_{DHW} = 1.05 \times [0.9 + [0.015 \times ((1.2 \times N) - 0.9)] + [2.1 + [(Apt\%) \times (0.015 \times 0.9)^{0.5} \times ((1.2 \times N) - 0.9)^{0.5}]]] \quad (2)$$

where Apt%= percentage of flats/apartment and N = number of consumers

The third section of the Swedish equation uses a factor of 2.1, that it states should be increased to 3.1 for non-apartment buildings or higher demand buildings (SF, 2004). A factor is therefore added within the model depending on the proportion of apartments to houses. The 0.9 and 1.2 factors in the equation account for the Swedish method basis of 27 kW typical and 36 kW maximum instantaneous demand per apartment against the model basis of a 30 kW Heat Interface Unit (HIU).

As per Gadd and Werner (2013), the sizing of the thermal storage can be approximated by accounting for typical daily, weekly and monthly variations. This study estimated that approximately 2.5 m^3 of thermal storage is required for each TJ of annual network demand. Given the low relative capital cost of thermal storage, this is considered sufficiently accurate.

Piping Optimisation

No simplified Excel-based model for piping optimisation in a heat network is available. Pressure loss and associated pumping costs, heat loss costs, and construction costs therefore need to be calculated and combined to find a minimum overall cost. Pumping head requirement and costs are calculated from standard methods. The construction cost basis is discussed in detail in 3.6.2.

The model for heat loss in community heating networks that is used is the industry standard method detailed in Zinko et al (2008). It includes a method for determining heat loss from a twin pipe. This is a complex calculation method and is therefore not discussed in detail here.

3.3 Model Development

Without a suitable existing model being identified, a model that would allow existing and proposed housing developments to be modelled quickly but with sufficient detail to be useful was required. The following section outlines how the model integrates the basic parameter models described in 3.2, and determines community heating feasibility.

3.3.1 Overall Structure

The model has been developed in Excel and the overall structure is as shown in Figure 6.

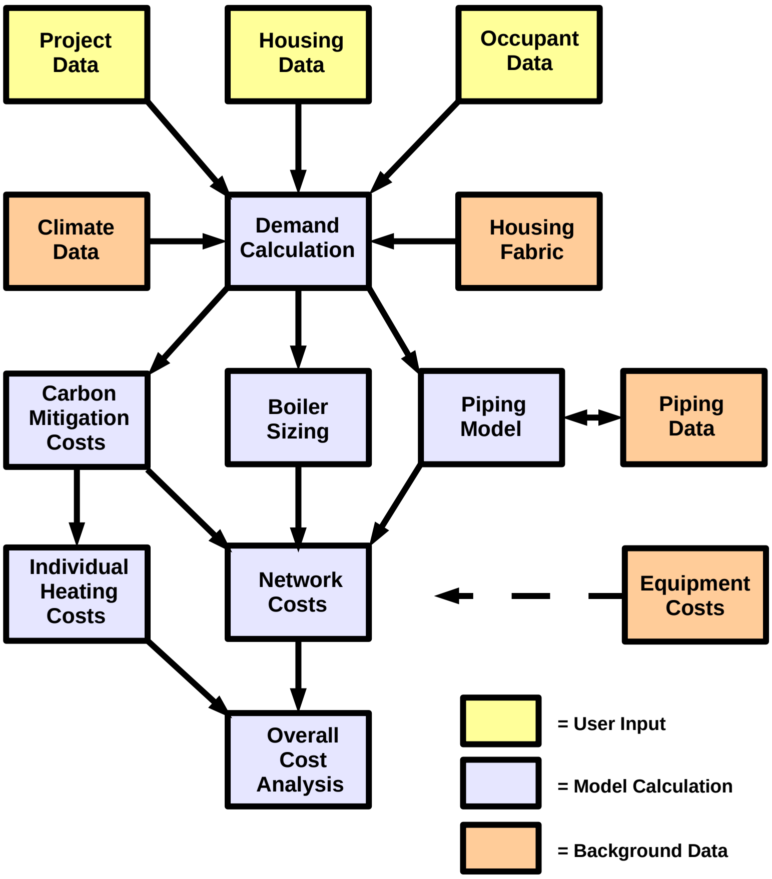


Figure 6: Developed Model Structure Overview

Three types of input data are required for the model; project, housing and occupant.

Project Input Data

Detailed project information, such as climate location, piping location type, operating temperatures, demand factors, and fuel cost data, is required as shown in Figure 7.

Base Project Data

Actual Project Location	Climate Reference Location	Project Lifetime (yrs)	Location (%) Inner City	Suburb	Parkland /Rural	New Dev	% of building units that are flats (%)	All houses have MVHR	RHI	FIT
Dunbeg	Oban	40	0	0	0	100	72	No	Yes	No

Supply Water Temp (°C)	Return Water Temp (°C)	Mean Water Temp (°C)	Hot Water Temp (°C)	Pipe Material	Pipe Type	Insulation	Manual Insulation Factor	Insulation TC (W/mK)	Soil z0	Pipe Depth (m)	Electrical Appliance Factor	Low Energy Lighting Factor
70	50	60	50	PEX	Twin	Standard	2	0.0225	2	0.6	0.75	0.7

Project Demand Factors

Demand Factor	Lifetime Demand Change (%)	Low Users (%)	Medium Users (%)	High Users (%)	SH User MIT Factor (+/- degC)	DHW User Demand Factor
0.95	0	30	40	30	0	1

Key Results

Lifetime P/L at NPV (£)	IRR%	Gas Equiv. Heat Charge (p/kWh)
0	0.00%	22.01

Zero P&L

Technical Data

Boiler Efficiency	Pump Eff.	Fuel	Total Plot Area (m2)	Aux Boiler	Thermal Store	Boiler Max Load (kW)	SH Diversity	Boiler Size % of Max	Selected Boiler (kW)	Thermal Store (lit)	HIU DP (bar)	HIU Heat Loss(W)
0.82	0.7	Chips	8650	Yes	Yes	164.92	0.93	80%	131.94	3000	0.5	20

Cost Data

Pellets	Chips	Elec	Discount Rate	Non-ECO Capital Grant	ECO Funding Available	O&M	Heat Charge Basis	User Heat Charge	Comparison Technology	Heat Charge	Standing Charge	RHI T1	RHI T2
(£/kWh)	(£/kWh)	(£/kWh)	%	£	%	(%/yr)		(£/kWh)		(£/kWh)	(£/house/yr)	(£/kWh)	(£/kWh)
0.04	0.028	0.1532	3.5	0	0	2	User	0.2001	Gas	0.2001	0	0.086	0.022

Figure 7: Project Data User Input Worksheet for Model

Housing Input Data

For accurate demand modelling, the Heat Loss Parameter (HLP) for each housing type is required. This defines the total heat loss per degree of temperature difference between the internal and external temperatures. Where the HLP is not already known, basic dimensional and fabric information is required to allow it to be calculated using the SAP (Standard Assessment Procedure) method detailed in 3.3.2 and Appendix B.

An estimation of floor area, external wall area, window and opening area, roof area, and ceiling height is required. The level of detail used will be determined by the size of the development to be studied, the availability of housing information, and type of study (first pass, feasibility etc.).

For smaller developments, the model allows each individual house type to be modelled. For larger developments, particularly with a mix of many house types, groups of similar houses can be modelled as a single average type, or grouped together.

For example, for the Govanhill case study (see 4.3.2), continuous blocks of 40-80 flats were modelled as a single building with an approximate number of individual flats. Compiling more accurate data would have been time-consuming, and unnecessary for an initial analysis.

Where accurate building fabric or HLP data is not known, typical fabric levels based on construction period, as detailed in 3.4, can be used.

Figure 8 below shows the housing input sections of the model.

Base House Data

#	House Type	Quantity	Type	MIT and Occupancy Basis	New or Retrofit	Built Period	'Zero Carbon'	Building Fabric Basis	HLP Basis	User HLP
1	P3 Type 1 GF	4	GF	Actual	New	11N	No	Typical	User	85.35
2	P3 Type 1 TF	4	TF	Actual	New	11N	No	Typical	User	108.20
3	P3 Type 2 SD	12	S	Actual	New	11N	No	Typical	User	137.96
4	P3 Type 3 SD	8	S	Actual	New	11N	No	Typical	User	140.00
5	P3 Type 9 SD	8	S	Actual	New	11N	No	Typical	User	158.11
6	P3 Type 11 D	1	D	Actual	New	11N	No	Typical	User	173.86
7	P3 Type 12 GF	4	GF	Actual	New	11N	No	Typical	User	85.35
8	P3 Type 12 TF	4	TF	Actual	New	11N	No	Typical	User	108.20
9	P2 Type 1 GF	6	GF	Actual	New	11N	No	Typical	User	85.35
10	P2 Type 1 TF	6	TF	Actual	New	11N	No	Typical	User	108.20
11	P2 Type 2 SD	18	S	Actual	New	11N	No	Typical	User	137.96
12	P2 Type 9 SD	4	S	Actual	New	11N	No	Typical	User	158.11
13	P2 Type 9 D	3	D	Actual	New	11N	No	Typical	User	173.86
14	P2 Type X D	3	D	Actual	New	11N	No	Typical	User	174.04
15	P2 Type X SD	4	S	Actual	New	11N	No	Typical	User	157.45
16										
43										
		89								

Habitable Rooms #	Bedroom #	Storey #	Height (m)	Overshading Factor	Area Roof (m2)	Per Storey Floor Area (m2)	Total External Surface Area (m2)	Window Area (m2)	External Door Area (m2)	Volume (m2)
3	1	1	2.4	0.77	0	67	56.6	10.3	1.8	160.80
3	1	1	2.4	0.77	66	66	56.6	10.3	1.8	158.40
4	2	2	2.4	0.77	52.4	49.4	113.3	11.3	3.6	237.12
4	2	2	2.4	0.77	54.0	51	116.2	14.2	3.6	244.80
5	3	2	2.4	0.77	61.7	61.7	116.2	14.2	3.6	296.16
6	4	2	2.4	0.77	75	75	116.2	14.2	3.6	360.00
4	2	1	2.4	0.77	0	77	71.8	12.1	1.8	184.80
4	2	1	2.4	0.77	75.3	75.3	71.8	12.1	1.8	180.72
3	1	1	2.4	0.77	0	65.2	56.6	10.3	1.8	156.48
3	1	1	2.4	0.77	66	66	56.6	10.3	1.8	158.40
4	2	2	2.4	0.77	52.4	49.4	113.3	11.3	3.6	237.12
5	3	2	2.4	0.77	54.0	49.4	116.2	14.2	3.6	237.12
6	4	2	2.4	0.77	61.7	61.7	116.2	14.2	3.6	296.16
5	3	2	2.4	0.77	60.3	60.3	137.3	15.2	3.6	289.44
5	3	2	2.4	0.77	60.3	60.3	234.7	15.2	3.6	289.44

Figure 8: Housing Data User Input Worksheet for Model

Occupancy Input Data

As defined further in 3.5, accurate occupancy data potentially allows better estimation of demand. Total number of occupants, number and age of children, pensioner occupancy, and income level are required for the socio-economic analysis in the model. Figure 9 shows the occupancy input sheet.

Actual Occupants	SAP Occupancy	Scot Avg. Occupancy	Tenure	Child <5	Children <18 #	OAP>65	Income Band	Total Occupants	Mean Internal Temp (MIT) Factor	DHW Use Factor
1.00	2.17	1.38	H	0	0	0.167	2	4.00	2.09	1.0076
1.33	2.15	1.38	H	0	0	0.167	2	5.32	2.17	1.0076
2.50	2.73	1.84	H	0.117	1.1	0	2	30.00	2.84	1.05
2.50	2.76	1.84	H	0.117	1.1	0	2	20.00	2.84	1.05
4.75	2.88	2.30	H	0	2.25	0	2	38.00	3.60	1.05
4.50	2.93	2.76	H	0	2.5	0	2	4.50	2.89	1.05
2.50	2.40	1.84	H	0.117	1.1	0	2	10.00	2.69	1.05
2.50	2.37	1.84	H	0.117	1.1	0	2	10.00	2.69	1.05
1.00	2.12	1.38	H	0	0	0.167	2	6.00	2.09	1.0076
1.33	2.15	1.38	H	0	0	0.167	2	7.98	2.17	1.0076
2.50	2.73	1.84	H	0.117	1.1	0	2	45.00	2.84	1.05
4.75	2.73	2.30	H	0	2.25	0	2	19.00	3.60	1.05
4.50	2.88	2.76	H	0	2.5	0	2	13.50	2.89	1.05
4.50	2.87	2.30	H	0	2.5	0	2	13.50	2.89	1.05
4.75	2.87	2.30	H	0	1.5	0	2	19.00	3.43	1.05
								246		

Figure 9: Occupancy Data User Input Worksheet for Model

Results Output

The main model output sheet details the overall heat demand, key project factors (as defined in 2.2.4), final cost and RHI income data for CHN, comparative costs for alternative heating options, and a summary of key individual costs (equipment, piping etc.). Figure 10 shows this output sheet.

Annual Demand		
Total	133888.89	kWh
Hot Water	83972.00	kWh
Space Heating	49916.89	kWh
Average Demand	2677.78	kWh
Average Demand Power	15.28	kW

System Scale		
Total Plot Area (m2)	8650	m2
Total Floor Area (m2)	3074.4	m2
Pipe Length (m)	529	m2
Average Pipe Dia (mm)	33.65	mm

System Factors		
Plot Ratio	0.36	(Floor/Plot)
Effective Width	16.35	(Plot/Pipe L)
Heat Density	1.36	GJ/m2
Heat Density	22.17	GJ/m
Occupant Density (Plot Area)	14.34	People per 1000m2
Occupant Density (Floor Area)	40.33	People per 1000m2
Pipe Length per connection	10.58	m

Heating Factors		
Boiler Use Factor	11.58%	RHI Tier 1 <15.7%
Pipe Heat Loss	47800.12	kWh/yr
Heat Loss (%)	26.31	
Heat Loss per m	10.31	W/m
Heat Loss per m	90.36	kWh/m
Average Total Power	20.74	kW

Costs (NPV Basis)	
Total (£)	761401.19

Income (NPV Basis)	
Total (20 year RHI)	761401.19

Profit/Loss	0.00
IRR	0.00%

RHI	
Tier 1 Limit	173365.8
Tier 1 %	77.2%
Tier 2	0.00
Avg. RHI per kWh	0.086

System Comparison	
Basis	New-Build
DH Heating (p/kWh)	20.01
Gas Heating (p/kWh)	22.01
Oil Heating (p/kWh)	21.30
ASHP (p/kWh)	22.39
Ind. Biomass (p/kWh)	33.54
Electric Heating	22.27
MVHR w/ASHP	No MVHR
MVHR+DH	No MVHR
Solar Thermal + Electric BU	27.46
Solver Run	Yes

DH Cost Breakdown	%
Capital (less Grant)	57.93%
O&M	23.84%
Fuel-RHI	18.01%
Pump	0.22%

Pipe Summary Size OD (mm)	Code	Length (m)	Cost (£/m)	Cost (£)
20	TS20	0	85.89	0.0
25	TS25	224	101.35	22702.6
32	TS32	0	117.96	0.0
40	TS40	305	137.43	41914.7
50	TS50	0	164.34	0.0
63	TS63	0	212.47	0.0
75	SS75	0	248.58	0.0
90	SS90	0	279.57	0.0
110	SS110	0	312.57	0.0
125	SS125	0	340.87	0.0
160	SS160	0	392.07	0.0
Total				64617.31
			Avg. per house	1292.3

Boiler	Max Load (kW)	Selected (kW)	Cost (£/kW)	Cost (£)
Biomass	164.92	131.94	630	83120.6
Aux				12468.09
Control System/Interco Pipe				23193.75

Thermal Store	Cost (£)	6500
Access Road	Cost (£)	1300
Utility Connections	Cost (£)	7600
HIU/Meter	Cost (£)	119600
Wet Heating System	Cost (£)	0
LT Radiator Adder	Cost (£)	3102.45
Retrofit – HookUp	Cost (£)	0
2016 Carbon Offset	Cost (£)	44579.53
Fuel	Cost (£/kWh)	0.028

Figure 10: Results Worksheet from Model

3.3.2 Demand Modelling

Space Heating

As outlined in Section 3.2.2 and 3.3.1, the general SAP (Standard Assessment Procedure) method for heating and hot water demand calculation has been selected. The method first requires the Heat Loss Parameter (HLP) for the dwelling to be given or calculated.

The detailed method and equations used for HLP calculation and space heating estimation are described in Appendix B.

Hot Water

Hot water demand per household is calculated using the following SAP 2012 equation (BRE, 2013).

$$Water\ Demand\ (kWh/month) = (36 + (25 \times N)) \times Days \times 4.187 \times Water\ \Delta T \times Month\ Use\ Factor\ /\ 3600 \quad (3)$$

where, the *'Month Use Factor'* is a usage factor defined in SAP 2012 for seasonal differences in water use, N is the number of occupants, and *'Water DT'* is the difference between mains and required temperature.

Demand Factors (Fixed and Linear)

As a 30-40 year investment, it is important to consider community heating network economic sensitivity to changes in user behaviour, periods of lower than normal demand (e.g. periodically empty dwellings), and gradual building fabric improvements.

The model allows a single demand factor to be set. For social housing projects, for example, this can be less than 1 to account for void periods or to account for secondary heating use (see 3.6.1).

The model also allows a linear reduction factor to be selected to account for a presumed energy demand change over the lifetime of the project. For post-1992 properties this should be close to 0% for heating if we assume that they already have a degree of cost effective thermal design and improvements. For pre-1992 developments it would be prudent to consider the potential for further fabric improvement based on existing improvement uptake. Hot water use may also reduce over time due to increasing use of low-flow fittings and equipment, or behaviour changes. Although this potential is not considered in detail.

3.3.3 Piping Network Modelling

There are two specific purposes for the piping section of the developed model. The primary purpose is to allow the heat loss from the pipe network to be calculated. For lower demand networks this loss is a significant proportion of the heat demand (up to 35%), and must be accounted for in the boiler sizing and fuel cost calculations. The model can also be used to size piping but this is a relatively simplistic method that is more suitable for feasibility costing than formal design.

Heat Loss

The standard method to determine the heat loss in a heat network is to determine heat loss per metre for each pipe section based on the average temperature of the network. The total heat loss is determined by summing the total heat loss for each pipe section. As outlined in 3.2, the method for calculating the pipe heat loss is the industry standard method taken from Zinko et al (2008).

Pipe Sizing

The lifetime cost of the piping network comprises the initial construction cost, the cost associated with the heat loss, and the pumping cost associated with the pressure drop in each section. The first two factors drive the selection of the smallest possible pipe size, until the pumping cost, velocity or overall system pressure drop become limiting factors.

The model calculates an annual effective cost for the construction, heat loss and pumping costs. The heat loss and pumping costs are converted to net present value based on 40 years to allow a fair comparison with the initial construction cost to be made. The construction costs are set dependent on the location type of the project (city centre, suburb, rural/parkland, or new development), and the cost basis is discussed further in 3.6.2.

For each section of pipe, the number of dwellings supplied are identified to allow the diversified heating and hot water peak loads to be calculated. The size can then be manually adjusted to first minimise the effective cost of the section within the velocity limits (3.5m/s for cross-linked polyethylene (PEX) pipe) (Ballanco, 2007). Critical paths are then identified to calculate maximum overall pressure drop, and linesizes can then be adjusted further based on the pressure limit of the pipework (typically 6-10 bar for PEX pipe), and to remove potential bottlenecks. For actual design further work would be required to consider specific pump models.

3.3.4 Financial Modelling

All system financial models use a calculated 'effective' cost per kWh at net present value (NPV) over the lifetime of the network or heating system for financial comparison. A fixed monthly charge can also be set, with the unit cost reduced accordingly. Unless otherwise stated the comparison basis is the total like-for-like cost of the heating system, including generating unit.

Models are included for the community heating network and a number of individual heating systems (gas, electric, oil, air source heat pump (ASHP), Solar Thermal, Mechanical Ventilation and Heat Recovery (MVHR) system with ASHP, Individual Biomass Boiler).

The project lifetime can be varied from 1-60 years. Replacement components are added at set intervals (20 and 40 years for boiler/heating systems, 30 years for Heat Interface Units etc.).

Renewable Heat Incentive (RHI) tariffs and project grants can be added as required. All incentives for the heat network and Feed-in-Tariff (FIT) electrical payments for CHP and solar panels have a 20 year duration in line with current Government guidelines. Eligible payments for individual heating system payments are made for 7 years. (EST, 2013a)

A simple discount factor basis is used to determine NPV. The model does not include individual inflation or interest rate assumptions.

3.4 Building Fabric / Regulations

For accurate demand estimation, particularly for developments with a common design basis, it is recommended that a detailed estimate of actual fabric thermal performance and air tightness is made for each dwelling type in line with the mandatory SAP requirement. However, to allow initial feasibility to be gauged, typical values can be used. The model, therefore, allows typical fabric values, user-specified fabric values, or a calculated SAP Heat Loss Parameter (HLP) to be used.

For the typical housing data, pre-2007 building fabric values are taken from the Energy Savings Trust study 'Scotland: Assessing U-values of Existing Housing' (EST, 2004).

For 2007, 2010, and 2014, the Scottish Building Regulations are used (ScotGov, 2013d). Improved CO_2 targets in each update are based on a package of measures of which fabric is only one element. Each Regulations release, therefore, has a minimum 'backstop' fabric requirement, and a 'nominal' basis for a typical house to meet the CO_2 targets. However, the actual fabric basis can vary significantly within a range. The model allows either to be selected, or user values can be entered.

Beyond the 2014 update, the roadmap for further improvements is less clear, but with a fixed EU target for 'zero carbon' homes by 2020. The definition of 'zero carbon' used throughout this study is net zero carbon dioxide (CO_2) emissions for heating, hot water and lighting use.

There is scepticism that designs with a high degree of air-tightness and all-room mechanical ventilation (such as the 'Passivhaus' design) will be suitable for general use in Scotland. The concerns are based on the cold and damp climate making the system uneconomic. Householders may also not be able to adjust to the operational requirements and limitations, where they have not specifically requested the system. This has been stated by the 'Sullivan Report' (SBSA, 2007). The 'zero carbon' basis, therefore, does not include an all-room Mechanical Ventilation with Heat Recovery (MVHR) system. A 'Passivhaus' model is included separately for comparison. The

'Passivhaus' design basis is from BRE (2012).

The fabric basis for the 'zero carbon' house is assumed to be Code 6 of the Code for Sustainable Housing. The example used is from EST (2011a) from a test project in conjunction with SSE, where a high level of building fabric with no all-room mechanical ventilation is used to achieve a 'zero carbon' design. An intermediate update, using a fabric basis between the 2014 and 'zero carbon' requirement, is predicted with a c.70% reduction target ('70% ZCH') as it is assumed that the change from the 2014 45% reduction basis to 100% will be staggered.

Table 2 gives the selected typical fabric and air infiltration values based on the build date. It is assumed that there is at least a one year delay between a new Building Regulations release and compliant buildings being completed (EST, 2004).

If all buildings are assumed to comply with the relevant Building Regulations for fabric and air tightness, and are designed with a safety margin, we would expect the above assumption of compliance with no margin to overestimate energy use. However, there is also evidence that modern houses are not performing as per the Regulations, with some new houses missing targets by over 100% (Sutton, Stafford and Gorse, 2012). As discussed further in 3.6.1, it is recommended that, where specific housing fabric information is unknown, a range of potential demands between the applicable and next Building Regulations release are considered rather than a fixed value to account for the potential variance in performance.

3.4.1 Improvements to Existing Housing

Care needs to be taken when defining building fabric properties for existing buildings. The system may be viable under present conditions but if the housing has remaining potential for the uptake of cost effective improvement options (e.g. double glazing, cavity wall insulation, roof insulation) then the demand could be reduced considerably during the 30-40 years network lifetime.

For this reason the model uses U-values for existing housing that are based on a reasonable assumption of further improvement over time. For example, a conservative value of 0.9 is selected for the 1919 to 1976 wall U-value, whereas the current average value is between 1 and 1.05 based on the current uptake of cavity wall insulation (see C1).

3.4.2 Model Building Fabric Basis

Table 2 details the selected building fabric basis for each construction period, and predicted levels for two further Regulations updates to an expected 'zero carbon' 'in use' basis by 2020.

A full analysis of how the selected values have been determined is included in Appendix C.

Built Period	Wall U-value (W/m².K)	Roof U-value (W/m².K)	Floor U-value (W/m².K)	Opening U-value (W/m².K)	Air Changes per hour @0Pa	Thermal Bridge Factor (Ψ)	Window Trans-mittance
Pre-1919	1.7	0.2	0.65	3.6	1	0.15	0.76
1919-1975	0.9	0.2	0.65	3.1	0.85	0.15	0.76
1976-1983	0.7	0.2	0.65	3.1	0.85	0.15	0.76
1984-1991	0.6	0.2	0.65	3.1	0.85	0.15	0.76
1992-2002	0.45	0.2	0.45	3.1	0.7	0.15	0.76
2003-2007	0.3	0.16	0.35	2	0.5	0.15	0.72
2008-2010	0.25	0.16	0.22	1.8	0.5	0.1	0.63
2011-2014 ('Backstop')	0.25	0.18	0.2	1.8	0.5	0.15	0.63
2011-2014 ('Nominal')	0.19	0.13	0.15	1.5	0.3	0.08	0.63
2015+ ('Backstop')	0.22	0.15	0.18	1.6	0.5	0.08	0.63
2015+ ('Nominal')	0.17	0.11	0.15	1.3	0.3	0.08	0.57
'70%ZCH' ('Backstop')	0.2	0.15	0.2	1.4	0.35	0.08	0.57
'70%ZCH' ('Nominal')	0.14	0.1	0.12	1.0	0.27	0.04	0.57
'Zero Carbon' ('Backstop')	0.17	0.11	0.15	1.3	0.3	0.08	0.57
'Zero Carbon' ('Nominal')	0.12	0.1	0.1	0.8	0.25	0.04	0.57
Passivhaus	0.15	0.15	0.15	0.8	0.03	0.01	0.57

Table 2: Typical building fabric factors for different construction periods

3.4.3 CO_2 Targets and Mitigation Costs

Current and future Building Regulations are not specifically focused on reducing energy demand but rather CO_2 emissions. The SAP 2012 method (BRE, 2013) is used to calculate the required maximum CO_2 emissions for each dwelling. As each heating and fuel option has a different CO_2 rating per unit heat consumed, the system selected has a direct impact on the building design.

SAP allow 'biogenic' fuels, such as wood fuels, to use life cycle net CO_2 emissions as the evaluation basis. Therefore wood fuels have a much lower SAP CO_2 rating than any relevant fuel as shown in Table 3 (BRE, 2013). Achieving the CO_2 targets required by the Building Regulations is, therefore, significantly easier than for any other potential heat source.

Fuel	$kgCO_2$ per kWh
Biomass Community Htg.	0.031
Gas	0.216
Oil	0.298
Grid Electricity	0.519
ASHP (COP 2.5)	0.239
Solar Thermal (40%+Electric)	0.311

Table 3: SAP 2012 CO_2 emissions rating per fuel (BRE, 2013)

Various means are available to allow the required CO_2 target associated with heat demand to be achieved. Building fabric can be upgraded to reduce heat loss, PV panels can be added to offset the heat related CO_2 emissions, and a penalty payment to fund national energy decarbonisation schemes has also been suggested as reviewed below.

Figure 11 shows a typical overall lifetime cost breakdown for a community heat network (CHN) and gas heated house using the developed model. The 'baseline building cost' can be considered the cost required to meet the Building Regulations minimum 'backstop' basis as defined in 3.4.

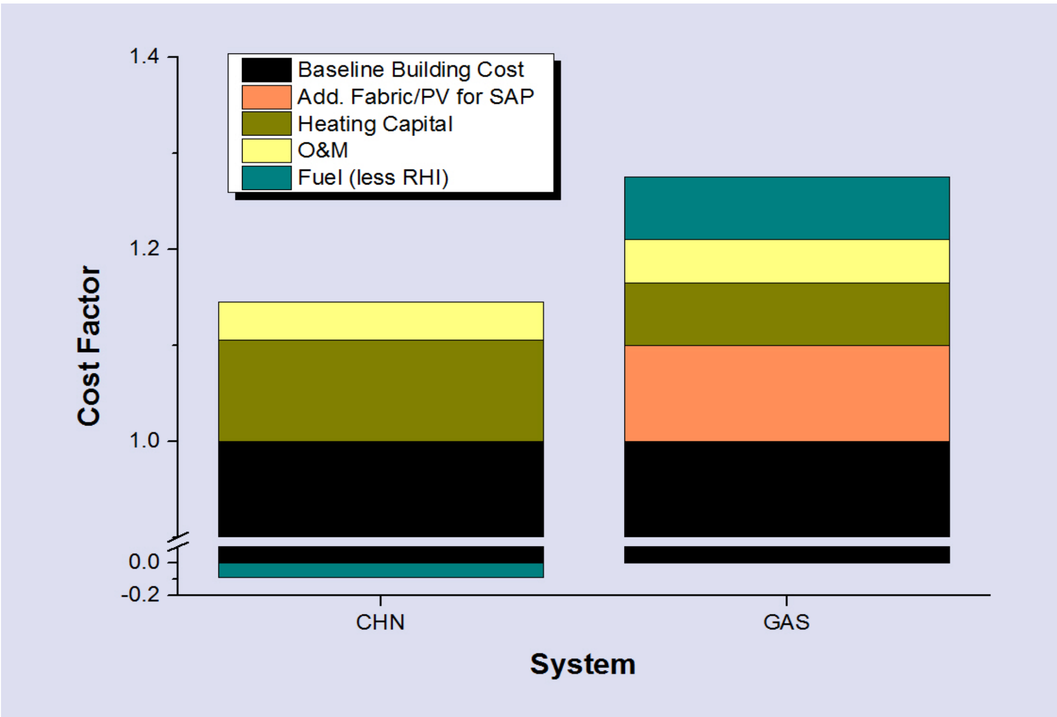


Figure 11: Typical overall building and heating cost breakdown for community (CHN) and gas heating

Beyond the baseline building cost, additional costs can be considered as a cost of providing heat. To allow the impact of the additional building fabric and other mitigation methods on the overall cost of supplied heat to be evaluated, a further module was added to the model as detailed below.

Modelling Method

A simplified method based on calculated $kgCO_2/m^2/yr$ has been used for this analysis. Focusing solely on heating and hot water use, a baseline value for $kgCO_2$/m2/yr is calculated for each house type using the 2007 Building Regulations 'nominal' fabric basis with gas heating (ScotGov, 2013d). This house would have been just acceptable at this time without further modifications or renewable microgeneration sources.

CO_2 targets for Building Regulations updates from 2010 use the 2007 version as the baseline with targeted reductions (e.g. the 2014 target is a 45% reduction) (ScotGov, 2013d). The analysis assumes that the heating and hot water related $kgCO_2/m^2/yr$ for subsequent versions is the calculated 2007 baseline value for gas heating factored by the target reduction. This is a simplification of the overall analysis required by SAP for total energy but provides a convenient comparison basis for heat related costs. It is, however, in line with the recent Government policy that only heating, hot water, cooling and lighting will be considered for future CO_2 targets, and that the final 'zero carbon' target will also use this definition (HMT, 2011).

For each Building Regulations update, the $kgCO_2/m^2/yr$ value is compared for the relevant 'backstop' and 'nominal' fabric basis (see Section 3.4 for definition) for each heating option. If the 'backstop' value allows the CO_2 target to be achieved, no further improvements are required. If the target is not achieved, the cost of using fabric, PV (solar panels), or penalty payments at the proposed 'shadow cost of carbon' (ZCH, 2013), are compared. If the target is not achieved using the 'nominal' fabric basis then only the cost of further PV or payments are considered. Fabric benefits only reduce space heating and will therefore only improve CO_2 emissions up to a certain limit, with increasingly marginal benefits as this limit is approached. The 'nominal' level is assumed to be close to this limit.

The calculated additional costs are then converted to an equivalent cost per kWh over the modelled lifetime of 40 years and added to the relevant values from the heating system-only analysis. This gives an overall housing plus heating system effective cost per kWh comparison between heating systems, including all relevant incremental carbon mitigation costs. The impact of this evaluation method is discussed further in 5.3.

Taki and Pendred (2012) reviewed the cost of fabric upgrades required to meet improved energy standards. The most cost effective methods of fabric improvement equated to a construction cost of c.£1520 per $kgCO_2/m^2/yr$ reduction based on gas heating. (For heating and hot water only, a typical value is 14-18 $kgCO_2/m^2/yr$ for gas heating).

For the West of Scotland, the 'nominal' capacity of a PV panel in Wp per annual kWh generated is c. 1.6 Wp/(kWh/yr) (Flett, 2012). Based on a mid-range panel, an installed cost of £2/Wp nominal rating is used (EST, 2013d). The PV installation is treated as a single 'standalone' system owned and operated by the Housing Association. Associated Renewable Heat Incentive (RHI) and Feed-in Tariff (FIT) payments are based on all power generated being exported to the grid. An integrated system may allow additional income to be generated from direct use of the electricity by the networked households but this is not considered.

The use of a penalty payment related to the shadow cost of carbon is not a formal policy, but is currently under consultation (DCLG, 2013). This has been suggested by the Zero Carbon Hub Trust (ZCH, 2013) as being a suitable way to achieve low carbon housing using all reasonable heating options without excessive use of fabric improvements and PV (solar panels). It is known as the 'Allowable Solutions' policy. The underlying philosophy being that, at a certain point, it is more cost effective to finance large scale generation and grid improvements than small-scale microgeneration.

It is proposed this charge would be levied as a single upfront payment based on emissions over a 30 year period and would require a reasonable CO_2 level to be achieved by other means first, with the payment covering the remaining CO_2 emissions. A payment level of £46/tonne CO_2 is used (DCLG, 2011). This policy is reviewed further in 5.3.

The following 'Worked Example' outlines the calculation process used by the model to determine the additional costs required for each heating system type.

Worked Example of Required Improvement Costs:

For a 2-bed semi-detached house (68m^2 floor area) at Dunbeg (see 4.2.2) the 2007 baseline was calculated to be 16.77 kgCO_2/m^2/yr.

For the predicted 70% reduction required by the 2017 BR update the new target is 5.03 kgCO_2/m^2/yr.

Using the predicted '70%ZCH' 'backstop' fabric requirement, biomass community heating meets the new target directly with an calculated emission rate of 2.81 kgCO_2/m^2/yr.

For a gas heating system, at this backstop fabric level the emission rate is 12.26 kgCO_2/m^2/yr, and at the 'nominal' fabric basis it is 8.65 kgCO_2/m^2/yr. The CO_2 target therefore requires further improvement beyond the 'nominal' fabric basis.

For the 'backstop' fabric plus 'shadow' cost payment case, the total additional cost per house is:

$$(12.26 - 5.03) \times (68.9\ m^2) \times (30\ years) \times (£0.046 / kgCO_2) = £688 \quad (4)$$

For the 'backstop' fabric plus PV case, the total additional cost per house is:

$$(12.26 - 5.03) \times (68.9) \times (1.6\ \text{Wp}/(kWh/yr)) \times (£2/\text{Wp}) / (0.519\ kgCO_2/kWh) = £3072 \quad (5)$$

For the 'nominal' fabric plus 'shadow' cost payment case, the total additional cost per house is:

$$(12.26 - 8.65) \times £1520 + (8.65 - 5.03) \times (68.9) \times (30) \times (£0.046) = £5833 \quad (6)$$

For the 'nominal' fabric plus PV case, the additional cost per house is:

$$(12.26 - 8.65) \times £1520 + (8.65 - 5.03) \times (68.9) \times (1.6)\,(£2) / (0.519) = £7025 \quad (7)$$

3.5 Socio-economic Demand Factors

The majority of demand prediction models assume an average consumer or at best, such as the BRE DEM model, allow the proportion of high and low relative users to be predicted. There is surprisingly little existing data on the relative level of heating and hot water used by different types of households, and how this influences demand within small developments and areas.

3.5.1 Mean Internal Temperature (MIT)

MIT Factors

A recent study by the Tyndall Centre (Kelly et al, 2012) has attempted to statistically analyse a number of parameters that could impact the mean internal temperature (MIT) of a dwelling. This uses an existing dataset from 280 randomly selected English houses taken between July 2007 and February 2008 (the 'CAR-HES' dataset).

It was determined that for this review, the socio-economic MIT factors from this study would, at best, allow better prediction of energy demand for individual communities, or at least allow potential sensitivities to the occupancy basis be gauged.

A significant number of parameters were analysed by the Tyndall Centre, including demographics and behaviours. Considering all heating system, behavioural, and socio-economic parameters, variations in MIT of up to 6.6°C can be explained. For a community heating network, however, several parameters associated with the system design (temperature controls, system response etc.) are fixed for all households. This model, therefore, allows both a baseline MIT to be set based on the overall network characteristics, and specific MIT adjustments for expected occupancy.

Random behaviour factors which could not be easily predicted for a given community were ignored, and therefore assumed to be averaged across any community. As the study did not include Scotland, the North-East England geographical factor was used as the closest approximation.

The overall accuracy for all modelled factors of the Tyndall Centre model was estimated to be ±0.71°C with a 95% confidence (Kelly et al, 2012). Figure 12 below shows the variation of modelled and actual mean internal temperatures over the six month monitoring period of the dataset, and also the spread of actual measurements taken.

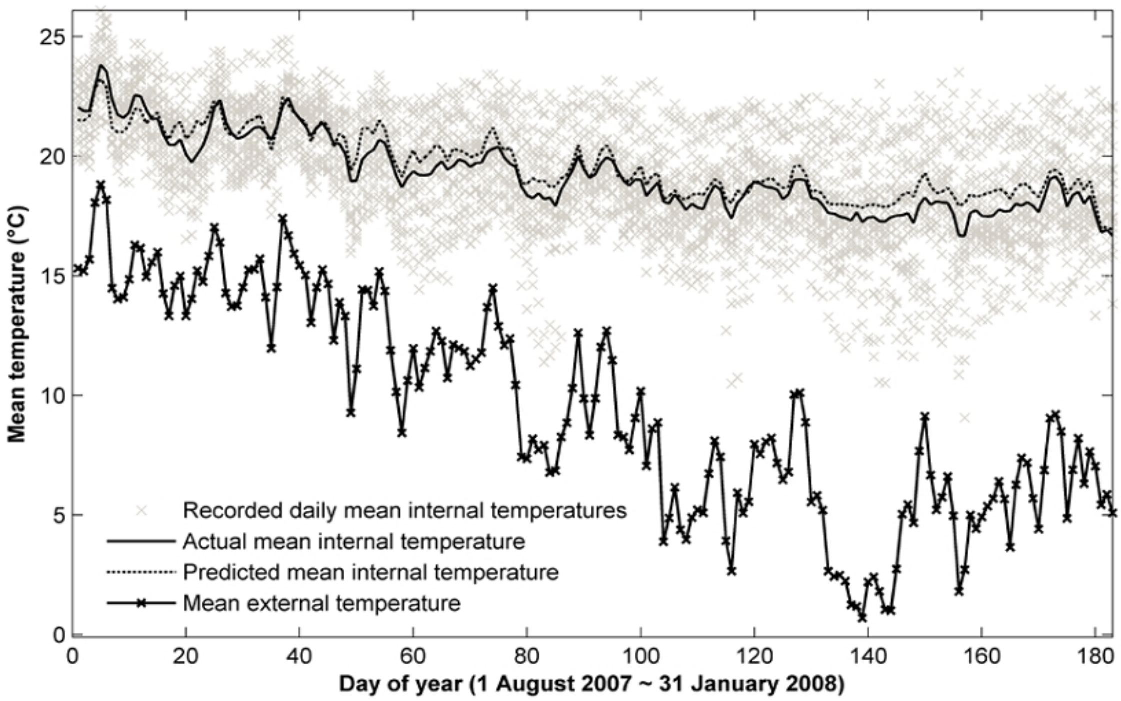


Figure 12: Modelled and actual mean internal temperatures from the Tyndall Centre MIT factor model (Kelly et al, 2012)

The key factors that were taken from the study and used in the developed heat network model were ones that could be determined or estimated with reasonable accuracy for a social housing network or for a particular area. Table 4 lists the factors selected, and the factor for mean internal temperature used based on either a yes/no, range (band) or absolute value.

Factor	Basis	MIT Adder (°C)	Factor	Basis	MIT Adder (°C)
Child <5	yes/no	0.495	**Detached**	yes/no	0.0
Children <18	value	0.219	**Semi-detached**	yes/no	0.694
OAP>65	yes/no	0.455	**Mid-terrace**	yes/no	0.607
Private-owned	yes/no	0.0	**All flats**	yes/no	0.541
Housing Assoc.-owned	yes/no	0.448	**Income***	Band (0-6)	0.084
Rented	yes/no	0.940	**Building Age***	Band (0-11)	0.042
Tenure average	yes/no	0.182	**Wall U-value***	Band (0-4)	0.076
Occupants	value	0.250			

*see Appendix A for band levels

Table 4: Housing, occupancy and socio-economic factors used for MIT calculation (Kelly et al, 2012)

The tenure results from the study were somewhat counter-intuitive. Private-owned homes have the lowest mean internal temperature (MIT), despite the likelihood of higher income levels. This, however, reflects the total time spent in the home, which is likely to be higher for Housing Association and rented properties with lower expected employment levels.

Other studies have also shown that the lower energy use by lower income households is reflected in the total energy cost per household, which for lower income families tend to be smaller per occupant (Cheng and Steemers, 2011). As MIT is not related to house size, the MIT can be higher but the overall spend lower compared to an equivalent higher income household in a larger house.

The factors for Building Age and Wall U-value account for the rebound effect in MIT as buildings are improved. Improved building fabric allows householders to increase heating use to raise comfort levels, in addition to driving lower demand.

Base Temperature

To allow the model to adjust the MIT for different parameters, a base temperature needs to be set. The Tyndall Centre data provides the average annual MIT, and the proportions or average values for the other parameters. By taking the average temperature given and adjusting using the given factors, a base (lowest) MIT value was determined based on a pre-1850, poor building fabric, privately-owned, detached house with no occupants and the lowest income level. This value is then adjusted upwards depending on the number and type of occupants, tenure, and dwelling type. The base temperature is calculated to be 16.8°C.

The second adjustment made was that the data used for the Tyndall Centre analysis was based on the arithmetic mean of the measured living room and a single bedroom temperatures. This is likely to overestimate the actual mean temperature across the whole house as these represent rooms that are most likely to be actively heated, and the typically colder bedroom area is larger on average.

The 'CARB-HES' data average mean internal temperature (MIT) is 19.6°C, which differs from the DECC whole house estimate of 17.5°C for the same winter heating period in 2007 based on the BREDEM method (Utley and Shorrock, 2008). The external temperature average for the two models is 9.7 and 7.3°C respectively. Adjusting the CARB-HES average to 19.35°C for the external temperature factor gives a difference of 1.85°C between the two datasets. The base temperature has therefore been reduced to 14.95°C to compensate as the developed model for this review uses the SAP/BRE whole house MIT definition as the basis.

The factors calculated in the Tyndall Centre analysis were not modified further to account for the new lower, overall house temperature. This may lead to a slight overestimate of calculated MIT factors but further data would be required to determine an appropriate factor.

3.5.2 Occupancy Models

An accurate estimate of the number and type of occupants per house type is important for demand estimation. The current data available does not give highly detailed analysis across different housing types, tenures and sizes, therefore it is difficult to estimate exactly.

Scottish Average Data

A detailed review of Scottish average data, including sources, is included in Appendix D. The summary is as follows:

- 2.19 people per household (2011 figures)
- 0.46 people per habitable room and 0.81 per bedroom (2009 figures)
- 45.7% of social housing is 1-person households, compared to 26.0% in the private sector
- Number of habitable rooms drops with income
- 0.49 children per household (2013 figures)
- Assuming one main non-child bedroom, average number of children per subsequent bedroom is 0.3
- 10.3% of households have a child under 5 (2013 figures)
- Assuming no children in 1-bed properties, likelihood of a child under 5 increases to 11.7% for 2+ bedroom properties
- 31.5% of Scottish housing has a pensioner resident (2009 figures)

Number of Occupants

An alternative occupancy model is provided by the SAP (Standard Assessment Procedure) 2012 method (BRE, 2013). An equation based on the total floor area (TFA) is used to determine the number of occupants (N). The equation is as follows:

$$N = 1 + 1.76 \times [1 - \exp(-0.00349 \times (TFA - 13.9)^2)] + 0.0013 \times (TFA - 13.9) \qquad (8)$$

West Highland Housing Association (WHHA) provided current occupancy data for the Glenshellach development (WHHA, 2013b). The comparison of the actual Glenshellach data, SAP and 'Scottish Average' estimations is shown in Table 5:

House Type	Actual (Averaged)	SAP	'Scottish Average'
1-bed Ground Floor Flat	1.00	2.12	1.38
1-bed Top Floor Flat	1.33	2.15	1.38
2-bed Semi-detached	2.50	2.73	1.84
3-bed Semi-detached (A)	4.75	2.73	2.30
3-bed Semi-detached (B)	4.75	2.87	2.30
3-bed Detached	4.50	2.87	2.30
4-bed Detached	4.50	2.88	2.76
Totals	**246**	**231**	**167**

Table 5: Actual and modelled occupancy data for the Glenshellach development

Assuming the Glenshellach actual occupancy data is relatively consistent with similar Housing Association developments, the results confirm the above conclusions. 1- and 2-bed social housing typically have lower occupancy than average models, and larger houses have higher occupancy levels. Overall the SAP model is relatively close for total occupancy but very inaccurate for small and large dwellings. The 'Scottish Average' model clearly underestimates for social housing, where ensuring maximised occupancy is a key criteria, and increasingly so with the recent 'Bedroom Tax'.

Where possible actual data should be used for any study. If unavailable, localised census data (Scrol, 2013) would give greater accuracy than national average data. The SAP model can be used with reasonably accuracy across a mixed range of house types and sizes. There is a lack of freely available data on the range of occupancies expected in social housing compared to all housing to allow a better assessment and specific occupancy model to be developed.

Number of Children

For the Glenshellach development the actual number of children is 101, with the Scottish average basis predicting only 29, so there is clearly a major discrepancy between the national average and actual numbers for a Housing Association development.

The Glenshellach average is 1.05 children per non-main bedroom, compared to 0.3. This is used for the other Housing Association (HA) developments in the absence of actual data for other developments. The discrepancy between house and household size, and the fact that only 26% of households have children, may mean that this overestimates number of children for 2-bed properties, so care should be taken for a development of primarily 1 and 2-bed properties.

However, the proportion of under-5's at Glenshellach closely matched the national average of

14.5% for 2+ bed properties. This value was therefore used for all model.

Pensioner (OAP) Households

For Glenshellach the actual number of pensioner household is significantly smaller than the national average of 31.5%, with only 4 properties out of 89 (4.5%) having a pensioner present. However, this development is a significant distance from Oban centre and more suitable for more mobile households. This factor may therefore be highly location dependent.

Occupancy and MIT Sensitivity Analysis

To determine the potential impact of socio-economic factors, a typical 2-bed, 4-person semi-detached property has been used to gauge sensitivity for a single house. It is based on a selected mid-size property from the Glenshellach development (see Section 4.2.1). The floor area is 98.8 m^2, and the actual SAP Heat Loss Parameter (HLP) value for this property of 137.96 W/K is used.

The base dwelling with average socio-economic factors based on the Tyndall Centre analysis (Kelly et al, 2012) has a mean internal temperature (MIT) of 17.63°C and annual space heating demand of 4326.3 kWh. The impact of a 1°C increase and decrease in MIT on annual energy demand is +918 kWh(+21.2%) and -829 kWh(-19.2%) respectively based on the actual HLP.

Table 6 gives the modelled MIT for the dwelling based on different occupancy factors:

Occupancy						MIT(°C)
Adults(No.)	**Child<5(Prob.)**	**Children(#)**	**OAP(Prob.)**	**Tenure**	**Income(band)**	
1.89	***0.08***	***0.41***	***0.33***	***Average***	***3.5***	***17.63***
1.89	0.08	0.41	0.33	HA	2	**17.62**
2	0	0	0	Private	4	**17.09**
2	0	0	0	HA	2	**17.37**
1	0	0	0	HA	2	**17.12**
2	1	1	0	HA	2	**18.33**
2	0	1	0	HA	2	**17.84**
2	0	2	0	HA	2	**18.30**
1	0	1	0	HA	2	**17.59**
1	0	0	1	HA	1	**17.49**
2	0	0	1	HA	1	**17.74**

Table 6: Modelled mean internal temperature (MIT) variation with occupancy

The results show that there can be a significant difference, particularly between houses with and without children. A single infant or two older children can, if the study is assumed to be accurate, add c.1°C to the MIT. For a development or community that is an approximately 50/50 mix of smaller flats and larger family houses it is likely that these variations would cancel out. Where this analysis is likely to be of greatest use is for developments that are primarily of a certain type.

Overall sensitivity analysis for an entire development is reviewed in 6.4.

3.5.3 Hot Water Usage

Few references exist for the variation of hot water use with any factor other than number of occupants. BRE (2005) provides water use data from a 1998 source for income and household type.

For income there was a 5-6% decrease in water use for the lowest income third and a corresponding 5-6% increase for the highest third. General energy use with income decile shows a relatively linear relationship between use and income (Utley and Shorrock, 2008). Based on the 7 income bands used in the Tyndall Centre analysis (Kelly et al, 2012) for space heating use, it was estimated that each band corresponded to a 3% increase in water use.

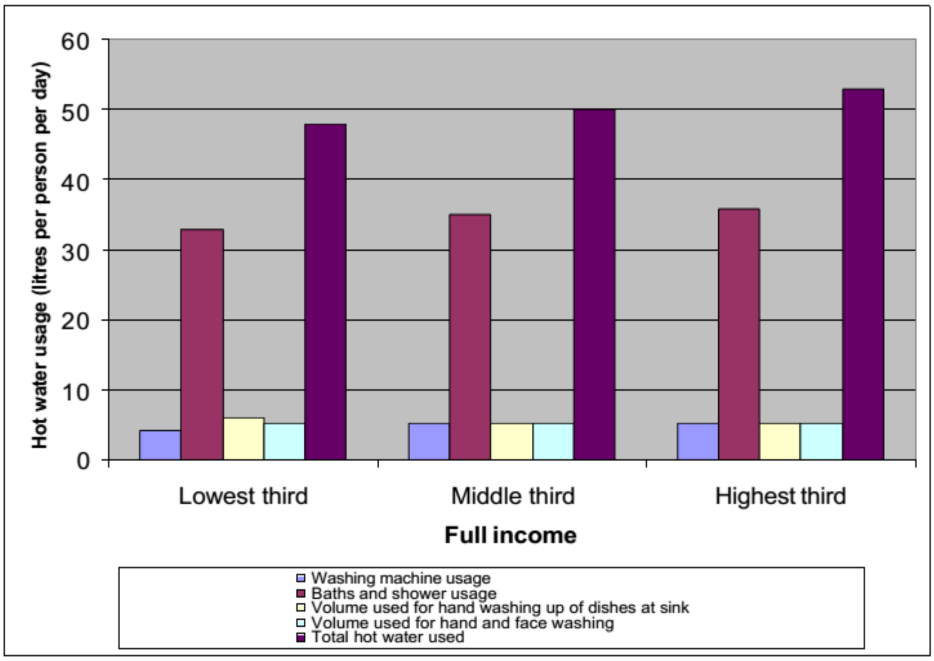


Figure 13: Hot water usage per-person for different income levels (BRE, 2005)

Further data was provided for use per type of household. This data showed that households without children or pensioners has the greatest use (10-20% more than average). Pensioner only households use less than average by 8-14%.

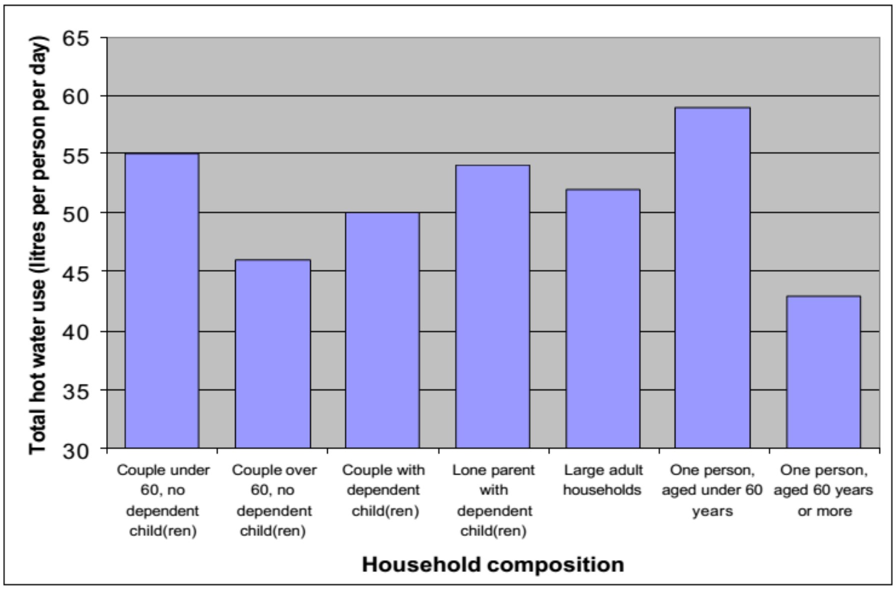


Figure 14: Hot water usage per-person for different household compositions (BRE, 2005)

The impact of children on household water use should largely be captured by the SAP '36x25N' factor used for average water use (see 3.3.2). Other factors such as single parent and adult only households are difficult to estimate for any smaller group of housing and are not significantly above average. However, the impact of pensioner-only households is significant.

Based on the factors used on the model this analysis is simplified to a 8% decrease for a pensioner only household. Pensioner (OAP)-only households make up 23% of the 31.5% households with at least one pensioner (ScotGov, 2012b), but the model assumes the presence of a pensioner will have some impact and uses 31.5% as the key statistic. It is expected that for most housing either 0, 0.315 or 1 will be used for pensioner occupancy likelihood. The main purpose of this factor is therefore to ensure houses where pensioners are either very unlikely (multi-bedroom, out-of-town) or highly likely (sheltered housing) are accounted for.

Assuming a linear response from the average to the minimum and maximum, the following simple factors for domestic hot water (DHW) are used:

$$For\ OAP\ likelihood\ (a) > 0.315 \rightarrow DHW\ use\ reduction\ factor = (1-((1-a)/0.685)) \times 0.08 \quad (9)$$

$$For\ OAP\ likelihood\ (a) < 0.315 \rightarrow DHW\ use\ increase\ factor = (1-(a/0.315)) \times 0.08 \quad (10)$$

3.6 Model Verification

Two Oban-based Housing Association case studies were selected to determine and verify and the model basis and assumptions. Overall cost and annual demand data was made available by West Highland Housing Association (WHHA) for the Glenshellach Phase 2/3 system and detailed cost estimate data was available from CPP (Campbell Palmer Partnership) for the proposed Dalintart scheme.

Glenshellach was a new-build development, built between 2005 and 2007, comprising 71 houses and 28 flats, and Dalintart is a proposed retro-fit scheme for 39 houses and 23 flats. Both are also used as case studies. See Sections 4.2.1 and 4.3.1 for detailed information and analysis.

3.6.1 Demand Verification

For the Glenshellach Case Study, WHHA provided annual usage data for the period 2009 to 2012 (WHHA, 2013a), and the capital cost of the project is available (ScotGov, 2009). Detailed planning drawings were available for the development which allowed accurate building design estimation. The occupancy data and the SAP Heat Loss Parameter (HLP) calculation results were also made available for the houses (WHHA, 2013b).

The initial model basis used was as follows:

- All houses are Housing Association owned.
- The Income Band '2' has been used which corresponds to a £11,000-21,499 average income.
- Actual occupancy data was used for household composition.
- Heating settings of 21°C for the living room, 18°C for bedrooms and 16°C for the remainder with an average 25/40/35% area split respectively assumed.
- For a 2005-2007 development, factors of 0.95 were used for electrical and lighting as per SAP 2012 as mostly standard appliances and lighting is assumed (see A.13).

WHHA confirmed that the housing was built with good energy performance as a key criteria. Table 7 shows the calculated demand using the actual SAP Heat Loss Parameter (HLP) data, the 2002 and 2007 Building Regulations (BR) basis (the houses were built under 2002 requirements).

Basis	Actual SAP HLP	2002 BR	2007 BR
Annual Demand (kWh)	511407	603459	491438

Table 7: Comparison of modelled Glenshellach demand estimates

The results highlight the potential error if the 'nominal' Building Regulations fabric basis for the build period is used. For Housing Associations, energy performance of the buildings is a key aim, and therefore where possible the actual SAP calculated HLP or building fabric basis should be used in place of the typical values. If this is not possible, it would be recommended to use both the current and next Building Regulations release basis to check demand sensitivity to this potential error.

The usage data provided by WHHA for 2009 to 2012 (WHHA, 2013a) gives the demands as shown the Table 8 below. The number of households with less than 500 kWh/yr consumption are shown (with 0 kWh consumers in brackets). As occupancy for the Glenshellach development is close to 100%, it is not clear why there are zero values. There is also evidence in the data of consistent very low usage (5 households) which suggests that a proportion of people do not frequently use the system, and may have secondary sources for heating and hot water.

As the model does not directly account for the use of secondary heating, the zero values were replaced with the average of the other three years. A 'nominal' value of 2000 kWh was used for <500 kWh values, which suggest more than simply exceptionally low use. The impact of this manipulation suggests that within this type of development a heat model may overestimate demand by several percent (2.8% in this case) and that this needs to be factored into the calculations.

To normalise demand for annual climate variations, the actual heating demand is factored for the ratio of actual to average number of heating degree days for West Scotland (2398 days with a 15.5 °C base) (Vesma, 2013). The modelled water demand is 168,600 kWh and this has been used as a fixed estimate for the heating day conversion as the exact water-to-heating ratio is unknown.

Year	Metered Demand (kWh/yr)	Heating Degree Days (Base 15.5 °C)	Normalised Demand (Avg. Degree Days)	No. of <500 kWh (0 kWh) consumers	Normalised Demand (Avg. Degree Days/Avg. Usage)
2009	454675	2352	460270	4	467577
2010	549904	2705	506628	2	512588
2011	445480	2213	468626	8(4)	493548
2012	502635	2556	481986	6(3)	498457
Avg.			**479378**		**493043**

Table 8: Actual demand data for Glenshellach normalised for climate and very low usage

This modified demand value is within 4% of the demand predicted using the actual SAP Heat Loss Parameter (HLP) values (511,407 kWh/yr). Based on this and the potential for secondary heating use, a factor of 0.95 is used to account for potential overestimation for network usage. A lower factor may be necessary but there is insufficient data to reduce further at this stage.

3.6.2 Cost Verification

For the Dalintart project, six constriction bids were made available by CPP. This data has been used to provide costs and verify generic cost assumptions taken from other literature. Piping and overall cost estimates from the model are reviewed against these bids.

Piping

With significantly more experience of community heating networks in Scandinavia, there is more installed piping cost data available. UK data tends to be 'typical' data and does not differentiate between location types. A detailed 2007 Swedish study (SFAB, 2007) detailed piping costs for four locations (city centre, suburb, parkland/rural and new development). This was used to give relative cost factors for each location and pipe size. The data was updated to 2013 prices and converted to Pounds at the current exchange rate. Tender data from the Dalintart case was then used to calibrate the UK/Sweden cost factor to allow for the different market conditions and contractor experience.

To simplify the analysis, unit pricing was selected that would apply to a 'new development' project (i.e. soft ground trench, sand fill and turf handling). The Dalintart pricing includes a one-size-fits-all averaged trench cost and the Swedish model assumes different trench widths based on pipe diameter. The average Dalintart cost across all pipe sizes (25 to 63mm) was therefore compared with the same average cost from the Swedish model. The Dalintart pricing was increased by 10% to allow for an allocation of preliminaries and contingency costs.

There was significant different between contractors with two contractors well above the equivalent Swedish price (+36% and +51%) and two contractors below (-13% and -15%). An average factor of +20% (1.2) was used for the model, and assumed to apply to all development types and locations. There are clearly, however, significant variations in cost estimate that suggest an immature market.

This highlights a potential for significant cost saving for UK networks. General construction cost indices for Scandinavian countries are considerably higher than in the UK, typically by 10-20% (Shaw, 2012). This suggests that, at least, cost parity is achievable in the long term. Sensitivity to cost estimation accuracy, potential variation, and the actual cost basis is discussed below.

The following chart shows the per-metre costs calculated for the preferred twin pipe with standard insulation design (with single pipe for >63mm sizes as twin pipe is not available) using the above method. The data highlights that the difference between a new development and city centre 'retro-fit' is at least 100% for larger diameters increasing to 200% for small diameters.

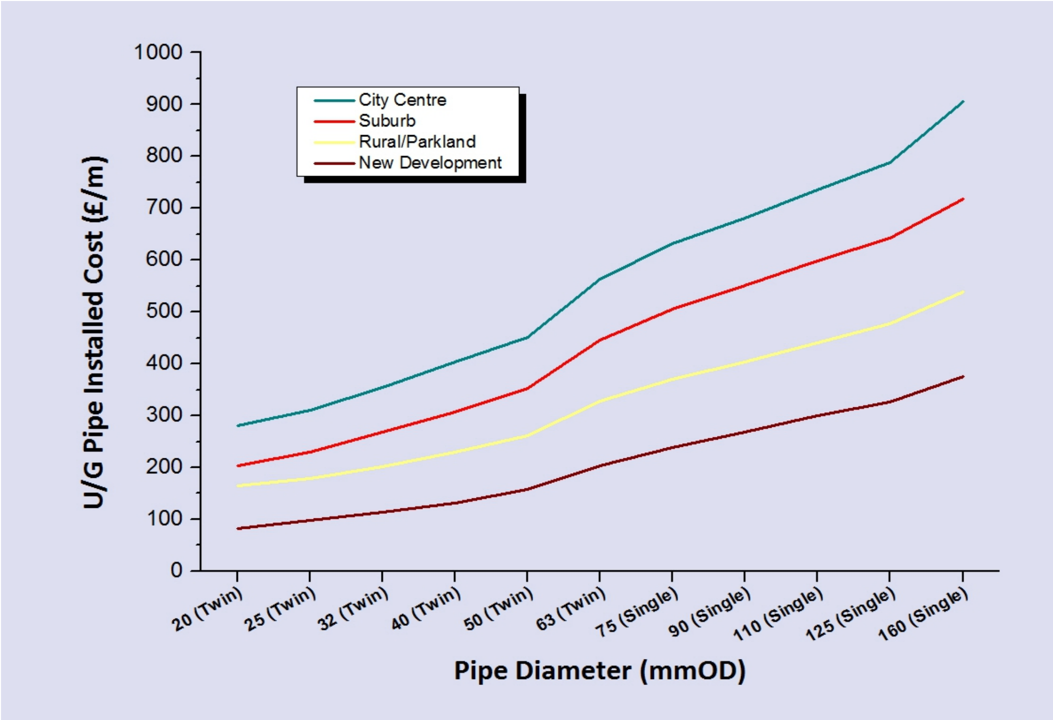


Figure 15: UK underground heat network piping installed cost estimate

Overall Capital Cost Estimate

Appendix A details the specific costs assumptions and basis for other system components, including Heat Interface Units (HIUs), wet heating system retro-fitting, and building connection costs.

The following outlines the overall cost model performance against known costs:

Glenshellach (see 4.2.1) – The stated cost of the system in 2005 was £635,000. On a like-for-like basis, the modelled cost at 2013 prices is £790,000. Based on a 22% increase in 'Infrastructure' project costs from 2005 (BIS, 2012), the updated contract value would be c. £775,000, within 2%.

Dunbeg (see 4.2.2) – As an ongoing project, specific costs are not given. The modelled capital cost on a like-for-like basis (199 kW boiler) is 4% higher than the West Highland Housing Association (WHHA) provided cost estimate.

Dalintart (see 4.3.1) – As an ongoing project specific costs are not given. The modelled cost estimate is 11% lower than the average of the lowest three estimates. This shortfall is likely to be a combination of the underestimation of contingency costs (typically 5%), complexities around the Energy Centre construction, and general inaccuracies in generic cost estimates for building connection and pipe laying costs. For the Dalintart case study the actual cost estimate basis has been used. For the other projects the cost model has not been updated, but sensitivity to cost estimation accuracy has been considered.

Cost Sensitivity Analysis

The inherent difficulty in making accurate future cost projections, and the lack of good data for some existing costs, means that there is little benefit in detailed analysis against changes in different costs. The following section therefore gives a general sensitivity to piping and overall capital cost changes to allow this to be gauged.

Piping

Table 9 shows the reduction in the effective heat cost for values of the UK/Sweden factor between 1.5 and 0.8. The case used is the Dunbeg study (see 4.2.2), using the 2010 'nominal' Building Regulations basis.

Piping Cost Factor vs. Swedish basis	1.5	1.2	1.1	1.0	0.9	0.8
Cost (p/kWh)	17.14	16.36	16.11	15.86	15.62	15.37

Table 9: Comparison of unit heat cost for various piping cost factors

As piping typically accounts for only 25-33% of the initial costs, the impact is relatively minor.

Overall Capital Cost

As heat networks are capital intensive projects, and the majority of equipment is currently imported, although mainly from the EU, equivalent savings could be expected for all capital costs. The heat cost is directly proportional to the overall capital cost (the fuel cost is offset by the Renewable Heat Incentive payment and therefore all net costs, including maintenance costs, are related to the capital cost (see Table 25)). A 10% capital cost saving therefore directly translates to a 10% network heat cost reduction. Significant savings can be expected if the capital costs in the UK can be reduced to typical EU levels, which are estimated to be up to 33% lower (GLA, 2013).

Fuel Cost

Wood fuel pricing in the UK is currently low and predicted to increase by c.10% by 2020 due to market pressures, and then to stabilise (AEA, 2011a). Therefore it is assumed that there is unlikely to be a significant impact from wood fuel pricing. The analysis shows that the fuel cost for all systems becomes an increasingly small proportion of overall heating costs and therefore fuel price changes are not considered in detail.

4. Case Study Details and Analysis

4.1 Case Study Selection

Community heating has the potential to support different network sizes and sources of demand. However, this study will focus primarily on residential developments with a total demand of less than 1 MW. Current business models also require an anchoring consumer base for which long-term demand is guaranteed, such as a large single community-owned user or significant concentrations of social or rented housing. As outlined, for this reason networks with private household connections are rare, so the case studies concentrate on social housing developments.

The viability of community heating in a particular location is also driven by the other fuels that are available. The case studies, therefore, also consider on and off gas grid locations.

Initially it was investigated whether the current Scottish Heat Mapping project (ScotGov, 2013g) could be utilised to identify areas. However, the process has not yet been completed, and the available data does not allow housing tenure to be identified.

There are other tools under development, such as the Energy Savings Trust's 'Home Analytics' tool (EST, 2013e), which would allow GIS technology to bring together the key information required for initial area screening for heat networks (demand, tenure, existing heating). Better tools that can be integrated with the network feasibility process may therefore be available in the future.

To obtain the case study developments for this study a simpler approach was taken. Focusing on Glasgow, and Argyll and Bute, online Housing Association information was obtained that identified areas with existing or proposed concentrations of appropriate housing (HomeArgyll, 2013; GlasgowGov, 2013). Mapping tools could then be used to gauge the housing layout for heat network suitability.

For the available West Highland Housing Association case studies (Glenshellach, Dalintart, and Dunbeg) further housing information was made available by West Highland Housing Association (WHHA, 2013b) and the Campbell Palmer Partnership (CPP, 2011; CPP, 2012a). For the other studies, a mixture of publicly available planning application drawings, and information on similar properties could be used to identify the housing details required to an appropriate level of accuracy. For larger proposed schemes, such as Govanhill, rough approximations based on average housing sizes and overall floor area determination can be used for initial feasibility reviews.

The following developments/areas were selected for review:

New-Build

1. Glenshellach (Oban) – Small-Scale, Low-Density, Off-Grid - Glenshellach is an existing WHHA development installed in two phases between 2005 and 2007 in the south-western outskirts of Oban. It comprises 89 dwellings (28 2-storey flats and 61 houses). It has a relatively low housing density , and is not on the gas network. For the verification analysis in Section 3.6.1 as-built house Heat Loss Parameter (HLP) data was used. For the following analysis it has been treated as a new-build project based on the same design.

2. Dunbeg (Oban) – Small-Scale, Medium-Density, Off-Grid - Dunbeg is a proposed new WHHA development of 26 flats and 24 houses in a village north of Oban. Planning permission has been approved for both housing and biomass energy centre. The housing layout has been specifically designed for community heating with a compact layout and efficient pipe routings considered. Not on a gas network.

3. Laurieston (Glasgow) – Large-Scale, High-Density, On-Grid - New 202-unit Housing Association development in the Gorbals area of Glasgow. Development is a mix of mainly 3- and 4-storey flats with some terraced town-houses. It has the highest housing density, if relatively low compared to older city centre developments, but typical of more recent examples. It is an on-going project that is being built with gas heating.

Retro-fit

Lower density networks were not considered as it is assumed they would not be prioritised.

1. Dalintart (Oban) – Small-Scale, Medium-Density, Off-Grid – An existing WHHA housing development proposed for biomass community heating retrofit. Comprises 39 houses and 23 flats. Currently at the project development phase, with potential to include the adjacent High School. Oban has a independent gas network but this is not available for this development. The existing houses have electric heating systems.

2. Govanhill (Glasgow) – Large-Scale, High-Density, On-Grid - Area surrounding Govanhill Park with a high concentration of tenements with near 100% Housing Association ownership. Highlighted as an area of high CO_2 emissions and poor housing stock. Two options reviewed: a small system covering three blocks sized to meet the <1 MW Renewable Heat Incentive (RHI) tariff limit (see Table 1), and a larger network covering c.40% of the potential Housing Association network area to allow comparison of a viable biomass steam CHP (Combined Heat and Power) unit against a large biomass boiler.

3. West Bowmore (Islay) – Large-Scale, Medium-Density, Off-Grid – Bowmore is a small town in the west of Islay. Potential for community heating in Bowmore has been mooted, and a current project will install a system for the adjacent Primary and High Schools. This case study will consider if this scheme could have been economically extended to the dispersed Housing Association housing in the western half of Bowmore, and could also be sufficiently competitive to encourage adjacent private home owners to connect. The area analysed comprises a total of 150 houses, of which 80 are Housing Association properties.

Other existing areas considered to have potential based on the selection criteria but not modelled were (1) North Campbeltown (Dalintober, High Street and Calton areas), (2) Tarbet, Kintyre, (3) Drumlemble, Kintyre, and (4) Ardrishaig (Primary School and surrounding Glenfyne estate).

(It should be noted that the use of the terms, 'low', 'medium' and 'high' for scale and density is for comparison between the case studies and they are not a defined term).

4.2 New-Build Projects

For all general assumptions and costs used see Appendix A. 'Nominal' building fabric basis is used, where applicable (see 3.4).

4.2.1 Glenshellach (Oban) Case Study

Area Summary

Location	Rural, off-grid
Number of Households	89
Plot Ratio (Floor/Land)	0.29
Area Heat Density (GJ/m²)	1.55 (Actual) / 1.00 (2010 BR)
Pipe Heat Density (GJ/m)	21.07 (Actual) / 13.56 (2010 BR)
Pipe Length per Connection (m)	24.0
Occupant Density (no./1000m²)	8.48

Table 10: Glenshellach Development Summary

The existing Glenshellach biomass community heating system owned by WHHA is located on the south-west outskirts of Oban, south of Glengallon Rd. The development comprises 89 houses, 28 2-storey flats, and 61 semi-detached and detached houses, built in two phases between 2005 and 2007.

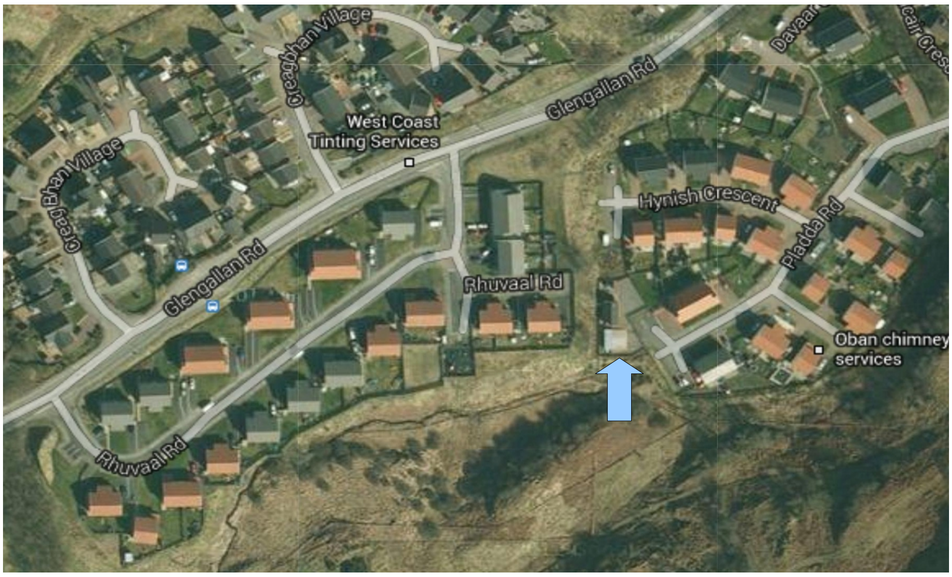


Figure 16: Glenshellach Development Aerial Plan (Google Maps, 2013a)

Housing Models

Housing design and dimensional information was taken from drawings and data provided by WHHA. Occupancy data was also provided, and averaged values for each house type used. Average income was assumed to be in the £11,000-£21,499 range (Band 2 for MIT Factor). SAP Electrical and Lighting Factors were set at 0.75 and 0.7 respectively (see A.13).

Network Layout

The existing Energy Centre is located centrally between the two phases (see arrow on Figure 16).

The existing piping network generally follows the roads of the development with individual hook-up connections to each house. Actual pipe lengths and sizes provided by CPP have been used in the analysis (CPP, 2011). The pipe installation pricing model assumes a 100% 'new-development' basis.

Heating System Cost Analysis

Table 11 compares for Glenshellach the effective cost per kWh for all heating options at 2013 prices for the calculated SAP Heat Loss Parameter (HLP) ratings, and for a range of construction periods. The cost basis for the heating systems is the total lifetime cost, including heat generating unit, maintenance, and fuel, but not in-house 'wet' heating system. Gas is not available but is included for comparison. (For further analysis and charts see 5.2)

(p/kWh unless stated)	Avg. Per-house Heat Demand (kWh/yr)	Boiler Size (kW)	CHN (Pellet)	CHN (Woodchip)	ASHP*	Electric Storage	*Gas*	Solar Thermal (+ Electric)	MVHR w/ASHP**
1992-2002	10027	400	10.2	8.5	9.5	13.7	*9.3*	12.7	n/a
2003-2007	6891	330	12.8	11.0	11.1	15.2	*11.4*	15.2	n/a
Actual HLP	5990	310	14.1	12.1	12.2	15.8	*12.4*	16.3	n/a
2008-2010	5665	300	14.8	12.9	12.6	16.1	*12.9*	16.9	n/a
2011-2014	3888	260	19.5	17.3	16.6	18.6	*16.6*	21.2	n/a
2015+	3671	250	20.3	18.1	17.4	19.1	*17.3*	22.0	n/a
'70% ZCH'	2833	230	25.2	22.8	18.9	21.6	*21.1*	26.4	n/a
'Zero Carbon'	2569	220	27.4	24.8	20.5	22.8	*22.7*	28.3	n/a
Passivhaus	2001	200	53.7	50.9	44.5	n/a	*47.2*	53.6	36.6
No Heating	1800	170	34.3	31.2	27.6	n/a	*30.5*	37.3	n/a

*12 kW air source heat pump (ASHP) for '1992-2002', 10 kW ASHP until '2015+', 8 kW afterwards
**inc. MVHR cost based on a 25 W/hr additional power requirement. Integrated ASHP within MVHR

Table 11: Glenshellach heating system total cost analysis for different construction periods

This heating system-only cost analysis shows the development was cost effective with community heating, using 2013 prices, as-built. From the 2007 Building Regulations update, ASHPs became the most cost effective modelled solution, with the benefit increasing for each subsequent update.

4.2.2 Dunbeg (Oban) Case Study

Area Summary

Location	Rural Village, off-grid
Number of Households	50
Plot Ratio (Floor/Land)	0.36
Heat Density (GJ/m^2)	1.43 (2010 BR)
Pipe Heat Density (GJ/m)	23.32 (2010 BR)
Pipe Length per Connection (m)	10.6
Occupant Density (no./1000m^2)	14.34

Table 12: Dunbeg Development Summary

WHHA are planning to build a Phase 1 development of 24 houses and 26 flats to the north of the existing Dunbeg village, near Oban. Planning permission has been granted for both the housing and central biomass heating system. A second phase of a further 100 houses may follow in the future.

Figures 17 and 18: Dunbeg Development Plan (CMA, 2013) and Dunbeg Aerial Location (Google Maps, 2013b)

Housing Model

Dimensioned layout and plans are available on-line with the planning application (ABC, 2013). Average income was assumed to be in the £11,000-£21,499 range (Band 2 for MIT Factor). SAP Electrical and Lighting Factors were set at 0.75 and 0.7 respectively (see A.13).

Network Layout

As per the approved planning application, the Energy Centre will be located in the south-east corner of the development adjacent to the housing.

The housing layout has been planned around community heating. The housing has a uniform rectangular arrangement allowing a simple ring main piping layout. The pipe installation pricing model assumes a 100% 'new-development' basis.

Heating System Cost Analysis

Table 13 compares for Dunbeg the effective cost per kWh for all heating options at 2013 prices for a range of construction periods. The cost basis for the heating systems is the total lifetime cost, including heat generating unit, maintenance, and fuel, but not in-house 'wet' heating system. Occupancy is based on the Glenshellach averaged data per house type. Gas is not available but is included for comparison. (For further analysis and charts see 5.2)

(p/kWh unless stated)	Avg. Per-house Heat Demand (kWh/yr)	Boiler Size (kW)	CHN (Pellet)	CHN (Woodchip)	ASHP*	Electric Storage	Gas	Solar Thermal (+ Electric)	MVHR w/ASHP**
1992-2002	6670	190	9.6	7.9	12.4	15.3	*11.7*	15.4	n/a
2003-2007	4676	170	12.0	10.2	14.5	17.3	*14.6*	18.9	n/a
2008-2010	3895	150	13.7	11.9	16.6	18.6	*16.6*	21.2	n/a
2011-2014	2816	140	18.3	16.4	21.5	21.7	*21.2*	26.5	n/a
2015+	2678	140	19.1	17.2	22.4	22.4	*22.0*	27.5	n/a
'70% ZCH'	2200	130	22.9	20.8	23.3	24.8	*25.8*	31.8	n/a
'Zero Carbon'	2045	120	24.4	22.3	24.7	25.9	*27.4*	33.7	n/a
Passivhaus	1736	110	50.3	48.1	50.8	n/a	*53.7*	60.7	41.4
No Heating	1679	110	28.5	26.2	29.3	n/a	*32.3*	39.4	n/a

*12 kW air source heat pump (ASHP) for '1992-2002', 10 kW ASHP until '2015+', 8 kW afterwards
**inc. MVHR cost based on a 25 W/hr additional power requirement. Integrated ASHP within MVHR

Table 13: Dunbeg heating system total cost analysis for different construction periods

Unlike Glenshellach, community heating remains competitive despite the expected reduction in demand predicted for forthcoming Building Regulations updates. The primary reasons for the lower relative cost at Dunbeg are eligibility for the higher 'small biomass' Renewable Heat Incentive (RHI) tariff, higher heat density, and a smaller pipe length per connection (10.6m vs 24.0m).

The community heating specific layout is sufficient to maintain the lower cost basis as the demand falls, as the maximised heat density and reduced piping cost sufficiently lowers the overall fixed costs compared to the fixed cost of the alternative heating systems (see 5.2.4 for more details).

4.2.3 Laurieston (Glasgow) Case Study

Area Summary

Location	City centre, on-grid
Number of Households	202
Plot Ratio (Floor/Land)	0.73
Heat Density (GJ/m²)	2.42 (2010 BR)
Pipe Heat Density (GJ/m)	26.07 (2010 BR)
Pipe Length per Connection (m)	10.1
Occupant Density (no./1000m²)	21.30

Table 14: Laurieston Development Summary

Laurieston is in the Gorbals area south of the Clyde adjacent to Glasgow City Centre. Existing high rise developments to the north of Cumberland St. have been removed and a new combined social/private development will be built in their place. The development is under construction and will be connected to the gas grid. This review is therefore to determine if a biomass heat network could have supplied heat for a lower overall cost.

The review concentrates on the social housing development in the southern half of the area. A future private development of similar overall scale and housing type will be located to the north. There is an existing part-Housing Association, part-private development (Eglinton Court) of 4-storey flats built in 1969 to the west. Potential benefits of integrating these other developments is not considered but could have been considered if the initial network plan is shown to be cost effective.

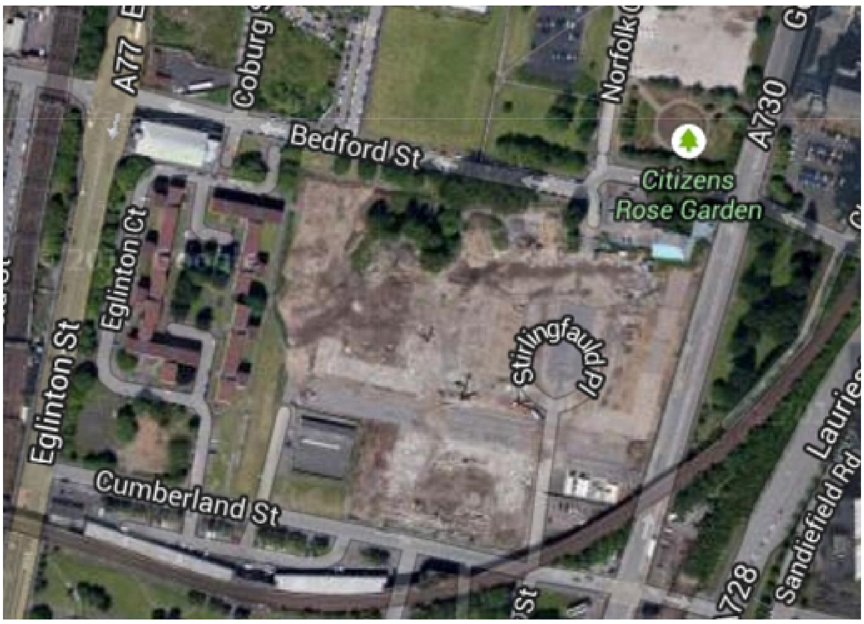


Figure 19: Laurieston Aerial Location (Google Maps, 2013c)

Housing Models

Detailed planning drawings have been used to determine exact floor and window areas for each dwelling type. The scale of the development has required that two developers with separate designs have been used. The development therefore has 43 different house designs. It is assumed that they will be intermediate between the 'nominal' design basis from the 2010 and 2014 Building Regulations (see 3.4) based on a planning application made in 2012/2013.

Average income was assumed to be in the £11,000-£21,499 range (Band 2 for MIT Factor). SAP Electrical and Lighting Factors were set at 0.75 and 0.7 respectively (see A.13).

Network Layout

A potential location for the Energy Centre would be a piece of clear ground in the south-east corner of the plot that is not marked as being used for housing or as a community space. The area is shown with an arrow on Figure 20.

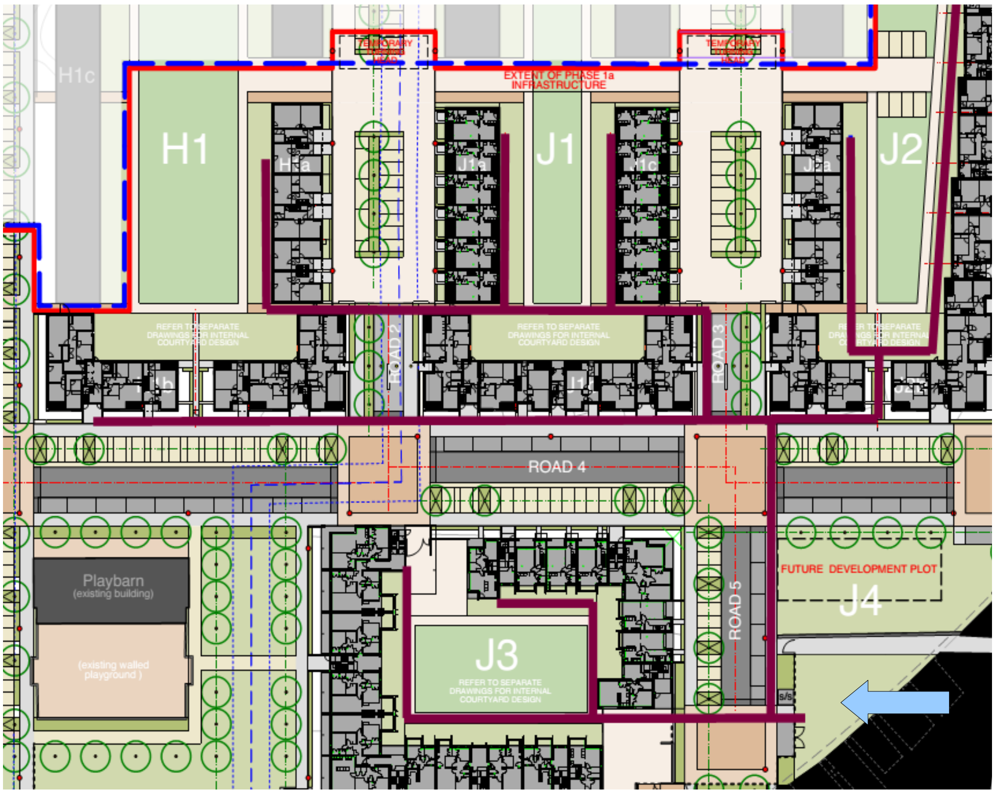


Figure 20: Laurieston Development Plan Drawing and Suggested Pipe Routing (PPA, 2011)

The modelled pipe network is as shown in purple in Figure 20.

The cost model for the pipe network is assumed to be 80% 'New Development' and 20% 'City/Town'. The 20% 'City/Town' factor allows for this being a brownfield site with the potential for construction disruption from existing buried infrastructure and poor soil compaction.

Heating System Cost Analysis

The equivalent analysis to Glenshellach and Dunbeg has been carried out for Laurieston.

The SAP occupancy model (see 3.5.2) has been used for the analysis. No data is available on specific occupancy for city centre social housing developments, it was therefore unclear if the Glenshellach occupancy data was consistent for city centre housing. The development has a range of house sizes therefore the identified SAP size-related inaccuracies for social housing (see 3.5.2) should balance out or slightly underestimate demand. (For further analysis and charts see 5.2)

The initial capital cost of the network was estimated to be c.£990,000

(p/kWh unless stated)	Avg. Per-house Heat Demand (kWh/yr)	Boiler Size (kW)	CHN (Pellet)	CHN (Woodchip)	ASHP*	Electric Storage	Gas	Solar Thermal (+ Electric)	MVHR w/ASHP**
1992-2002	7421	520	9.4	7.8	11.5	15.9	*10.6*	13.5	n/a
2003-2007	5017	420	12.1	10.3	13.8	17.9	*13.4*	17.0	n/a
2008-2010	4286	380	13.2	11.7	15.4	19.0	*14.9*	18.8	n/a
2011-2014	3006	320	17.2	14.8	20.4	22.1	*19.2*	24.1	n/a
2015+	2829	300	18.0	16.2	21.4	22.8	*20.1*	25.3	n/a
'70% ZCH'	2254	270	21.5	19.1	22.8	25.6	*24.1*	30.1	n/a
'Zero Carbon'	2044	250	23.0	21.0	24.7	27.0	*26.0*	32.5	n/a
Passivhaus	1636	210	50.7	48.6	53.3	n/a	*54.7*	62.5	42.9
No Heating	1511	180	27.2	24.9	32.1	n/a	*33.6*	41.8	n/a

*12 kW air source heat pump (ASHP) for '1992-2002', 10 kW ASHP until '2015+', 8 kW afterwards
**inc. MVHR cost based on a 25 W/hr additional power requirement. Integrated ASHP within MVHR

Table 15: Laurieston heating system total cost analysis for different construction periods

With a high plot ratio and a housing layout that allows efficient pipe routing, community heating is economic under current and predicted future Building Regulations, based on the assumptions of the model. Compared to gas heating, a saving of c.4p/kWh is estimated for the lifetime cost based on the current project build period. This saving level is maintained as demand reduces. This suggests that for high density developments with efficient pipe routings, community heating remains a viable option for on-grid locations in the future.

4.2.4 New-Build Project Analysis Summary

- Community heating networks remain cost effective for two of the three case studies analysed at all expected demand levels.
- Significant cost savings against other heating options are possible for higher density developments irrespective of gas availability.
- For a mixed development of houses and low density flats, more care needs to be taken on system layout and housing density. However, this type of scheme can remain suitable for community heating system with an appropriate design.
- In all cases, even where heat networks remain viable, the cost per kWh increases significantly as demand falls. Determining fair charging mechanisms that discourages either excessive or insufficient use will be challenging. For further analysis see 6.3.
- Competitiveness of community heating is significantly improved with woodchip fuel use in comparison to wood pellets. For the further analysis in Sections 5 and 6, woodchip fuel use is assumed.
- Area heat density alone cannot predict community heating effectiveness. Other factors such as pipe heat density, development size and capacity, and demand per connection also must be considered. Further analysis of relative importance is discussed in 6.2.
- Gas heating becomes increasingly uncompetitive as demand falls. This is a result of the standing charge becoming an increasingly significant factor in overall costs.
- Electric storage heating becomes increasingly competitive at lower demands as the lowest capital cost solution. However, under all scenarios considered, air source heat pumps (ASHPs) are the lowest cost electrically powered option, and has a significantly lower CO_2 rating making SAP compliance more straightforward (see 5.3 for SAP compliance cost analysis).
- Solar Thermal with electric back-up heating is not competitive as a standalone option.
- Passivhaus costs are significantly higher than the alternative 'zero carbon' option without very low infiltration and all-house mechanical ventilation. If a Passivhaus design is chosen, in all cases an integrated ASHP within the Mechanical Ventilation with Heat Recovery (MVHR) system would be lowest cost. The use of community heating with Passivhaus-type designs is therefore not considered further.

4.3 Retrofit Projects

For all general assumptions and costs used see Appendix A.

4.3.1 Dalintart (Oban) Case Study

Area Summary

Location	Town, off-grid
Number of Households	62
Plot Ratio (Floor/Area)	0.39
Area Heat Density (GJ/m²)	3.43 (Actual)
Pipe Heat Density (GJ/m)	50.36 (Actual)
Pipe Length per Connection (m)	14.0
Occupant Density (no./1000m²)	12.32

Table 16: Dalintart Development Summary

Dalintart is a mainly residential area directly south-east of Oban town centre. WHHA have properties in the area, including three blocks of flats on Miller Road (Burnside Court), and all houses in Nelson Road and Campbell Crescent. The viability of installing a biomass-fueled, community-heating system is currently being investigated for the 62 WHHA properties.

Two options are being reviewed for the development. One is for a standalone system, and the other for a combined system with the adjacent High School.

The Burnside Court properties were built in 1979. There are 16 flats of which 11 are 1-bedroom and 5 are 2-bedroom. The Nelson Road and Campbell Crescent properties were built in the mid-1990s. The development comprises 14 3-bedroom and 18 2-bedroom semi-detached houses, 2 4-bedroom detached houses, and 12 1-bedroom flats. All properties currently have electric storage heating. Although Oban has an independent gas network, connection for this area is not possible.

Figure 21 and 22: Dalintart Development Plan Drawing (CPP, 2012a) and Dalintart Aerial Location (Google Maps, 2013d)

Housing Model

Basic housing information for all property types was available from existing planning applications (ABC, 2013). The 1976 Building Regulations basis was used for Burnside Court and the 1992 update for the remainder. Improvement assumptions as detailed in Section 3.4.1 were included.

The Glenshellach occupancy basis gives 157 residents, and the SAP (Standard Assessment Procedure) model gives 146. The Glenshellach basis was used for consistency with the other WHHA developments. Unlike more remote Glenshellach and Dunbeg areas, average OAP occupancy factors were used. Average income was assumed to be in the £11,000-£21,499 range (Band 2 for MIT Factor). SAP Electrical and Lighting Factors were both set at 0.9 (see A.13).

Network Layout

The Energy Centre is to be located adjacent to the Burnside Court properties. The piping layout is as shown in Figure 21. A '100% Suburb' location is assumed for the cost model.

Heating System Replacement Cost Analysis

The cost estimation from the model underestimated the actual cost (based on the average of the three lowest bids) by c.10%. (As this is an ongoing project in the bidding phase detailed or total costs are not given). There were some project-specific sources of extra costs, such as the conversion of an existing basement as part of the energy centre, and the model may not capture the typical 5% contingency cost allocations accurately. Therefore the actual costs has been used, based on an average of the three lowest bids, rather than the modelled cost. This highlights the need to analyse retrofit projects against a range of potential costs if no detailed costs are available, and that further work is required to verify the retro-fit cost model.

The proposed project may be a standalone project or combined with a system for the adjacent High School. For the combined project, it is assumed that 40% of the boiler costs and 80% of other shared costs are allocated to the housing scheme. The respective heat costs for the two options are within 1% due to the increased controls required for the combined case offsetting the boiler and shared cost savings. There is therefore no meaningful benefit for the domestic network.

The annual demand for the housing is estimated to be 498,750 kWh (101,170 kWh hot water, 397,580 kWh space heating). The boiler size is estimated at 240 kW. The existing electric heating is assumed to have 8 years life remaining, although no residual value is included for simplicity. Gas is included for comparison only, with a £2000 per connection installation cost (SGN, 2010). For air source heat pumps (ASHPs), it is expected that the existing electrical capacity is sufficient.

System	CHN (Woodchip)	Electric Storage (existing)	ASHP	*Gas*	Solar Thermal (+Electric)
Total Cost (p/kWh)	16.3	14.9	13.0	*12.9*	16.1
Annual CO_2 (tonnes)	21.3	254.7	115.2	*117.8*	152.8

Table 17: Dalintart replacement heating system total cost analysis

The analysis suggests that the lowest cost option for the Dalintart scheme over a 40-year period would be installation of ASHPs, or connection to the gas network if it was available. A 50% electricity unit cost increase would be required for ASHPs to be a comparable cost to community heating. The capital cost of the conversion, including wet heating systems, would be less than 70% of the community heating cost.

As shown in Table 17, the CO_2 saving using community heating is substantial, however, the effective cost per tonne CO_2 saved between community heating (CHN) and ASHPs is £72 over a 40-year period. This is higher than the suggested value of £46 for policy decisions (DCLG, 2011). The use of community heating at Dalintart may not therefore be justified by either fuel poverty reduction or cost effective CO_2 reduction, compared to a ASHP retrofit. Further review would be required to determine if ASHP performance and retrofit installation was suitable for this location.

Despite a higher area heat density than the West Bowmore model, Dalintart is much less viable. The higher cost piping installation location, combined with lower demand per connection (8000 vs. 11500 kWh/yr), a lower pipe heat density (50 vs. 66 GJ/m), and longer pipe length per connection (14.0 vs. 10.8 m) are the primary reasons for this result. These factors are discussed further in 6.2.

4.3.2 Govanhill (Glasgow) Case Study

Area Summary

	<1 MW Area	>1 MW Area
Location	City, on-grid	City, on-grid
Number of Households	370	1125
Plot Ratio (Floor/Area)	1.21	0.75
Area Heat Density (GJ/m^2)	12.18	7.79
Pipe Heat Density (GJ/m)	103.33	125.8
Occupant Density (no./1000m^2)	32.42	18.82

Table 18: Govanhill Development Summary

Govanhill is a community in the Southside of Glasgow. The area has retained a significant proportion of its pre-war tenements and the majority are ranked in the lowest 5% for housing conditions by the SIMD (Scottish Index of Multiple Deprivation) survey (South Seeds, 2013).

With over 3000 Housing Association flats and three schools (plus multiple other civic buildings) in a small area, and an estimated peak thermal demand of 10-12 MW, it would be a candidate area for a much larger area-wide CHP (Combined Heat and Power) scheme. The main issue with this, however, would be finding a suitable location for a large energy centre, and installing connections to each block within a short period and without major disruption. A series of phased smaller c.1 MW boiler heating-only schemes may therefore be more practical in such a densely populated area.

Two scales of project are considered. One is a smaller < 1 MW scheme encompassing three tenement blocks (the area is enclosed by Calder St.-Cathcart Rd.-Allison St.-Garturk St.). The other is a larger (c.2.6 MW) scheme that includes the majority of tenements shown in Figure 23.

Figure 23: Govanhill Aerial Location (Google Maps, 2013e)

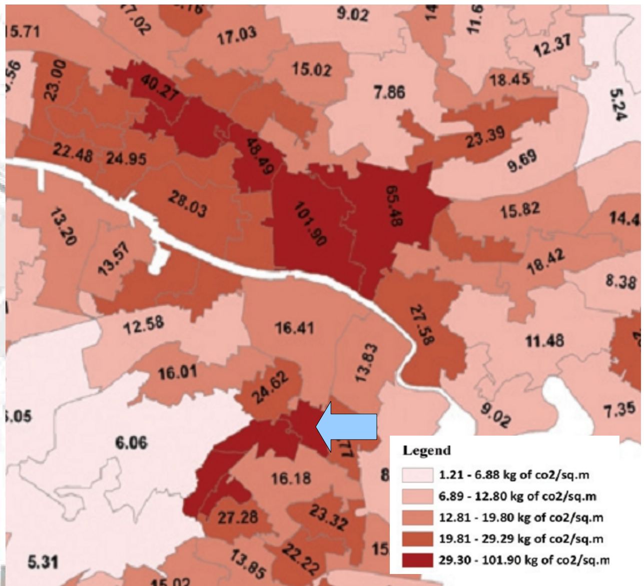
Housing Model

The developed model allows housing to be defined in detail at an individual level. However, given the scale of the area, with 1000+ Housing Association dwellings and limited available information, it has been defined at the block level. A block being defined as a connected series of multiple tenement 'closes'. Each 'close' (entrance) is assumed to have 2 flats per floor with an average of 2 bedrooms and overall occupancy based on the SAP floor area model (see 3.5.2).

The majority of the housing in the area is pre-1919 tenement stock. The exceptions are the north-east section and the area to the west of Govanhill Park, which are inter-war 3-storey 'Short' tenements. There is one late-1980s development on Bankhall St. (South Seeds, 2013)

The analysis assumes that all have a minimum level of energy improvements as defined in 3.4.1. This may be an overestimate but a detailed study would be required to confirm actual conditions.

The socio-economic factors were set at 'Scottish Average' levels for children and pensioner (OAP) occupancy (see 3.5.2). Average income was assumed to be in the £11,000-£21,499 range (Band 2 for MIT Factor). SAP Electrical and Lighting Factors were both set at 0.9 (see A.13).



Figures 24 and 25: Govanhill Tenure Plan (South Seeds, 2013) and Central Glasgow Heat Density Map (Sustainable Glasgow, 2010)

Network Layout

Locating the Energy Centre for a town or city centre retro-fit project is difficult. It was assumed that Govanhill Park would not be suitable and similar community-use areas were avoided. Several unused or wasteland areas were identified, and the area to the west of Holy Cross Primary School on Calder St. was identified as being the best centrally located area without a clear present use (see area identified on arrow on Figure 23) for both scales of development analysed.

Piping mains were assumed to follow the road network, and that hook-up piping could potentially be installed in the roof space of each tenement minimising necessary excavations of roads or tenement back-greens. The piping installation cost basis is assumed to be 100% 'City Centre'.

<1 MW System Cost Analysis

The smaller area reviewed encompasses three sections of tenements south of Govanhill Park with c.370 flats. This area was selected to give an boiler size of slightly less than 1 MW (a 950 kW unit is required by the model). This area would be too small for current biomass CHP technology.

As Govanhill is on the gas network, it is assumed that all flats have gas central heating. A cost is also included for electric storage heating based on it being existing. This is done to highlight the potential of community heating for areas of similar buildings, that are common throughout Scotland, with existing electric rather than gas heating.

The most significant unknown for this type of retrofit is the building hook-up cost. The model assumes a general figure of £1560 per flat, adjusted from Poyry (2009). However, the solid wall construction of tenement flats may make this estimate too low, and ultimately retrofitting to tenements may be uneconomic or too damaging to the fabric. Analysis with a doubled hookup cost of £3120 per flat was also made to highlight cost sensitivity to this generic cost.

The area is within the lowest 15% of the SIMD rankings and therefore would be potentially eligible for an 'ECO' grant (Ofgem, 2013). Further evaluation was conducted using the base £1560 hookup cost assumption with a 40% of initial capital cost grant (£3.2m).

As for Dalintart, 8 years residual life is assumed for existing heating systems for replacement scheduling, but no residual value is included in the analysis.

Total demand is 3,153,400 kWh per year (341,300 kWh hot water and 2,812,100 kWh space heating). The initial capital cost for the base case is estimated to be c.£3.0 million.

System	CHN (Woodchip)	CHN (x2 hookup)	CHN (40% Grant)	Gas (existing)	Electric Storage (existing)	ASHP	Solar Thermal (+Electric)
Total Cost (p/kWh)	8.4	9.6	6.9	9.0	14.7	11.8	13.9
Annual CO_2 (tonnes)	127.5	127.5	127.5	756.8	1636.6	752.8	982.0

Table 19: Govanhill '<1 MW' case replacement heating system total cost analysis

With mainly pre-war tenements, the Govanhill area has a very high heat demand and CO_2 footprint. However, without a significant capital grant, community heating is likely to be a similar cost to the existing gas infrastructure. The potential overall Renewable Heat Incentive (RHI) cost of £1.4m, giving £120/tonne CO_2 saved, is higher than the 'target' CO_2 saving cost of £46/tonne (DCLG, 2011). Additional 'ECO' funding may therefore be better spent on equivalent areas with significantly higher electric heating levels, where a heat network will generate larger cost and CO_2 savings in line with the RHI outlay (£50 per tonne CO_2 if 100% electric). Areas with at least 25% electric heating would justify further review on this basis even if the higher hookup cost estimate is more realistic.

Impact of Future Fabric Improvements

For new-build projects, the risk from further energy improvements in the future is relatively small. As shown in Section 3.4, the current uptake of cost effective improvements in existing housing is already high, particularly where mandated for Housing Association properties. However, over time further improvements may become more cost effective, and also become mandatory. Over time hot water demand may also fall, if proposed low flow system become widely used.

A simplified analysis for the small (<1 MW) case study area shows the potential impact of a linear 10%, 20% and 50% reduction in demand over a 40 year period for the 40% grant case.

Basis	No demand reduction	10% demand reduction	20% demand reduction	50% demand reduction
Cost (p/kWh)	6.92	7.09	7.28	7.95

Table 20: Lifetime unit heat cost impact for different linear demand reductions

The impact on effective system cost is not particularly significant on a net present value basis. The majority of the impact is in the latter years when the discounted values have a smaller impact. Assuming demand reductions are not expected in the short-term, and the reduction is gradual and no greater than 20-30%, the impact on heat charges or cost coverage should be manageable.

>1 MW System Cost Analysis

The smaller area reviewed above is only a small section of the concentrated area of Housing Association (HA) owned tenements surrounding Govanhill Park. There is therefore considerable scope for a more extensive heat network. A larger section of the area was modelled to determine if biomass CHP (Combined Heat and Power) could be a viable option where a development of this scale is possible. The selected area has approximately 1125 tenement flats and is c.30-40% of the overall concentration of HA housing around Govanhill Park.

Two community heating systems have been modelled, one with a c. 2.66 MWth biomass boiler and one with the equivalent biomass CHP system (based on the 17% electrical and 63% thermal efficiency assumption used by Poyry (2009)). The initial capital cost for the CHP base case is £9.6 million and £7.7 million for the biomass boiler base case.

Table 21 compares the costs using the base £1560 hook-up cost assumption.

System	CHN (Woodchip) (Biomass CHP)	CHN (Woodchip) (Biomass Boiler)	Gas (existing)	Electric Storage (existing)	ASHP	Solar Thermal (+Electric)
Total Cost (p/kWh)	7.8	8.3	8.6	14.4	10.7	12.8
Annual CO_2 (tonnes)	(938.6)*	411.2	2525.1	5460.4	2511.8	3276.3

* Including reduction for displaced grid electricity (1473.8 tonne CO_2/yr saved).

Table 21: Govanhill '>1 MW' case replacement heating system total cost analysis

The cost sensitivity to £3120 hook-up cost and 40% 'ECO' funding is as follows.

System	Boiler (base)	Boiler (x2 hookup)	Boiler (40% ECO)	CHP (base)	CHP (x2 hookup)	CHP (40% Grant)
Total Cost (p/kWh)	8.3	9.4	7.0	7.8	8.9	6.2

Table 22: Govanhill '>1 MW' case community heating cost sensitivity

CHP is lower cost that the equivalent boiler-only system and also lower cost than all individual heating alternatives. The reduction in CO_2 emissions compared to gas heating over the modelled 40 year life of the overall system is equivalent to £6.4m at 2013 prices, using £46/tonne CO_2. This compares to £5.2m in Renewable Heat Incentive (RHI) and Renewable Obligation Certificate (ROC) payments. The use of CHP in this situation therefore has the potential to reduce heating bills and effectively payback any central incentive investment in CO_2 savings. The viability of the scheme is, however, closely linked to the assumptions made and requires further investigation.

Another key conclusion is that the benefits of the larger scheme are marginal (7.8p vs 8.4p/kWh for the base case). Given the likely construction disruption, the use of several smaller systems, at least as a first phase, may be more realistic. The piping can be planned such that it will eventually be connected as a single system. At the end of the initial boiler lifetime, a single CHP system could then replace the multiple smaller units.

The main barrier to implementing this scale of system is the upfront cost for CHP of c.£9.6m. This is almost four times the replacement cost for individual gas boilers, and with the low rate of return would likely require significant central support and income guarantees to proceed. The potential disruption to the area of installing community heating would also require careful consideration.

4.3.3 West Bowmore (Islay) Case Study

Area Summary

Location	Rural town, off-grid
Number of Households	150 (80 HA)
Plot Ratio (Floor/Area)	0.25
Area Heat Density (GJ/m^2)	3.03
Pipe Heat Density (GJ/m)	66.47
Occupant Density (no./1000m^2)	7.07

Table 23: West Bowmore Development Summary

Bowmore is a town on the west of Islay. Despite a relatively small population of around 850, it has the main hospital and high school for the island plus a primary school. It also has a total of 96 Housing Association properties spread across several developments, although there are three separate Housing Associations involved making shared network ownership potentially difficult.

Figure 26: West Bowmore Aerial Location (Google Maps, 2012f)

Bowmore has been selected for review because there is a current project to install a 360 kW biomass heating system to supply Islay High School and Bowmore Primary School, which are located together on the western edge of town. Bowmore has been identified as potentially suitable for a wider scheme, with a formal feasibility study proposed (Heggie et al, 2010). This will indicate the potential for connecting an off-grid area of disparate housing types and tenure, which would be common in smaller off-grid towns and villages in rural Scotland.

This case study will consider whether this school heating scheme could have been economically extended to include the Housing Association properties in close proximity, including a new 20-home development to the south-west that is currently under planning review. As an extension to this, the feasibility of connecting all houses in the area of Bowmore to the west of the Main Street is reviewed. If it can be shown that this could be done economically in comparison with existing heating systems, then a wider investigation for a town-wide scheme could be considered.

Demand and Shared Cost Model

Peak heating demand for the schools and local housing are expected to occur in approximately the same period (6-9am) so no diversity benefit between the two uses is taken for this simplified analysis. The boiler sizing is therefore based on the school peak demand added to the peak load calculated for the housing. The heat cost for the housing is calculated with any shared costs (boiler, Energy Centre etc.) for school and housing allocated proportional to the respective peak loads.

Housing Models

The identified area is a mix of pre- and c.1900 traditional properties on Flora Street and School Street, the 'Stanalane' development of Housing Association properties built around 1970, a small 11-property development of properties on School Lane built in 1995, one new 4-flat development adjacent to Stanalane, and a 20-flat proposed development to the south-west. Where building age is not clear, a 1919-1975 construction period is assumed.

Freely available planning application drawings were used to determine general layout and material information for examples of the different housing types in the village. Detailed information is available for the new and proposed developments. The traditional properties are all slightly different and many have been significantly extended. Two main types were identified, a one-storey detached cottage and two-storey detached house. A typical example was used for each and the other similar properties modelled as equivalent.

The Stanalane development of 51 properties, the School Lane development of 11 properties, and 21 sheltered housing flats on Flora Street are assumed to be Housing Association owned. There are several 'right-to-buy' houses in the Stanalane area but this is assumed to have no impact on demand or potential for network hook-up. All other houses are assumed to be privately owned.

Average income was assumed to vary between bands 0 and 3, with an average of 1 (see A.11). SAP Electrical and Lighting Factors were both set at 0.9 (see A.13).

Network Layout

The Energy Centre for the school development is located to the west of the primary school. The same location has been used for the expanded system.

For the housing network, two separate main piping systems are used. This allows the system to be entirely constructed from twin pipe to minimise trench size. It is modelled that the piping will largely follow the road network except where the use of back gardens is considered more practical.

The following layout (shown in red) is used for the pipe system analysis. A 90% 'Parkland/Rural' and 10% 'New Development' cost basis was assumed.

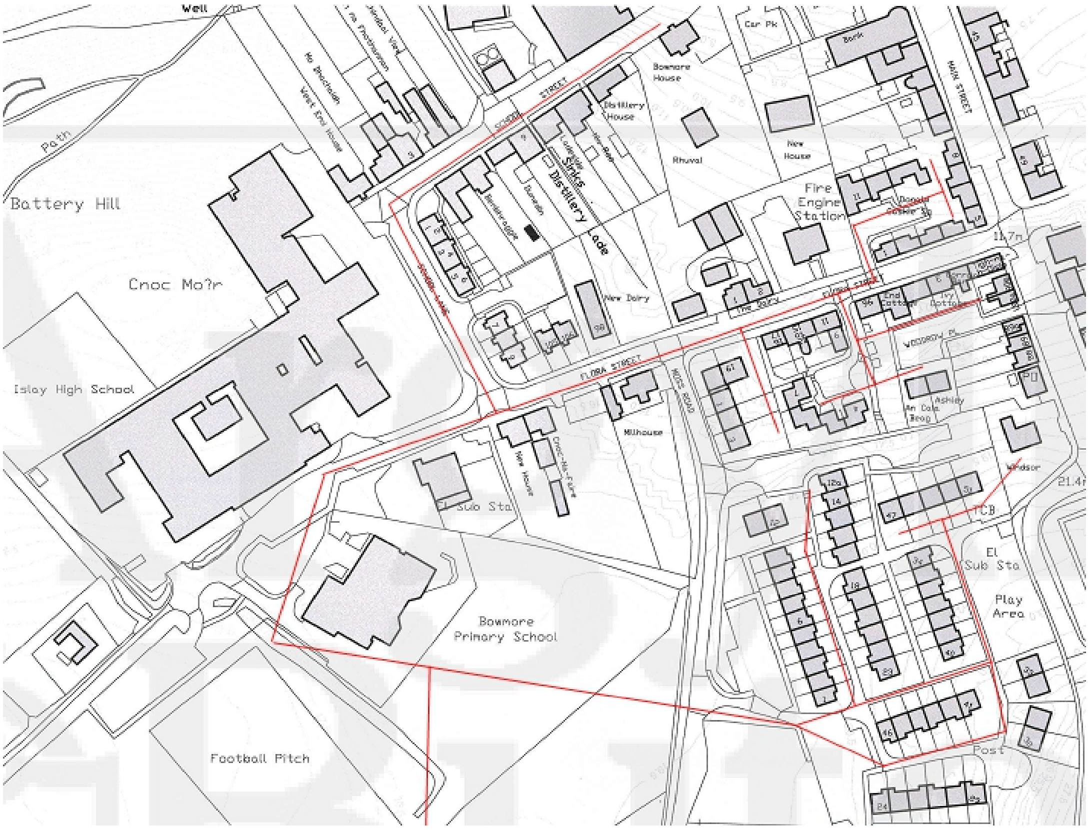


Figure 27: West Bowmore Piping Plan (CE, 2013)

Heating System Replacement Cost Analysis

Impact of Private House Uptake

The Housing Association housing is located in three main areas (Stanalane, School Lane and Flora St/High St junction). Four different scenarios were reviewed, Housing Association (HA) properties only, all HA and private dwellings within the study area, and all HA plus 33% and 66% of the private dwellings in the study area to confirm sensitivity to the extent of private dwelling uptake. All private dwelling scenarios are based on the full piping system. The 'HA-only' scenario includes piping only for the connected housing. The SAP occupancy model is used (see 3.5.2).

Basis (p/kWh unless stated)	Demand (kWh)	CHN (Pellets)	CHN (Woodchips)	CHN (Woodchips) (40% Grant)	Oil	Electric Storage	Solar Thermal	ASHP
HA only	755365	13.6	11.9	9.2	10.6	13.5	15.3	12.1
HA + 33% Private	1078903	12.0	10.3	8.0	10.1	13.2	14.3	11.1
HA + 66% Private	1413171	10.7	9.1	7.1	9.9	12.9	13.9	10.5
HA + 100% Private	1713656	10.0	8.4	6.7	9.7	12.8	13.5	10.3

Table 25: West Bowmore replacement heating system cost analysis for different levels of uptake

The analysis shows that with a significant uptake from the private residents that community heating could be viable. Assuming that the majority of existing system are oil (or LPG) heating, the community heating network becomes viable around a 40-50% private home uptake, allowing for a margin of error in hook-up costs. As for Govanhill, if 'ECO' funding is available the scheme is economic for all defined cases. The total initial capital cost for the 'all dwellings' case is estimated to be c.£1.7 million.

Impact of Non-domestic Load

For the combined Dalintart case a relatively complex interconnecting piping arrangement between two separate Energy Centres was required. Assuming a single Energy Centre for both domestic and school loads with simpler interconnections is possible for the West Bowmore case, the potential cost savings were investigated for the combined load case against housing load only.

The boiler for the school has been sized at 360 kW. For the 'HA-only' case, the standalone boiler size would also be c.360 kW. For the 'all dwellings' case it would be c.630 kW.

For the HA only woodchip case the cost reduces from 11.78p to 11.38p/kWh if the school is included and shares a proportion of the boiler costs.

For the 'HA+100%' woodchip case the cost reduces from 8.42 to 8.29p/kWh if the school is included.

The boiler cost reduces exponentially with size, and the cost impact on the housing system cost is therefore greater where the domestic boiler requirement is less than or equal to the non-domestic load. Where there is no significant increase in piping costs associated with the combined scheme, there is a small benefit. The benefit will be greater for the supply to the School where the boiler/Energy Centre costs are a much more significant proportion of the project costs. The benefit could, however, be easily lost if there are additional piping or installation costs associated with the combined scheme. This analysis ignores any land cost benefits or allocations at this stage.

4.3.4 Retrofit Project Analysis Summary

- Definitive conclusions regarding viability of heat networks as retrofit projects for existing buildings are difficult due to marginal modelled benefits and cost uncertainty.
- Where 'ECO' grant funding at a significant proportion (30-40%) of initial capital costs is available, heat networks were shown to be a viable option for relevant high deprivation, poor housing stock, or rural areas.
- For older buildings with higher heat demand, air source heat pumps (ASHPs) are a less viable alternative low carbon option than heat networks. Although, potentially less disruptive to install.
- In rural towns with dispersed social housing concentrations, integration of heat networks into mixed tenure areas will require either significant additional grant funding or significant levels of private household uptake.
- Demand per-connection is more important than for new-builds due to higher proportional integration costs per connection. This allows the less heat dense but higher demand per connection West Bowmore case to be more viable than Dalintart. Areas of older, difficult-to-heat buildings should therefore be prioritised.
- Integration with adjacent non-domestic loads only provides, at best, a small cost benefit to the domestic network.
- The income risk from further building fabric improvements or hot water usage reduction in high demand older building (e.g. tenements) is relatively small if assumed to be a steady improvement over time.

5. New-Build Project Cost Evaluation Basis

As outlined in 2.4, the economic evaluation of heat network projects requires a clear definition of the relevant like-for-like costs, and an understanding how these costs will be accounted for with regard to system ownership and the heat charging basis. Networks with a single owner for the network and connected housing can be analysed differently from systems with mixed ownership.

The case study economic analysis is based on lifetime costs for all comparable heating systems. However, many networks are still reviewed on a simple comparison basis with supplied fuel or power costs for individual systems. As detailed in 3.4.3, there are also housing costs related to SAP emissions compliance that are directly impacted by the choice of heating system. These costs can be considered as essentially additional heat costs, particularly for single ownership schemes.

The economics of new-build projects were therefore analysed using the three different criteria.

1. Unit heat cost comparison for a community heating network (CHN) and fuel- or power-only costs for alternative heating systems.
2. Lifetime total cost comparison for a CHN and alternative heating options (including all like-for-like capital and running costs). (Same basis as Section 4 analysis)
3. Analysis as per 2. but also including any addition CO_2 mitigation costs required for SAP compliance for each heating system as detailed in 3.4.3. Further comparison is also made between the different mitigation options (i.e. building fabric, PV, penalty payments).

5.1 Utility Cost Only Comparison

The simplest analysis that could allow biomass community heating to be justified, and to be priced in a way that was acceptable to consumers, would be for the total system cost to be less than the equivalent utility supplied cost for gas and electricity. This is not a like-for-like comparison, as it ignores the cost of the individual heating units, but it is a method that is currently used.

Figures 28 and 29 show the heat cost variation between community heating, and gas and electricity costs for different construction periods based on the 'nominal' fabric assumption (see 3.4).

The on-grid Laurieston model (see 4.2.3) is used for the gas comparison. The gas cost is a £89.20 standing charge plus 4.2p/kWh based on current location pricing (British Gas, 2013).

The off-grid Dunbeg model (see 4.2.2) is used for the electricity comparison. The comparison cost basis is 8.5p/kWh (Electric Storage Heating tariff provided by West Highland Housing Association (WHHA)). (No standing charge is included for electric heating (see 2.5))

In all cases the 'Annual Demand' shown is the average per house for the development.

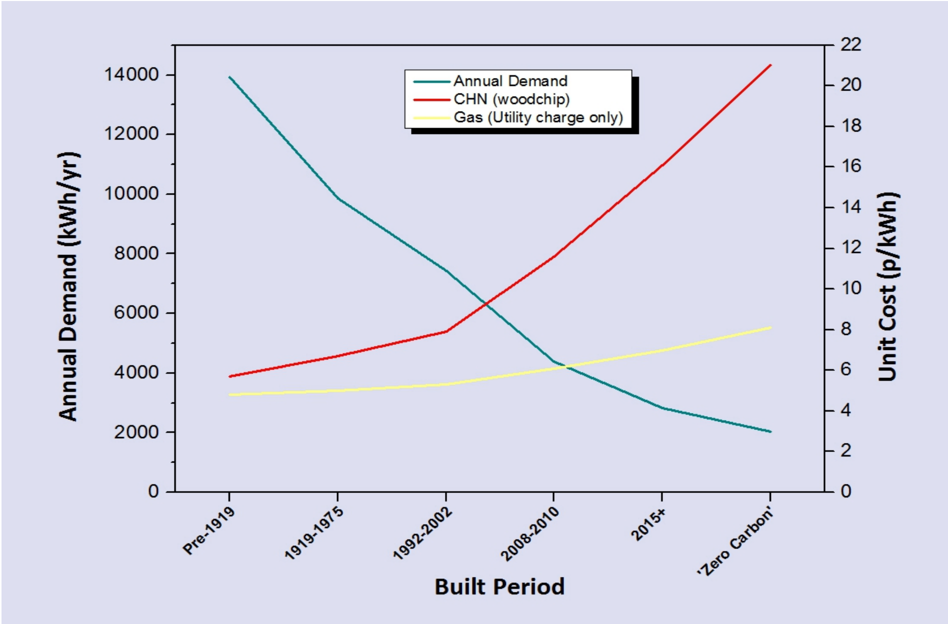
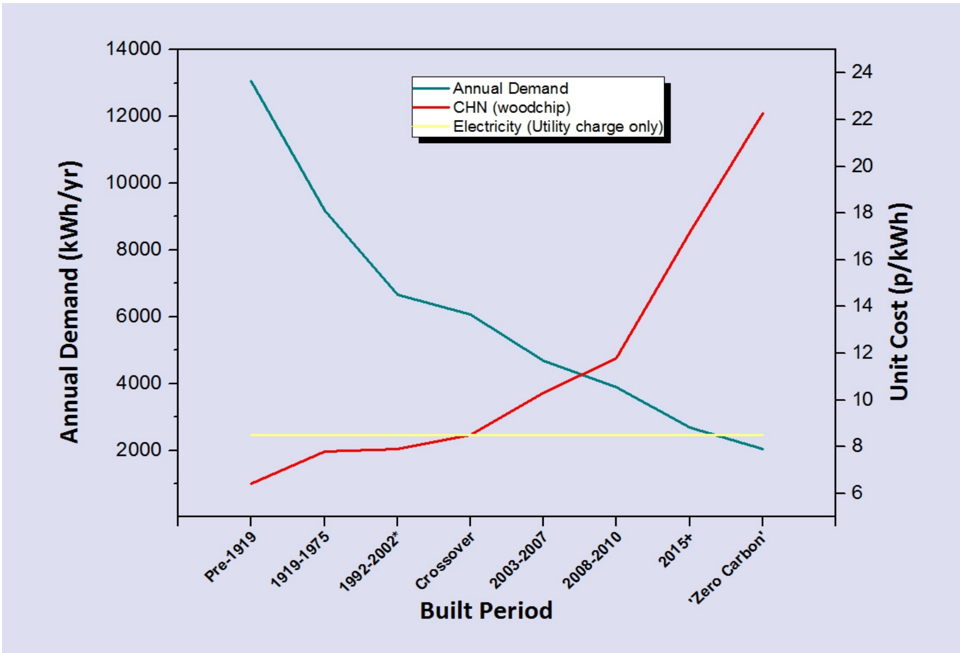


Figure 28: Comparison of community heating (CHN) and gas fuel-only heat cost for on-grid case



*from 1992 boiler size falls below 200 kW and 'small' biomass RHI tariff is applicable

Figure 29: Comparison of community heating (CHN) and electricity power-only heat cost for off-grid case

For the on-grid comparison, the community heating unit cost is always higher than the supplied gas cost regardless of age or demand. For the off-grid, small-scale and medium-density Dunbeg scheme, the crossover point where the electricity cost becomes less than the total heat network cost is a c.1995 development. (For the larger ('medium' RHI tariff) and less heat dense Glenshellach development the equivalent was a c.1990 development.)

The cost of community heating cannot therefore be justified on this basis alone for any area. The comparison must be extended to include installed capital costs for each individual heating systems.

5.2 Total Heating System Cost Comparison

The next level of analysis considers the total lifetime cost if all heating system costs are considered, including the installed capital costs of the individual heating units. This basis was used for the initial case study analysis shown in 4.2, where relevant tabulated data is detailed.

Each of the three new-build case studies are reviewed below to determine biomass community heating performance against individual heating system costs for a variety of built periods.

For 'wet' heating systems, the cost up to the boiler outlet is included. For electric storage systems the costs have been normalised to account for an additional 'wet' heating system not being required. In all cases the 'Annual Demand' shown is the average per house for the development.

(It should be noted that the use of the terms, 'low', 'medium' and 'high' for density is for comparison between the case studies and they are not defined terms).

Glenshellach (Low-density)

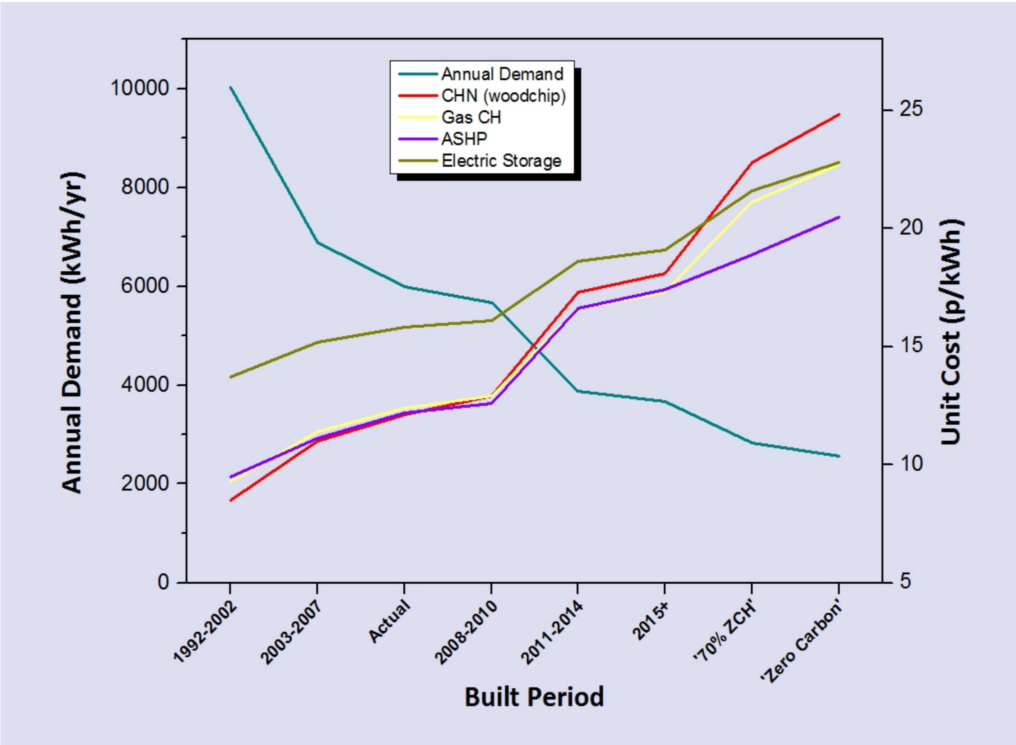


Figure 30: Total heating system cost comparison for low-density Glenshellach development

The analysis shows that for the low density Glenshellach development community heating became more expensive than air source heat pumps (ASHPs) at the level of demand associated with the as-built period of 2005-2007. Community heating remains competitive against electric storage heating until c.2018. Based on this comparison basis and the model assumptions, air source heat pumps would be the preferred option for similar developments from the current period forward.

Dunbeg (Medium-density)

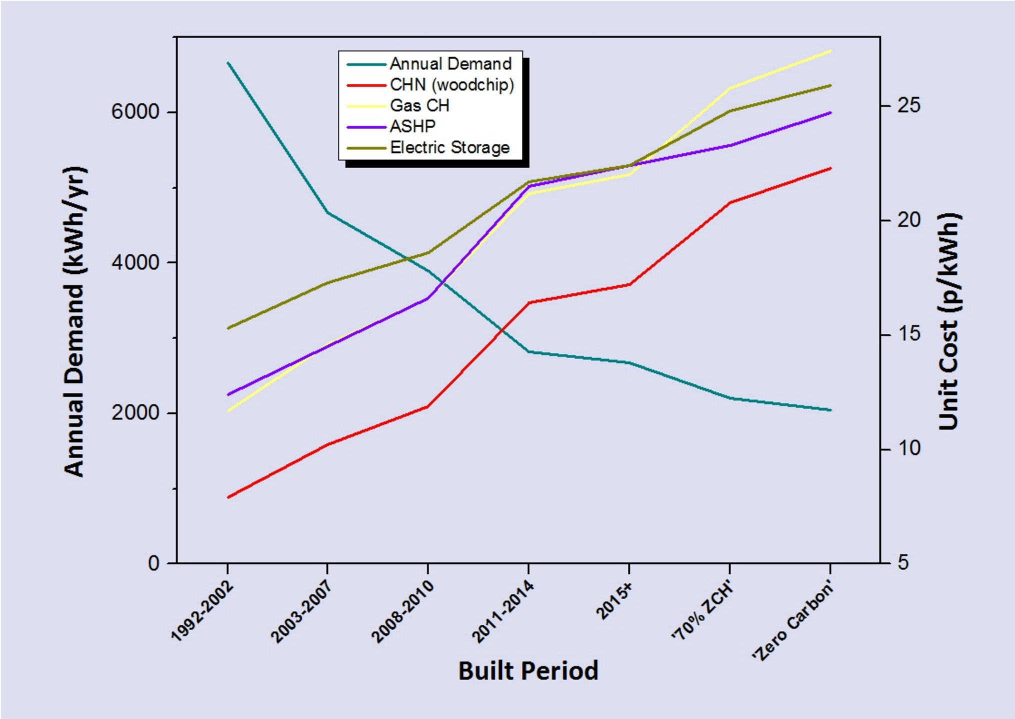


Figure 31: Total heating system cost comparison for medium-density Dunbeg development

For the medium density Dunbeg scheme, compact and planned for community heating, a CHN remains competitive against the alternative options under all predicted demand scenarios.

Laurieston (High-density)

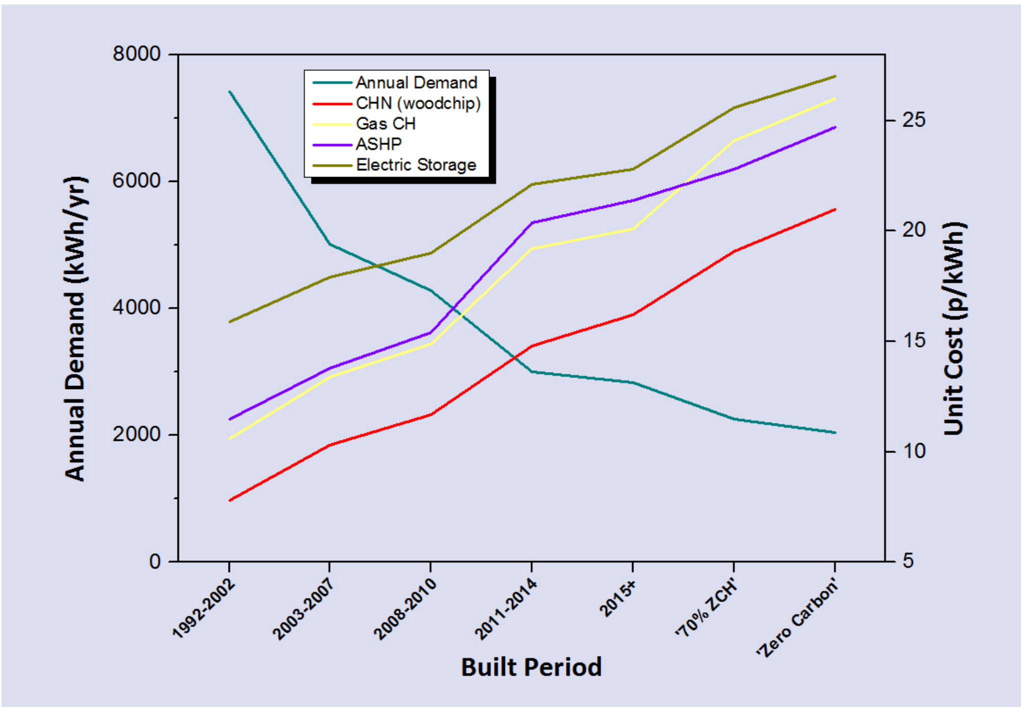


Figure 32: Total heating system cost comparison for high-density Laurieston development

For the high density Laurieston project, the analysis shows that biomass community heating would give a consistent and significant cost-per-kWh saving compared to the planned gas heating or air source heat pumps (ASHPs). For gas heating the standing charge becomes increasingly relevant which drives the divergence as demand drops.

Summary

The results for the three case studies shows that, when the total heating system costs are considered, the relative cost of community heating does not change significantly with demand for currently viable schemes at Dunbeg (small, medium-density, off-grid) and Laurieston (medium, high-density, on-grid). Schemes, such as Glenshellach, that are not longer viable have proportionally higher capital costs, and therefore show a significantly greater relative cost increase as demand drops.

The reason for this, perhaps counter-intuitive, result is that while the initial capital costs for community heating can be higher than for conventional heating, lifetime fixed costs (including Operation and Maintenance (O&M) and standing charges), are not. Table 25 shows normalised cost results at net present value over 40 years based on the Dunbeg model for the 2010 Building Regulations case, with the equivalent total for the 'zero carbon' house shown for comparison.

	CHN	Gas	ASHP	Electric Storage
Capital	0.796	0.490	1.144	0.329*
O&M + Standing Ch.	0.282	0.623	0.024	0.386
Total Fixed	**1.078**	**1.113**	**1.168**	**0.715**
Fuel *less* RHI (2010)	-0.078	0.315	0.290	0.758
Total All (2010)	**1.0**	**1.428**	**1.458**	**1.473**
Total All ('Zero Carbon')	**0.993**	**1.342**	**1.219**	**1.276**

*cost of wet heating system subtracted

Table 25: Relative fixed and total costs for different heating systems

As demand drops total costs for the community heat network (CHN) remain stable as the system cost is not significantly demand dependent, and the fuel cost is completely offset by the RHI payments. The other systems all show a drop in overall cost between 2010 and 'zero carbon' levels, but insufficient to overcome the original cost difference.

5.3 Total SAP Compliance Cost Comparison

As detailed in Section 3.4.3, the current SAP (Standard Assessment Procedure) CO_2 emissions evaluation method used by the Building Regulations to set CO_2 targets can lead to significant differences in the minimum carbon mitigation costs required for each heating option.

Section 5.2 considers heating capital, maintenance, and fuel costs (less RHI payments) only. The following analysis also considers the 'additional fabric/PV' element (see Figure 11), that is associated with SAP/Building Regulations compliance for higher CO_2 rated fuel sources, as a directly related heat cost differential between heating types. This cost is converted to a lifetime per-kWh basis in the same manner as used in Section 4 and 5.2.

It is assumed that any solution is acceptable provided it meets the minimum mandatory requirements, and there is no restriction on incentive payments if this is the case. In reality, it may be necessary to go beyond this level to further reduce sustainable fuel use or household demand, but this is not considered. The principle is to determine the lowest potential lifetime cost as a baseline.

As detailed in 3.4, the current domestic Building Regulations structure, provides an absolute minimum 'backstop' level for building fabric that must be achieved by all houses. The Regulations also provides a better 'nominal' example fabric basis plus the additional microgeneration elements required to achieve the relevant CO_2 target for common heating systems. For this analysis, the 'nominal' level detailed is considered to be a realistic upper fabric level that would be used for a building fabric-prioritising solution.

Three scenarios are therefore considered. The first is a PV prioritising solution that assumes the house is built to the minimum 'backstop' fabric level and PV (solar panels) are used to achieve the required CO_2 emission target (see 5.3.1). The second is the fabric prioritising solution discussed above, only using PV where the CO_2 target is not achieved using the 'nominal' fabric basis alone (see 5.3.2). The third considers the potential for using a suggested penalty payment in lieu of fabric or PV improvement, which is discussed further in 5.3.3. In all cases the Dunbeg case study model is used for the analysis, which was viable for community heating but by a relatively small margin.

5.3.1 PV Prioritising Case

This case considers the scenario where the minimum 'backstop' building fabric level per the relevant Building Regulations has been used and solar panels (PV) has been used to reduce net CO_2 emissions to the target level.

The Dunbeg development has c.800 m^2 of usable housing roof space for PV installation (50% SSW and 50% ESE). Solutions marked (*) exceed this for required PV panel area. Underlined solutions meet the target CO_2 directly with the 'backstop' fabric level. The value in brackets is the cost associated specifically with the additional PV installation required to meet SAP requirements.

(p/kWh unless stated)	Avg. Per-house Heat Demand (kWh/yr)	CHN (Woodchip)	ASHP*	Electric Storage	Gas
2011-2014	4242	11.0 (0)	17.4 (1.8)	31.4 (13.4)*	17.5 (1.9)
2015+	3486	13.2 (0)	20.0 (2.0)	33.4 (13.7)*	20.0 (2.0)
'70% ZCH'	2933	15.7 (0)	21.5 (3.1)	36.9 (15.6)*	23.6 (3.1)
'Zero Carbon'	2678	20.0 (2.8)	25.0 (3.6)	41.4 (19.1)*	27.2 (3.6)

*10 kW air source heat pump (ASHP) until '2015+', 8 kW afterwards

Table 26: 'PV Prioritising' case total heating system and carbon mitigation cost comparison (for Dunbeg)

Compared to the 'nominal' fabric case reviewed in 4.2.2 (see Table 13), all costs are reduced and the gaps between community heating and the alternatives has increased approximately by the PV specific value in brackets.

5.3.2 Fabric Prioritising Case

This case considers the scenario where fabric improvements up to the better 'nominal' building fabric level per the Building Regulations have been used for all options where the 'backstop' requirement (see 5.3.1) does not meet the CO_2 target directly. If the 'nominal' fabric does not yet achieve the CO_2 target, solar panels (PV) are used for the additional CO_2 mitigation required.

Solutions marked (*) exceed the available c.800 m^2 for required PV panel area. Double-underlined solutions meet the CO_2 target with the 'backstop' fabric basis and no further improvement is added. The per-kWh value in this case has been factored for the demand difference between 'backstop' and 'nominal' cases. The value in brackets is the cost associated specifically with the additional fabric and PV installation required to meet SAP requirements.

(p/kWh unless stated)	Avg. Per-house Heat Demand (kWh/yr)	'Backstop' to 'Nominal' Cost Diff. (£/house)	CHN (Woodchip)	ASHP*	Electric Storage	Gas
2011-2014	2816	8820	16.4 (0)	35.8 (14.3)	53.8 (32.1)*	35.5 (14.3)
2015+	2678	5000	17.2 (0)	31.9 (9.5)	47.2 (24.9)*	31.5 (9.5)
'70% ZCH'	2200	4530	20.8 (0)	35.0 (11.7)	53.4 (28.6)*	37.5 (11.7)
'Zero Carbon'	2045	3920	(BS)26.3**(3.7) / (Nom)41.7(19.4)	38.6 (13.9)	58.2 (32.3)*	41.2 (13.8)

*10 kW air source heat pump until '2015+', 8 kW afterwards

**20.0p/kWh at 'backstop' demand of 2678 kWh is converted to 26.3p at 2045. Same conversion for other periods.

Table 27: 'Fabric-Prioritising' case total heating system and carbon mitigation cost comparison (for Dunbeg)

The estimated cost difference between the 'backstop' and 'nominal' fabric housing varies between Building Regulations but in all cases is a significant proportion of the overall community heating network costs. Before the 'zero carbon' requirement, biomass community heating meets the CO_2 target with the 'backstop' fabric requirement. Therefore the cost, assuming the backstop requirement is sufficient, is significantly less than all alternative options, which require 'nominal' fabric and PV.

For the 'zero carbon' case, the residual carbon emissions for a biomass community heating network are very low (<3 $kgCO_2/m^2/yr$). The last row of Table 27 shows the impact of allowing the predicted 'backstop' (BS) fabric basis to be used rather than the 'nominal' (Nom) basis is critical (26.3 vs. 41.7 p/kWh). Figure 33 shows the overall cost impact of using increasing levels of building fabric rather than PV beyond the minimum 'backstop' level that has been predicted for the 'zero carbon' case.

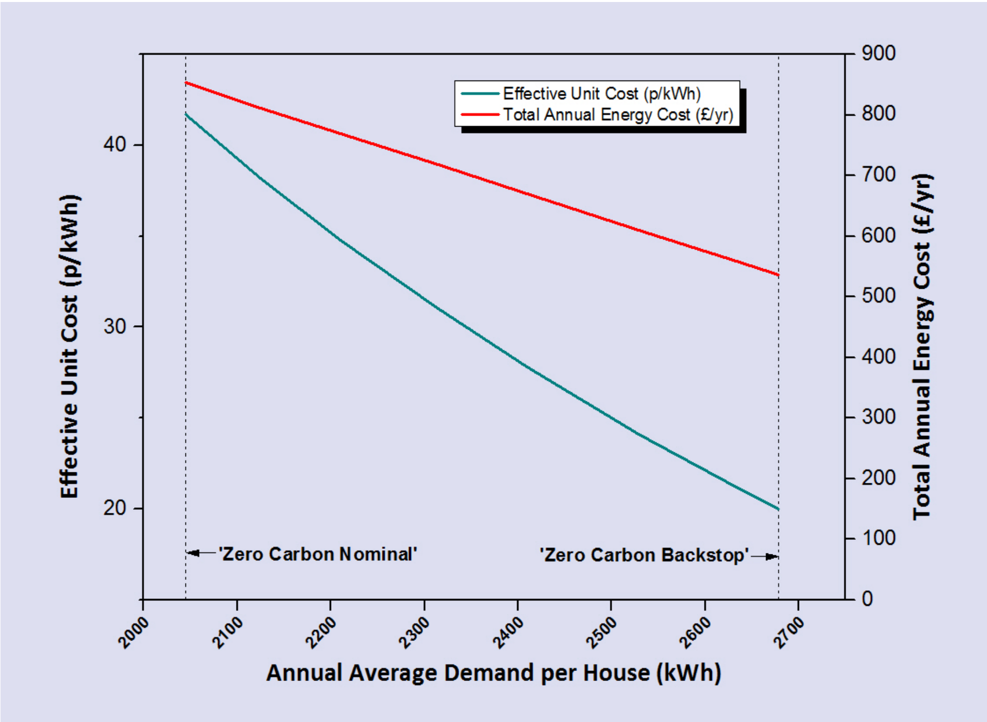


Figure 33: Cost of increasing housing fabric improvements from 'zero carbon' 'backstop' to 'nominal' level

The conclusion is that community heating is increasingly cost effective the less strict the actual minimum 'backstop' fabric level is at the 'zero carbon' requirement, compared to what level has been predicted (see 3.4.2). This is a result of PV being significantly more cost effective as a carbon mitigation solution than fabric improvements. However, whether it is prudent to use indirect PV mitigation rather than direct fabric mitigation is debatable.

5.3.3 'Shadow Cost of Carbon' Payment Case

This case is similar to 5.3.1 and 5.3.2 except that any CO_2 target shortfall beyond the stated fabric basis can be mitigated by a payment equivalent to the 'shadow cost of carbon', which is significantly lower than equivalent PV or fabric costs. As outlined by the Zero Carbon Hub (ZCH, 2013), a 30 year basis for total CO_2 emissions and a £46/tonne CO_2 'shadow' cost is suggested (DCLG, 2011), although there is currently no such formal policy. (Since the analysis was completed the UK Government has released a consultation document regarding this proposed 'Allowable Solutions' policy with three 'shadow' cost levels of £36, £60 and £90/tonne CO_2 proposed (DCLG, 2013)).

A minimum level of CO_2 emissions would need to met before the payment can be used for the remainder. A suggested level is 11 $kgCO_2/m^2/yr$, which is easily met using biomass heat networks (see Table 29). This is approximately the level for a home with gas heating at the 'nominal' fabric assumption for the 'zero carbon' home.

As any implementation basis is not defined, particularly the minimum CO_2 emission level before the 'shadow' payment is possible, a full analysis is difficult. However, for Dunbeg, the additional cost per house to achieve 'zero carbon' using air source heat pumps (ASHPs) for various cases is as follows:

'Zero Carbon' Basis	'Backstop' + 'Shadow'	'Backstop' + PV	'Nominal' + 'Shadow'	'Nominal' + PV
Cost per house (£)	930	4150	4625	7085
Cost per kWh (p)	26.8	31.5	35.0	38.6

Table 28: Additional cost per house to achieve 'zero carbon' basis for ASHPs from 'backstop' baseline

The shows that the balance of fabric, solar panel, and any additional 'penalty' payments, will be critical for the carbon mitigation cost of the different heating options. The 'shadow' payment basis is significantly lower than for PV, which in turn is significantly lower than using building fabric. One potential use for this policy could be to encourage direct fabric emission reductions over indirect PV reductions by only allowing payments in conjunction with 'nominal'-level fabric improvements.

For community heating the impact will be less significant. For Dunbeg, the 'zero carbon' cost above the predicted 'backstop' fabric level is c.£900 per house if using PV to mitigate the remaining CO_2. Assuming the 'Allowable Solutions' policy would allow £46/tonne 'shadow' payments with no further improvements beyond the 'backstop' level, this drops to £200 per house. This reduces the heat cost from 22.0 to 19.8p/kWh.

Assuming the other heating options all require at or close to the 'nominal' fabric level before being eligible there is still a significant cost benefit as the equivalent cost for ASHPs would be 35.0p/kWh. The benefit is reduced if all options are allowed to use the 'backstop' fabric basis plus payments, although this is considered unlikely (ZCH, 2013). This policy is therefore unlikely to reduce the viability of heat networks, and could potentially be beneficial if the target emissions level using building fabric alone is set low enough to sufficiently penalise other heat sources.

5.3.4 Optimal Building Fabric Level for Biomass Heat Networks

The central premise of 5.3 is that beyond any mandatory minimum building fabric requirement set by the Building Regulations, all additional costs to meet CO_2 targets should be considered as heat costs and included in the heating system cost benefit analysis. As heat networks are likely to be focused on social projects, one of the two main criteria for driving heating system selection should be cost effective reduction of CO_2 emissions on a national basis, rather than minimising demand, CO_2 emissions or fuel use for individual projects. (The other being minimising overall energy cost to developer and end-user within the minimum requirements for emission reduction, again in preference to reducing demand to the absolute minimum in specific cases.) What, therefore, should the minimum building fabric basis be for biomass systems to achieve these goals?

The impact of increasingly stringent mandatory building fabric levels is to reduce the space heating demand to a significantly lower level than hot water demand by the 2020 'zero carbon' update. This reduces the effective benefit of fabric improvements as they are acting on an increasingly small proportion of the overall demand.

The assumption of £1520 per $kgCO_2/m^2/yr$ reduction is based on a gas heating system (see 3.4.3), with a SAP CO_2 rating of 0.216 $kgCO_2/kWh$ (BRE, 2013). Over 30 years for a 90 m^2 house, this equates to £422 per tonne CO_2 saved. However, for a biomass community heating network (CHN), rated at 0.031 $kgCO_2/kWh$, this cost increases to c.£10000 per $kgCO_2/m^2/yr$ reduction (depending on relative boiler efficiencies), which equates to c.£3000 per tonne CO_2 saved. Compared to the shadow cost of carbon (£46/tonne) (DCLG, 2011), and the effective cost of PV to offset a biomass CHN (£206/tonne), this suggests extremely poor value.

For the Dunbeg development, the average $kgCO_2/m^2/yr$ rating for heating and hot water using biomass CHN is 3.33 $kgCO_2/m^2/yr$ for the minimum 'backstop' fabric requirements of the current (2010) Building Regulations. This is c.20% of the baseline 2007 gas CO_2 target value (17.24 $kgCO_2/m^2/yr$). Therefore, even for at the current Building Regulations minimum requirement, biomass CHN systems already achieve low levels of CO_2 emissions.

The following analysis in Table 29 therefore considers the impact on demand, costs, and CO_2 emissions, if the present 2010 'backstop' level is maintained for future biomass systems, and what is the additional cost per biomass network-connected house for the increasingly strict 'backstop' levels that are expected for each future Building Regulations update. (See 3.4 for details of the 'backstop' fabric levels used for this analysis)

Factor	2010 'Backstop'	2014 'Backstop'	'70%ZCH 'Backstop'	'Zero Carbon' 'Backstop'
Total Demand (kWh/yr)	4242	3486	2933	2678
Space Heating (kWh/yr)	2563	1807	1253	998
Demand Factor vs 2010 (%)	1.0	0.82	0.69	0.63
Heat cost (p/kWh) (inc. additional fabric cost vs. 2010)	11.0	24.6	39.3	47.9
Heat cost per house per year (£)	466.3	858.9	1151.2	1283.7
Cost Factor vs 2010	1.0	1.84	2.47	2.75
Actual $kgCO_2/m^2/yr$	3.33	2.84	2.49	2.33
Target $kgCO_2/m^2/yr$	17.26	8.72	4.75	*0.0*
Tonnes of CO_2 saved over 40 years vs 2010	*0.0*	57.2	99.0	118.3
Fabric cost per house £ vs 2010	*0.0*	4673	8099	9673
Fabric £ per tonne CO_2 saved vs 2010	*0.0*	4166	4090	4088
PV cost per house £ vs 2010	*0.0*	237	426	521
PV £ per tonne CO_2 saved vs 2010	*0.0*	207	215	220
'Shadow' cost per house £ vs 2010	*0.0*	53	91	109
'Shadow' cost per tonne CO2 saved vs 2010	*0*	46	46	46

Table 29: Cost per tonne CO_2 saved for increasing 'backstop' fabric levels from a 2010 baseline for Dunbeg

The assumption for the analysis is a fixed cost per $kgCO_2/m^2/yr$ saved, which may not be accurate as the fabric requirements become increasingly strict. However, this should be at least partially offset by improvements becoming lower cost over time as they become relevant. Further work would be required to determine an accurate additional fabric cost basis depending on the base emission level and period of construction.

A 37% reduction in demand, and therefore fuel consumption, between the 2010 and estimated 2020 'zero carbon' minimum fabric requirements, results in an almost three-fold increase in energy costs if the additional fabric cost (£9673/house) is accounted for. The cost per unit CO_2 saved (c. £4000/tonne) is two orders of magnitude higher than the assumed 'shadow cost' of £46/tonne CO_2 saved (DCLG, 2011), and 20 times higher than the PV mitigation cost (£207-220/tonne CO_2 saved).

For Dunbeg, the per-dwelling cost of the heat network is c.£7000 for the initial investment, and £8500 for the lifetime capital costs at NPV. The potential minimum additional building costs by the '70%ZCH' and 'zero carbon' updates are of the same order as the capital cost of the CHN network, for a marginal improvement in CO_2 emissions.

Summary

Using the lowest cost of CO_2 reduction and lowest overall cost criteria, it could therefore be a better approach to relax the minimum fabric requirement for biomass heat network housing in future Building Regulations, and accept a higher level of CO_2 emissions to allow significant building cost savings. For social housing, part of the saving could be allocated to the Housing Association to reduce the rent or heat cost for tenants, in order that the higher demand but lower overall cost is also of overall benefit to the consumers.

If required, 'shadow cost' payments or PV units can be used to mitigate the CO_2 penalty of limiting required fabric improvement. However, at c. £220 per tonne of CO_2 saved, PV is also not a highly cost effective approach considering biomass CHN CO_2 emission levels at all considered fabric levels are much lower than other viable heating options. However, if some form of installed mitigation is required, this would be the most cost effective approach, with the possible benefit that tenants electricity costs could be reduced if the PV scheme was integrated with the household grid.

If the 'Allowable Solutions' 'shadow cost' policy is implemented as outlined in 5.3.3, biomass heating will meet the c.11 $kgCO_2/m^2/yr$ requirement easily at current fabric levels. Therefore, rather than set increasingly stringent fabric requirements, a better option might be to set maximum $kgCO_2/m^2/yr$ level specifically for biomass CHN. A potential option would be to set a limit of, say, 3 $kgCO_2/m^2/yr$ for biomass heated social housing, with perhaps a lower value required for private schemes. This is likely to be achieved with a fabric requirement between the 2010 and 2014 minimum levels (see Table 29).

For the final 'zero carbon' requirement, a payment in line with the shadow cost of carbon would be the lowest cost method of further mitigation as shown in Table 29.

One potential argument against this approach would be that any heating system can be removed and replaced with a more polluting type. For social housing, it may, however, be possible to consider relaxing fabric requirements based on guaranteed use of biomass heat networks for a certain period, with planning regulations or penalties in place to prevent early system replacement.

The Glenshellach demand analysed in 3.6.1 showed that there may be a some network connected users that do not use the system, but that they are a small minority. The final target levels could therefore reflect a small number of users that may be using other more polluting heat sources.

The other strong argument against would be that it does not reduce fuel use, and associated CO_2 emissions, as far as possible. For a sustainable fuel with a finite supply this is not ideal. However, in order to ensure the lowest possible cost solutions are focused on those most at risk from fuel poverty, there may be enough justification to reduce requirements specifically for social housing with tight controls on how and where it is implemented.

The overall conclusion that can be drawn from the above analysis is that increasingly stringent minimum fabric requirements in combination with biomass networks are not cost effective against the twin criteria of lowest CO_2 reduction cost and lowest overall cost of heat supply, assuming the additional building costs are also considered. There may therefore be a case for setting minimum fabric requirements that are dependent on the heating system used, using $kgCO_2/m^2/yr$ targets rather than, or in parallel with, fabric performance targets, or simply relaxing targets specifically for social housing to achieve the best overall use of central funding.

6. Further Analysis

The following section details additional analysis that has been undertaken using the developed model. **Section 6.1** reviews the impact of different supply and return water temperatures on the lifetime costs of the system. **Section 6.2** analyses whether the model method can be simplified to allow the key project selection factors identified in 2.2.4 to be used directly, and whether this simplified version can be used for initial investigations or sensitivity analysis using these factors. **Section 6.3** considers the implications for heat charging strategies from the increasing unit cost associated with falling demand, and expected demand variability. **Section 6.4** discusses the use of the socio-economic factors in the model, and whether they improved model accuracy.

6.1 Optimum Operating Temperature

As detailed in 2.2.3, current network designs typically operate with a 80°C supply and c.60°C return water temperature. Lower temperature networks have been suggested (Wiltshire, 2012) as a means to reduce heat loss costs, particularly for lower demand networks. However, much of the analysis undertaken has not considered the cost impact on each dwelling heating system. Lower network temperatures reduce the difference between the heating system and room temperatures, which increases the required surface area, and therefore the cost, of the heating system.

The following section details the cost analysis for different operating temperatures. 6.1.1 details the specific costs related to the heat loss and heating system. 6.1.2 reviews the overall impact of lifetime heat cost taking all factors, including pipe lifetime, into account.

6.1.1 Heating System and Heat Loss Costs

Table 30 below shows the estimated heat loss saving and additional radiator costs at 'Gen 3' and 'Gen 4' temperature levels for the Dunbeg case study. (Boiler and pipe sizes are assumed to be constant for all Building Regulations versions). Dunbeg is a medium density development for which heat networks remain viable. It would therefore be better placed than more heat dense networks to benefit from heat loss savings.

A 'Gen 3' system is modelled with a 80°C supply and 60°C return temperature basis, and a 'Gen 4' system with a 55/35°C basis.

The radiator sizing method for different temperature differences is detailed in Appendix F.

Building Regulations Basis	'Gen 4' vs 'Gen 3' Heat Loss Saving (£NPV)	'Gen 4' vs 'Gen 3' Radiator Additional Cost (£)	'Gen 4' vs 'Gen 3' Net Saving/(Cost) (£)
2010 BR 'Nominal'	10660	22524	(11924)
2014 BR 'Nominal'	10660	20554	(9554)
'70% ZCH' 'Nominal'	10660	14019	(3359)
'Zero Carbon' 'Nominal'	10660	11534	(934)

Table 30: Comparison of heat loss savings and additional radiator costs for 'Gen 3' and '4' systems

This initial review suggests that there is a high potential for the additional heating system costs to be higher than the potential heat loss savings. These additional heating system costs for networks with large numbers of smaller users, and the higher water temperature requirement for networks with larger volume users (see 2.2.3), may render low temperature networks unsuitable in all cases. More work would be required to confirm the basis for additional radiators costs, and to explore other options such as underfloor heating (UFH). UFH is, however, relatively expensive, only generally suitable for ground floors, and therefore not typically a universal low-cost solution.

6.1.2 Water Operating Temperature and Total Costs

Figure 34 shows the variation in the effective cost per kWh using the total heating system basis (see 5.2) for three water temperatures. For the 80/60°C and 70/50°C case, a DHW temperature difference of 45°C and an outlet water temperature of 55°C is assumed. For the 55/35°C case, 35°C and 45°C respectively are used.

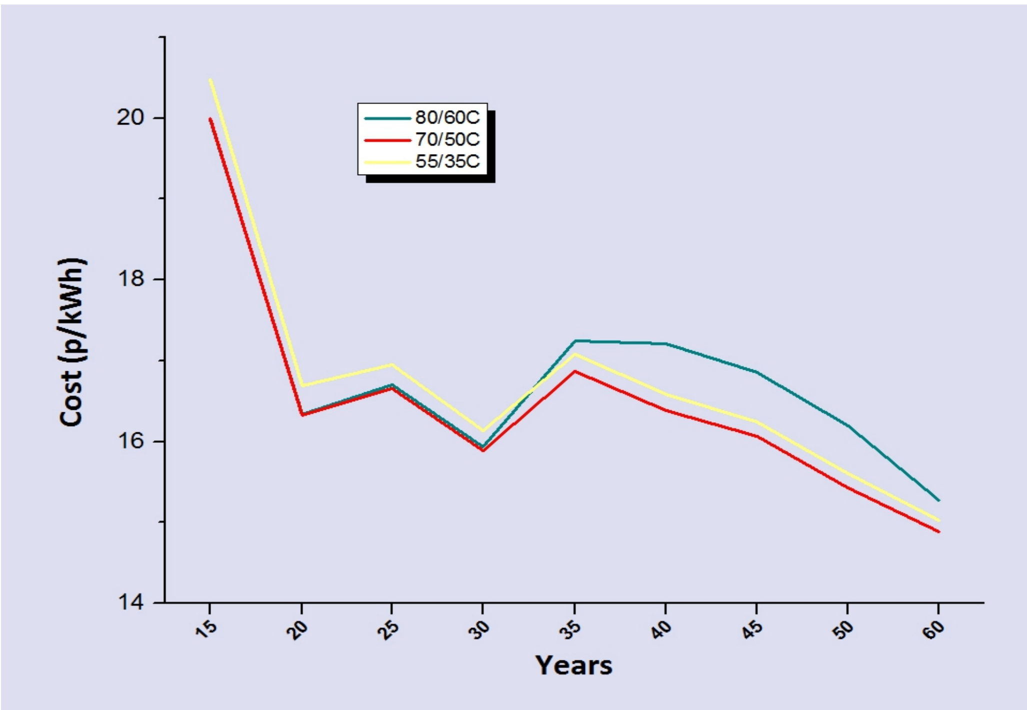


Figure 34: Cost impact of different supply and return water temperatures for different network lifetimes

The cost impact of the water temperature variation is relatively small using this static model with a fixed temperature difference between supply and return. A dynamic system model that analyses impact on boiler operation and accurate return temperature changes at smaller timescales may, however, give different results. Freely available dynamic models are not currently available.

The major influence is the expected pipe lifetime in each case. For the 70 and 55°C cases, 50 years is used as per Brugg (2013). This reinvestment has a small impact as the net present value (NPV) at Year 50 is small. At 80°C the pipe lifetime is only 30 years, and this reinvestment has a significantly greater effect on a NPV basis.

The relatively small variation in cost per kWh from 20 years onwards suggests that the initial Renewable Heat Incentive (RHI) income period is critical to cost recovery. Beyond this point the effective heat cost is relatively constant for the next 20 years as significant reinvestment is required. The boiler reinvestment after Year 20, and Heat Interface Unit reinvestment after Year 30 have noticeable impacts in the period immediately afterwards. Care therefore needs to be taken with reinvestments to ensure that the system is likely be operated for a further significant period.

Very basic network cost analysis highlights why improvements in heat loss performance associated with operating temperature will only make a marginal difference to project profitability as demand reduces. Heat loss costs are linked to fuel cost (2.8p/kWh for chips) and the additional capital cost of the increase in boiler size (c.£500/kW). The demand reduction impact on income has a much higher basis as it is linked to heat cost (10-20p+/kWh) plus the Renewable Heat Incentive (RHI) contribution (3-9p/kWh for 20 years). Heat loss is already a relatively small proportion of overall demand (10-20%), therefore even if it is eliminated with no additional costs, the impact on network profitability is marginal (<<1p/kWh) in comparison with the loss of demand and overall costs.

The overall conclusion that can be drawn is therefore that the suggested 'Gen 4' systems do not give an overall cost benefit if the overall costs, including the heating system, are considered. A 70°C supply temperature system delivers the benefits of a 50-year pipe lifetime, without the significant water temperature and heating system cost penalties.

6.2 Project Selection Factors

To further simplify initial area analysis it would be useful to have a factor, correlation or method that could approximate the likely economic viability of community heating. As outlined in 2.2.4, various simple factors are available to help differentiate between different areas and networks.

Area heat density is a useful starting measure, and this data will be readily available for Scotland on completion of the Heat Mapping Exercise (ScotGov, 2013g) (although this is not actual heat demand but calculated demand using similar methods to the model developed for this study). However, as per the case study analysis, other key factors are seen to be equally important. These were identified as: on- or off-grid location (in the short term), pipe heat density and length per connection, and network size/capacity.

The location with respect to the installed piping cost is also important but that is not considered in detail as the impact is relatively straightforward to determine with the cost factors identified below.

6.2.1 Simplified Key Factor Model

An attempt was made to determine if a proportional combination of the various factors listed above could be used for a simple definition of area feasibility. However, it is clear that this would require significant statistical analysis, and that the developed model could be more easily simplified to use and manipulate the key network factors as input variables. As an additional benefit, the model also allows a direct comparison with other heating options for the same input basis.

The full model does not allow the various factors to be easily manipulated. However, it is possible to approximate the results of the model assuming the heat density, number of connections, and pipe length is known. From these heat demand and therefore system costs can be identified.

The most significant difficulty for any simplified analysis is the piping design and cost basis. However, analysis of the case studies show that the average pipe cost is relatively consistent across each project types (with the exception of Govanhill). For the new developments, the per-metre installed cost, including hook-up pipe, is £137, £122, and £127 for Laurieston, Dunbeg and Glenshellach respectively. For the retrofit examples, using the 'new development' cost for baseline analysis, the costs are £147, £160, and £324 for Dalintart, Bowmore, and Govanhill respectively.

Therefore a cost of £130/m could be assumed for new developments of this size range for first pass analysis. For retrofit projects, the value should be higher as a proportion of the small pipe hookup scope is included as a lump sum. This also means that the per-metre cost is likely to vary more significantly depending on system size. More analysis is therefore require to determine if a simple estimate method for retrofit project piping costs can be defined. Based on the pipe cost analysis in

SFAB (2007), costs should then be factored by 1.7 for 'rural/parkland', 2.3 for 'suburb' and 3.1 for 'city centre' locations.

The pipe length per unit area varies significantly from development to development, particularly as the measurement of the plot area is somewhat arbitrary. The case studies suggest that a value of 0.067 m/m^2 would be a reasonable first pass, but again further work would be required to confirm.

With the above piping cost assumptions, the simplified model was able to generate the same cost data as the full model. It was then verified against the full model for Dunbeg and found to correlate within 1%. This allowed sensitivity analysis of the various factors for this modelled location to be undertaken as detailed in 6.2.2 below.

Further work would be required to determine if the various assumptions made are appropriate over a wider range of areas and developments, and whether this method could be used accurately for a range of locations. Given the simplicity of the method and the availability of the input data, it would be worth reviewing this further.

6.2.2 Key Factor Sensitivity Analysis

The following analysis considers the sensitivity to key design factors for new-build projects. Similar analysis could be carried out for retro-fit projects, but as discussed the impact of grant funding and installation costs are more significant, and make reaching conclusions difficult. Retrofit projects are best modelled on a case-by-case basis rather than trying to define broad criteria for feasibility.

Air source heat pump (ASHP) equivalent costs are provided for comparison. The analysis in Sections 4 and 5 showed that by the 'zero carbon' housing requirement, with no significant change in the standing charge basis for gas, they represents the most cost effective alternative individual heating solution. The comparison between on- and off-grid areas is therefore also not considered.

The key factors for the three new development case studies are as follows. The various factors are defined in 2.2.4:

Factor	Lauriesten 2010 BR	Dunbeg 2010 BR	Glenshellach 2010 BR	Lauriesten 'Zero Carbon'	Dunbeg 'Zero Carbon'	Glenshellach 'Zero Carbon'
Gas Grid	Yes	No	No	Yes	No	No
Area (m^2)	22000	8650	29000	22000	8650	29000
Plot Ratio (Floor/Land)	0.73	0.36	0.29	0.73	0.36	0.29
Area Heat Density (GJ/m^2)	2.42	1.39	1.00	1.64	1.00	0.67
Pipe Heat Density (GJ/m)	26.01	22.69	13.56	17.69	16.18	9.06
Pipe Length per Connection (m)	10.12	10.58	24.01	10.12	10.58	24.01

Table 31: Key selection factors for new-build case studies

The analysis is 4.2.2 and 5.2 showed that the Dunbeg scheme was an example of a marginal area for using heat networks. For the selected 'zero carbon' basis, considering only total heating system costs, the cost per kWh was 23.5p for community heating and 25.7p for ASHPs. The following analysis considers the impact on the Dunbeg analysis, if heat density, pipe length per connection, and network capacity are varied using the 'zero carbon' housing basis while keeping other factors constant.

For all calculations the calculated boiler size is used directly and not rounded up to nearest discrete size to remove data inconsistencies created by arbitrary increases in boiler size ranges.

Area Heat Density Sensitivity (Dunbeg)

Area = 8650 m^2, Pipe Length=550 m, constant demand per connection (1975 kWh/yr)

Heat Density (GJ/m^2)	Number of Connections	Pipe Heat Density (GJ/m)	CHN (p/kWh)	ASHP (p/kWh)
1.00 (base)	**50**	**15.73**	**23.13**	**25.48**
0.95	47.5	14.94	23.72	25.48
0.90	45	14.15	24.38	25.48
0.85	42.5	13.37	25.10	25.48
0.825	41.25	12.98	25.50	25.48
0.80	40	12.58	25.92	25.48

Table 32: Area heat density sensitivity for Dunbeg

For the Dunbeg development under 'zero carbon' conditions, the crossover point against air source heat pumps (ASHPs) would be a development of the same area with 41-42 equivalent households.

Pipe Length per Connection Sensitivity (Dunbeg)

Area = 8650 m², Connections=50, heat density=1.0, constant demand per connection (1975 kWh/yr)

Pipe Length (m)	Pipe Heat Density (GJ/m)	Length per Connection (m)	CHN (p/kWh)	ASHP (p/kWh)
550 (base)	**15.73**	**11.0**	**23.13**	**25.48**
600	14.42	12.0	23.72	25.48
650	13.31	13.0	24.31	25.48
700	12.36	14.0	24.90	25.48
750	11.53	15.0	25.49	25.48
800	10.81	16.0	26.08	25.48

Table 33: Pipe length per connection sensitivity for Dunbeg

For the Dunbeg development under 'zero carbon' conditions, the crossover point against ASHPs would be a development with approximately 35% more pipework for the same overall demand.

The Glenshellach development under current conditions has the same heat density as the 'zero carbon' Dunbeg development, but only the Dunbeg case is viable. For Glenshellach it can be shown that the key factor against heat network viability after the 2003-2008 period is the high pipe length per connection (24.0m). All the other key factors are marginal but within acceptable ranges. The compact rectangular layout of the Dunbeg development instead of the more dispersed, multiple cul-de-sac layout of Glenshellach is therefore crucial.

Network Size/Capacity Sensitivity (Dunbeg)

Heat density=1.0, constant demand (1975 kWh/yr) and pipe length (11 m) per connection, base area=8650 m²

Plot Area Size Factor	RHI Tariff	Number of Connections	Pipe Heat Density (GJ/m)	CHN (p/kWh)	ASHP (p/kWh)
0.5	Small	25	14.42	29.15	25.48
0.75	Small	37.5	15.26	24.68	25.48
1.0 (base)	**Small**	**50**	**15.73**	**23.13**	**25.48**
1.25	Small	62.5	16.02	22.15	25.48
1.5	Small	75	16.22	21.46	25.48
1.75	Small	87.5	16.36	20.95	25.48
2.0	Small	100	16.48	20.55	25.48
2.25	Medium	112.5	16.56	22.20	25.48
2.5	Medium	125	16.63	21.95	25.48

Table 34: Network size/capacity sensitivity for Dunbeg

The analysis shows a significant improvement in heat network viability between a half-scale project and the actual development as would be expected for an already small-scale development such as Dunbeg. Doubling the size while keeping within the 'small' Renewable Heat Incentive (RHI) tariff band, could reduce the effective heat cost by 13%.

Key Factor Conclusion

The three factors considered above (heat density, pipe length per connection, size/capacity) were all shown to have an impact of heat network potential within the range of realistic values reviewed.

The simplified model used was straightforward to manipulate, and could be used for initial first-pass area analysis with more verification of piping cost assumptions.

6.3 Heat Charge Basis

As highlighted in 2.4.1, the majority of existing social housing networks have a simple unit pricing structure with no fixed charges. In 5.1 it was also shown that all heating system costs, including generating units, must be considered in the economic analysis. What is less clear is if there is explicitly or nominally a portion of the rent charge that is associated with heating system provision, or clear rent charge distinctions between houses with and without community heating to account for whether or not a generating unit is present.

Figures 28 to 32 show that based on a simple unit charge cost basis, the required cost per kWh would increase significantly as demand drops. This has the potential to create either confusion or anger among householders when compared directly with other utility-only costs, and where the effective cost of individual heating systems is not well understood.

The issue is made worse by the fact that the total annual income required to cover the overall network costs remains steady as demand drops (see Table 35 below). The equipment and fuel saving at lower demand levels is largely offset by the increased capital allocation per unit consumed and the loss of Renewable Heat Incentive (RHI) income. (For 'medium' biomass systems the reduction is higher at c. 5% between 2010 and 'zero carbon' due to the lower RHI tariff level).

Setting a fair charging basis with a significantly lower demand but less than 5% reduction in the total annual cost will be challenging. As will making a clear and fair distinction between rent, individual heating system costs, network costs, and per-unit charges.

For connected private housing, an option would be to charge for connection and have the householder purchase the Heat Interface Unit (HIU), with the investment offsetting the heat charge.

For Housing Association tenants the situation is more difficult. The simplest solution may be to retain a similar rent basis regardless of heating system, and allocate the equivalent cost of individual heating systems (i.e. £300-£350/yr) to cover the heat network costs. Table 35 shows the impact of charging, or allocating from rent payments, different levels of annual fixed cost.

	Average Demand (kWh)	Annual Average Required Heat Income (£)	No Fixed Charge Unit Cost (p/kWh)	£150 Fixed Charge Unit Cost (p/kWh)	£300 Fixed Charge Unit Cost (p/kWh)
2010 BR 'Nominal'	2816	461.8	16.4	11.1	5.7
2014 BR 'Nominal'	2678	460.6	17.2	11.5	5.9
'70% ZCH' 'Nominal'	2200	457.6	20.8	14.0	7.1
'Zero Carbon' 'Nominal'	2045	456.0	22.3	14.9	7.6

Table 35: Unit heat cost for various fixed charge levels for Dunbeg

The primary benefit of the higher fixed charge is that the unit cost is kept within the range of standard utility costs, and therefore easier to justify to users. This also offers the Housing Association a significant degree of protection against expected demand variations.

A variety of different factors can result in significant changes in demand from year-to-year and between similar developments. Models, which have their own inherent inaccuracy, are based on average behaviour, climate, and occupancy. Within small developments in single locations, all three could vary significantly from the mean over the short and longer term.

Impact of Demand Variability

The Glenshellach demand data (see 3.6.1), highlights that year-to-year there can be 20-25% variations in total demand. By the 'zero carbon' house basis we would expect the climate-related variation to fall significantly as space heating falls from c.66% to 20% of total demand. However, based on the variability seen at Glenshellach, we could still expect at least ±6% variations from year-to-year based on behavioural and occupancy variations, and the reduced climate impact.

Table 36 outlines the potential variance in income for the Dunbeg 'zero carbon 'nominal' fabric case for various levels of fixed charge based on ±6% variations in demand.

	Average Demand (kWh)	'Break Even' Heat Income (£)	No Fixed Charge Heat Income (£)	£150 Fixed Charge Heat Income (£)	£300 Fixed Charge Heat Income (£)
-6% Demand	1922	456.0	428.6	436.4	446.1
Average Year	2045	456.0	461.8	454.7	455.4
+6% Demand	2168	456.0	483.5	473.0	464.8

* based on 'zero carbon' case and 22.3, 14.9, and 7.6p/kWh heat charge respectively

Table 36: Income variation for expected demand variations for various fixed charges for the 'zero carbon case

Table 36 shows that the potential year-to-year income variation that can be expected varies from 6% if no fixed charge is levied, to 2% if a £300 fixed charge equivalent to the annual cost of a gas boiler is set. The use of fixed charges can therefore be used to reduce the impact of natural demand variations.

Summary

For the average consumer there would be a potential benefit from fixed charges in that heat costs are more equally spread over the year. However, the obvious drawbacks of a significant fixed charge are that all users are required to pay a large proportion of the annual heat charge regardless of usage, and the cost incentive to lower demand is reduced.

It is beyond the scope of this analysis to suggest a preferred cost model for community heating but it will clearly be a difficult exercise to balance cost coverage, protection against demand variations, and fairness to consumers. However, the single entity business model for heat networks allows the fixed charge and unit cost to be freely and fairly set, unlike individual heating systems where the fixed charge is, in reality, set automatically. The viability of heat networks for social housing as demand drops will depend on finding a suitable strategy for the balance of fixed and unit charges, and how these are integrated with overall rent charges.

6.4 Occupancy and Socio-economic Model Accuracy

As defined in Section 3.5, a study by the Tyndall Centre (Kelly et al, 2012) has determined that there can be significant, and to some degree predictable, differences in mean internal temperature (MIT) between different household types. Much of the variation is based on geographical location, heating system type and house type, and therefore would not apply to localised developments of similarly aged housing with identical heating systems. However, 1-2°C of MIT variations for individual dwellings can be attributed to socio-economic and occupancy factors (see Table 6). Although across sizeable developments of various housing types and sizes we would expect overall variations from the mean level to reduce.

Table 37 below shows the variation in modelled demand for Glenshellach (see 4.2.1) between the actual occupancy Tyndall Centre (TC) MIT basis, average occupancy (SAP and Scottish average basis) TC MIT basis (see 3.5.2), and a fixed national average 17.5°C MIT basis. Equation (3) is used for the water demand in all cases based on determined 'total occupants'.

Basis	Actual	Actual Occupancy / 'TC' MIT	SAP / 'TC' MIT	Scot / 'TC' MIT	SAP / Avg. MIT	Scot Avg. / Avg. MIT
Total Occupants	246	246	231	167	231	167
Children	101	101	44	44	n/a	n/a
OAP Households	3	3	28	28	n/a	n/a
Average MIT (°C)	n/a	17.73	17.61	17.45	17.50	17.50
Total Demand (kWh)	493093	511407	493847	487726	477950	483633
Space Heating (kWh)	n/a	342791	343226	364093	322670	360000
Hot Water (kWh)	n/a	168616	150621	123633	155279	123633

Table 37: Demand estimates for different occupancy and MIT models

The results show that individual space heating and water estimates vary significantly but that overall the various models give relatively consistent overall results that are within 5% of the modified actual demand (see 3.6.1). The occupancy levels estimated from the national average data is significantly different from the actual Glenshellach data, but the various errors to some degree balance out. As shown for the 'Scot Avg./Avg. MIT' case, the underestimate of occupant number reduces water demand but also reduces some indirect heat gains to a similar degree, which reduces the total demand error even if the individual estimates are inaccurate. Without a detailed breakdown of heating and water use, however, it is difficult to estimate the extent of this inaccuracy.

While there is insufficient evidence from this one example to suggest that using the socio-economic data is more accurate, the variations between models of heating and water demand estimation suggest that it is a potentially important area to consider further. There may be developments with occupant compositions that do not allow the errors to cancel out as conveniently.

The potential error is likely to be c.10% as a worst case, which is significant for marginal networks. Although, for social housing the tendency is likely to be to underestimate demand, which is a less critical error for long-term economics.

Further work is required to determine if the MIT factors used are accurate, what the base temperatures should be for the analysis, and to review the benefit of their use across a wider range of developments.

7. Conclusions

7.1 New-Build Projects

Although heat demand is estimated to fall by a further 30% from the current 2010 Building Regulations basis by 2020. The overall conclusion from the study is that biomass community heating networks remain competitive for a range of new-build projects as the demand reduced. The number of projects that remain competitive under 2020 'zero carbon' housing requirements, will depend on several factors, but particularly how overall development costs are considered in light of SAP CO_2 targets.

Overall Cost Comparison Basis

The main factor in determining network viability identified is the cost comparison basis used for the potential alternative options. The current practice of comparing network costs with the fuel-only costs can no longer be justified, and may result in some viable schemes being discounted.

Using a comparable overall lifetime cost basis for all heating options, viability of heat networks is maintained for a range of schemes with either high density flats, or suitable lower density mixed developments where community heating is a key determining factor in the layout design.

For schemes that are currently viable, the impact of falling demand on the relative competitiveness of heat networks is small. For a scheme to be viable now, the lifetime fixed costs must already be lower than for the alternative heating options. As the current Renewable Heat Incentive income covers the fuel costs for a biomass network, the total lifetime cost remains stable as demand falls, while falling slightly for the other options. However, the relative change will only be significant for already marginal areas.

Carbon Mitigation Cost Impact

If the total cost of the entire development, including building fabric and other carbon mitigation costs, can also be considered. Using this extended basis can strongly favour community heating if certain assumptions regarding CO_2 emissions targets and Building Regulations minimum requirements can be made. This analysis is most applicable to social projects where a single entity is responsible for construction and operation of the entire development.

Biomass heat networks have a SAP CO_2 emission rating that is 15% of gas, and 6% of grid electricity. This allows housing that is connected to biomass heat networks to meet required CO_2 targets with significantly lower levels of building fabric or additional renewable microgeneration. Recent Building Regulations have minimum (backstop) levels for building fabric. By setting this level as the zero-cost baseline for the housing, and considering any additional costs as effectively heat costs, biomass heat networks are shown to be significantly lower cost than the alternatives.

The drawback of reducing building fabric levels if connected to a biomass heat network is that demand is not reduced as far as possible. However, the cost of fabric improvements for biomass network housing in terms of CO_2 'saved' is two orders of magnitude higher than the UK Government's 'shadow cost of carbon'. The total 'break-even' heat cost is also not significantly lowered by further reducing demand at this level, therefore fuel poverty reduction is also not best served by enforcing increasingly stringent requirements. Minimising sustainable fuel use is the only clear argument against such an approach.

A possible conclusion from this analysis is that imposing strict minimum fabric conditions on all housing regardless of heating system used hinders the development of low CO_2 rated systems, such as biomass heating. A backstop fabric level or fixed $kgCO_2/m^2/yr$ target specific for biomass heating would ensure that poorly cost effective fabric improvements are not required for schemes, such as social housing projects, were the continuing use of the biomass network can be guaranteed. This could be used as a specific policy for social housing where fabric and microgeneration savings are passed on to tenants as lower rent or heat charges.

Alternative Heating Options

For on-grid locations, the gas connection charges can be significant, and this helps to offset some of the initial community heating costs. As shown for the Laurieston study, for higher density schemes, community heating can currently compete directly with gas. As demand drops, the high maintenance cost and typical gas standing charge also becomes increasingly relevant with gas systems becoming less competitive by the 2020 'zero carbon' housing requirement.

Air source heat pumps (ASHPs) are a viable alternative option, although with the associated performance risk at extremely low ambient temperatures. For the cases reviewed, they are increasingly competitive against gas heating as demand falls, and competitive against heat networks for low heat density developments, or those with poor piping layouts.

If the SAP CO_2 rating for grid electricity continues to drop, the main decision by 2020 for new developments in all locations should be between community heating and heat pumps. In all cases ASHPs were shown to be the most cost effective of the electrically powered options, particularly if CO_2 emissions-related costs are included.

Network Operating Temperature

Lower temperature networks, with supply temperature between 50 and 60°C, have been suggested as a means to reduce heat loss related costs for low demand networks. However, it was found that the increased heating system costs associated with lower water temperatures are generally higher than any potential fuel and boiler savings from reduced heat loss. There is a benefit in piping lifetime and pressure rating associated with lower temperatures, but the benefit does not markedly increase below 70°C. A 70°C supply temperature is used for the analysis as the model showed no compelling financial reason to reduce the temperature further.

The analysis also shows that operating for the first 20 years is critical as a result of the Renewable Heat Incentive income during this period. Beyond this point income and costs tend to largely balance if the same unit cost basis is maintained. Extending the system life beyond this point is of marginal cost benefit, and the long-term benefit of each necessary reinvestment would need to be carefully considered at the time.

Heat Charge Basis

One of the most significant impacts of falling demand is that the unit heat cost for all heating systems markedly increases. For individual heating systems this impact is masked by the fact that the generating equipment is generally treated as a single fixed cost and its effective unit cost is not considered. For heat networks, where the network cost is currently typically recovered on a per-unit basis, setting an acceptable unit heat charge that can be fairly compared against the alternative heating options will be difficult. A combination of a fixed and unit charge may therefore be necessary to provide an acceptable unit charge and a degree of income insurance against natural demand variance.

Housing Associations would like to decouple heat costs from rent and charge solely based on usage but this will be increasingly challenging as the effective unit heat charges increase. This may be the main barrier to heat network introduction, unless a fair and transparent method can be found to set rent, any separate fixed heat costs, and unit heat costs.

Component and Cost Improvements

Relative costs for UK heat networks remain high compared to other EU countries. Analysis showed that there was potential for piping costs to fall by up to 25% over time. Others have determined that the costs of currently imported capital equipment also have scope to be reduced with increasing market development, with a proportional heat cost savings to any capital cost reduction. Alternative piping designs may also reduce piping costs by a further 5-10%. There was, however, little evidence of potential cost effective improvement of pipe insulation materials.

Key Network Selection Factors

Heat networks have a complex balance of economies of scale and cost factors that need to be considered. However, with certain reasonable assumptions, a simplified analysis can be performed if only heat density, number of connections, and number of occupants can be determined.

Heat density is considered to be the key factor in determining relative viability between different sites. This is not, however, the only factor that has a significant impact. The pipe length per connection and the development size, were shown to be equally important. For first-pass analysis for areas and developments it is therefore important to look beyond simple heat density analysis and consider other factors that can also be easily determined or estimated.

7.2 Retrofit Projects

With the higher demand of older housing, but higher associated integration costs, network retrofit projects have a significantly greater demand and cost modelling risk than new-build projects. The impact of building age, construction costs, and the existing heating systems are all significant. It would be necessary therefore to identify a larger modelled benefit between a community heating network and the alternative options than would be required for new-build projects.

Given the potential risks, it is likely that retrofit projects will be restricted to dense or large-scale off-grid locations with high concentrations of Housing Association properties. For these locations an 'ECO' grant is likely to be available, which is shown to significantly improve network viability. However, there are few identified areas of high density, off-grid, social housing is Scotland. A case can also therefore be made for very dense housing where gas is available, if the integration costs are low and available grants are sufficient to provide the necessary cost coverage and overrun protection. The reality is that significant numbers of cost effective social housing-only retrofit schemes are unlikely, although there is a stronger argument for implementation if CO_2 reduction benefits are also considered.

The system at Home Farm in Portree, where a biomass heat network was installed for the Housing Association (HA) housing but not for the adjacent private development highlights the main barrier to wider use, which is private householder uptake. Schemes for entire rural towns, such as Bowmore, where HA housing is typically in several small areas, would require significant private uptake to be effective. There is no evidence that this is possible without prescriptive policies.

The type of retrofit projects that are existing and planned, generally confirm the above conclusion.

All are typically replacing electric heating and either high density (Aberdeen, Dundee), or very large scale (Cardenden). All are planned solely for HA properties, with private connection potentially offered but not essential in Cardenden.

7.3 Modelling Method and Further Work

The use of the SAP (Standard Assessment Procedure) method for demand modelling was found to be computationally straightforward and provided data that matched the available real data with reasonable accuracy. As a means to gauge initial feasibility, the method allowed network models to be set up with relative ease, and provided a means to quickly gauge sensitivity to various factors.

Verification of the model was hindered by the lack of readily available usage data for different networks. A reasonable level of accuracy was shown against the data available for the Glenshellach development but it is difficult to make broad judgements against such a small dataset. Specific heating and water demand data, at least on a monthly basis, would be necessary to further refine the specific models for these parameters. Further work would therefore be required to source data and gauge accuracy against a number of schemes.

For the same reason, it was difficult to gauge the effectiveness of the socio-economic and occupancy factors in providing more accurate demand estimates. With only one study analysing these factors and one set of usage data, conclusions are difficult. The potential inaccuracies of using more general data are relatively small (in the region of 10%), but this level of error remains significant for a typical low financial return network. Further work in this area could provide an additional level of accuracy for small-scale developments in particular, and is recommended.

In general, the results from the analysis are extremely sensitive to the assumptions made. The availability of recent cost estimate data for one retrofit project allowed the equipment and installation cost assumptions to be verified and updated as required. Overall cost estimates were shown to be accurate against two new-build examples, with a degree of underestimation for the one retro-fit scheme reviewed. As UK costs are likely to change over the next few years, and there is evidence of wide variations in quoted costs, further and ongoing checking of these costs is required.

For the key analysis regarding carbon mitigation costs for SAP compliance, further work to determine the cost basis for the fabric improvements per unit of emissions saving is necessary. A conservative cost assumption was used for the analysis and showed some additional benefit for heat network justification, therefore more accurate cost data may provide further justification.

Perhaps the most significant assumption made was the use of a simple 3.5% discounted cost basis. This was assumed to be the minimum potentially acceptable level, and the financial analysis should be considered on this basis. With a different business model in comparison with individual heating systems, and the likelihood of mainly 'non-profit' schemes where fuel poverty reduction is a key requirement, comparative financial analysis is difficult other than by simply considering total lifetime costs as a baseline. More detailed financial analysis to consider the impact of different inflation factors for costs, realistic income risks, and heat charging methods would be beneficial.

The use of a static model with average temperatures modelled and monthly demand estimation generated also has significant limitations. Dynamic modelling of the system at much smaller timescales would be required to determine if some of the assumptions made, particularly regarding operating temperature, are accurate under real conditions. The static model does not allow the implications of improvements in dynamic performance from improved heat interface unit exchangers, in-house heating system designs, and benefits of reducing relative return water temperatures to be gauged. No freely available models are available and further work is therefore also required in this area.

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Appendix A Case Study Model Assumptions and Cost Basis

A.1 Biomass Boiler Sizing

Efficient economic and operational performance of a biomass boiler based system requires careful sizing of the biomass system. The existing Biomass Decision Support Tool (BDST) tool (Carbon Trust, 2013) is available to size boilers more accurately and the model therefore does not cover this in detail. Where possible it is therefore recommended that the BDST is used to determine the most effective boiler size, expected efficiency, and optimal sizing of associated thermal storage units and backup/peak demand fossil fuel boilers.

Thermal storage is used to boost supply during short periods of high demand, which ensures that the boiler can be sized below the peak estimated load. This is critical for biomass-based system, which typically only have a 3:1 to 4:1 useful turndown ratio before fuel is effectively wasted to simply keep the system running (Palmer et al, 2011).

Based on demand analysis provided by the Campbell Palmer Partnership (CPP) for the Glenshellach development (CPP, 2011) used as a case study for this project (see 4.2.1), the most efficient sizing of the biomass boiler is between 55 and 70% of peak load. However, at this level the use of a fossil fuel boiler is required to provide backup during peak demand periods. The model therefore uses 80%, as this represents the point at which the biomass system plus thermal storage can typically supply 100% of annual demand. This simplifies the cost, CO_2 emission, and Renewable Heat Incentive (RHI) calculations. This is likely to lead to a slight overestimate of the unit heat cost from a community network. The cost of an auxiliary fossil fuel boiler can be included as an option for cost purposes, but does not automatically update the assumed efficiency.

The same analysis shows that an 80% sized system will spend c. 1260hrs below the turndown level. The analysed system was 90% efficient above the turndown level, and c.33% efficient below, therefore an average efficiency of 82% is used for the 80% sizing case on a pro-rata basis.

A.2 Climate

Climate data has been taken from the Retscreen Energy Management software program (Retscreen, 2013). Nearest locations have been used where local data is unavailable. Monthly average data is used.

A.3 Project and Equipment Lifetimes

An overall network lifetime of 40 years is modelled for all projects. The expected lifetime for the main biomass boiler unit(s) is 20 years (AEA, 2011b), and one replacement unit at 50% of the original cost is included in Year 20. 50% is used as only the boiler unit rather than all 'Energy Centre' infrastructure needs to be replaced (same basis as Poyry, (2009)).

The same 20-year lifetime is assumed for all individual heating systems, with a 100% cost of replacement. 15 years is generally used (Poyry, 2009) but it is assumed that for social housing the units will be well maintained and have a slightly longer lifespan.

Cross-linked polyethylene (PEX) piping is selected which will have a lifetime of 50 years, if operated at a maximum of 70°C and 8.5 bar (Brugg, 2013).

Heat Interface Units (HIUs) have an expected lifetime of 30 years (Olsen et al, 2008) and are assumed to be completely replaced at this point.

Where PV panels are used for CO_2 emission compliance, no replacement is assumed within the 40 year review period.

A.4 Fuel Costs

All prices are based on gross energy available before generator efficiency is taken into account.

Wood pellet pricing is set as 4.0p/kWh based on an average of £192/tonne for Dec-Feb 2013 and assuming 4800 kWh/tonne for bulk pellet supply (EnAgri, 2013).

Wood chip pricing is set as 2.8p, based on an assumption that log and chip prices are approximately equivalent, an average log cost of £98/tonne, and assuming 3500 kWh/tonne for 30% moisture chips (EnAgri, 2013).

For Glasgow (Laurieston and Govanhill) the gas price for domestic cost comparison is set to be £89.20 standing charge plus 4.2p/kWh based on Scottish Gas single tariff pricing sourced on-line on 18th July (British Gas, 2013). The equivalent for the Oban SGN gas network is £100 standing charge and 4.32p/kWh from Scottish Hydro (Hydro, 2013). The Oban gas price was used for the Bowmore cost comparison purposes. Gas is not available for the Argyll and Bute case studies.

For Glasgow (Laurieston and Govanhill) the electricity cost for domestic comparison is set to be £58.30 standing charge plus 12.9p/kWh based on 18th July Scottish Gas single tariff pricing sourced on-line (British Gas, 2013). The equivalent for the Oban area is 14.46p/kWh from Scottish Hydro (Hydro, 2013).

For electric storage heating in Oban a cost of 8.5p/kWh was used based on the relevant Total Heat Total Control tariff as supplied by West Highland Housing Association (WHHA).

The non-domestic electricity cost assumption for pumping costs is the Standard Rate used by the

SAP 2012 methodology for comparisons and is 15.3p/kWh (BRE, 2013).

A.5 Equipment Costs

Fully installed costs for a biomass boiler system are taken from the Energy Savings Trust (EST, 2009a) using mid-range costs. Prices have been increased by 4% in line with Poyry (2009) projections for 2013 prices. These range from £735/kW for a 100 kW system to £315/kW for a 3 MW+ system.

Thermal Storage costs are £1000/m^3 plus £3500 for instrumentation (Martin and Thornley, 2013).

Based on the Dalintart cost estimates provided (CPP, 2012b), the auxiliary boiler cost is assumed to be 15% of the biomass boiler cost. Additional control costs for a multi-boiler system were assumed to be £10,000 plus £100/kW.

Household Heat Interface Unit (HIU) costs are £2392, inclusive of unit, metering and installation. The cost was taken from Poyry (2009) with a 4% cost increase for current pricing and confirmed to be accurate with Dalintart project cost estimates provided by CPP (CPP, 2012b).

For water storage tanks an installed cost of £800 in included based on the modern, well-insulated Dimplex EC-Eau model. (ElectricPoint, 2013)

For a Gas Boiler an installed cost of £2300 is assumed based on an Energy Savings Trust estimate (EST, 2013g). The same cost is used for an Oil Boiler as costs for both are primarily for installation.

For electric storage heating an installed cost of £2500 is used based on an average of 5 off 700W radiators per house and using high efficiency Quantum models, which are assumed to be the minimum necessary specification for new housing (ElectricPoint, 2013). A saving of £2000 is included against the baseline of a wet heating system based on the installed cost of a radiator system in a new-build house.

For air source heat pumps (ASHPs), a cost of £700/kW is used based on Poyry (2009) and confirmed with current online pricing for Mitsubishi Ecodan systems (Dean Wood, 2012). Sizing is 8 kW for an average post-2015 new-build house based on 60mins to heat a 120l tank plus small heating load. For recently built housing (post-2007), 10 kW is used, and 12 kW for older housing, as a result of the larger heating loads.

For a Solar Thermal system, an installed cost of £4800 is used based on Energy Savings Trust data (EST, 2013f).

For Individual Biomass Boilers, an installed cost of £12500 is used based on a Euroheat K10 pellet boiler (Euroheat, 2012).

For a Mechanical Ventilation with Heat Recovery (MVHR) system integrated ASHP an additional cost over a standard MVHR of £5000 is included based on a Genvex Combi 185 (Genvex, 2012). A cost of £5000 is used for standard MVHR and ducting system from an example Passivhaus project at Denby Dale (Building, 2009).

A.6 Piping/Hookup Costs

A detail review of the piping cost basis is in Section 3.6.2.

For new-builds it is assumed that the building will be designed for district heating pipe connection and that connection is straightforward. Therefore a piping hookup cost of 5m of 25mm underground pipework (c.£500) is included per house connection assuming an adjacent main is available. An additional 5m of pipe is added per upper floor of a block of flats.

For retrofit projects, piping hookup costs may vary significantly depending on the age and type of building. A base cost assumption from Poyry (2009) is used of £1560 per individual flat and £3120 per house. Additional hook-up pipe lengths are not included in the model.

A.7 Wet Heating System Costs

Where a wet heating system with radiators is to be installed in an existing house, a cost of £2000 plus £500 per bedroom is assumed. This basis was taken from Poyry (2009) and confirmed using the Dalintart project cost estimates (CPP, 2012b). An average cost of £3000 is used if required.

For low temperature systems (air source heat pumps (ASHP) and solar thermal), an additional £1000 is included for low temperature radiators based on typical pricing.

A.8 Operation and Maintenance (O&M) Costs

For the biomass system an annual O&M allocation of 2% of total capital is used (EST, 2008).

For gas boilers an annual charge of £160 for maintenance is used based on a selection of available packages. Similar costs were assumed for oil, electric and individual biomass heating systems, all based on Poyry (2009).

For ASHPs, an annual maintenance cost of £10 is used (Poyry, 2009)).

A.9 Pipe Type

All models are run using cross-linked polyethylene (PEX) material piping with polyurethane (PUR) insulation. Up to 63mm diameter pipes are twin pipe design as initial analysis showed this to be most cost effective in all scenarios. Larger pipes are single type as twin pipes are unavailable.

Pipe sizes are based on the Calpex Standard design from Brugg Pipesystems (Brugg, 2013).

A.10 Pipe Insulation

Standard (Series 1) insulation thickness is used as this has been shown to be the optimal available thickness under typical conditions (see Appendix E).

Calpex insulation has a thermal conductivity of 0.0216W/mK at 50°C. However, insulation performance varies with both temperature and time. Calpex state an increase of 3% in thermal conductivity is to be expected (Brugg, 2013). Therefore an average lifetime value of 0.0225 W/mK is assumed.

A.11 Socio-economic Model

For the socio-economic modelling for Mean Internal Temperature (MIT), the following bands are used as part of the analysis as detailed in 3.5.

Band	Income (£)	Wall U-Value (W/m².K)	Building Age
0	<5500	>1.6	pre-1850
1	5500-10999	0.6-1.6	1850-1899
2	11000-21499	0.4-0.6	1900-1918
3	21500-37499	0.2-0.4	1919-1945
4	37500-53999	<0.2	1946-1964
5	54000-99999		1965-1975
6	>=100000		1976-1981
7			1982-1991
8			1992-2002
9			2003-2007
10			2008-2014
11			post-2015

Table A1: Tyndall Centre MIT factor model bands for income, wall U-value and building age (Kelly et al, 2012)

A.12 Equipment Efficiencies

The biomass boiler efficiency is set at 82% are detailed in A.1.

The >1 MW biomass CHP plant is assumed to have 17% electrical and 63% thermal efficiency. (Poyry, 2009).

The gas boiler efficiency is assumed to be 90%, based on best-in-class condensing boilers from the SAP Boiler Efficiency (Sedbuk) Database (Sedbuk, 2013). This is based on certified laboratory test data from the manufacturers and therefore may overestimate installed efficiency. However, this data is used as the basis for the SAP evaluation method which is used as the basis for this analysis. Similarly, oil heating is assumed to be 92% efficient from the same source.

The air source heat pump (ASHP) coefficient of performance (COP) is modelled to be 2.5. The reference Mitsubishi Ecodan model has a rated COP of 3.1, with a 2°C ambient temperature and 35°C water outlet temperature (Mitsubishi, 2011). 2.5 was selected as it is the maximum COP that can currently be selected for SAP calculations which form the basis of the model (BRE, 2013). This is based on an average value of 2.45 from Energy Savings Trust field trials (EST, 2013g).

The model assumes that 90% of the heating energy is supplied by the ASHP with the remainder by electrical immersion booster heating within the water tank.

For solar thermal heating the proportion of heating supplied by the solar unit is set as 40%. An Energy Savings Field Trail determined that a well installed system could generate c.60% of hot water demand for a UK house (EST, 2011b). At future low demand levels, where space heating is c.50% of water demand, this was approximated to 40% of total heat energy as a best case for simplified analysis. The remainder is supplied by water tank immersion heating.

A.13 Electrical and Lighting Factors

The SAP 2012 space heating demand methodology (BRE, 2013) requires additional factors to account for energy performance improvements for electrical equipment and lighting, and the impact on associated internal heat gains.

The factor for electrical equipment can vary from 1 to 0.67, with 0.67 relating to use of mainly highly energy efficient units.

The factor for lighting can vary from 1 to 0.4, depending on the degree of low energy lighting used.

For older dwellings, 0.9 is assumed for both factors assuming some conversion has taken place but mainly older or less efficient equipment is in place.

For current and future new-build properties, 0.75 and 0.7 are assumed for electrical equipment and lighting respectively. This assumes that new housing will have high performing equipment but that some older equipment and lower efficiency lighting will also be used by residents.

A.14 Miscellaneous Factors

- Pipe depth to centreline – 0.6m (based on standard minimum soil coverage of 0.5m (Zinko et al, 2008), single centreline depth used for all pipe sizes)
- Heat Interface Unit (HIU) DP – 0.4 bar (based on Danfoss Lux II model (Danfoss, 2012).

- HIU Heat Loss – 20 W (CPP, 2011)
- User Basis – 30% (low) / 40% (mid) / 30% (high) (i.e. 'average' modelled behaviour is used for standard analysis)
- Demand Factor – 95% (see 3.6.1)
- Lifetime Demand Change over 40 years – 0%

Appendix B Space Heating Calculation Method

As outlined in 3.3.2, the SAP 2012 (BRE, 2013) method has been used for monthly heat demand calculations. The method incorporates a detailed calculation of the internal heat gains and the Heat Loss Parameter (HLP) for a dwelling. For this study a simplified approach was taken, considering only major non-heating gains.

The calculation method is as follows:

$$Heat\ Loss\ Parameter\ (W/K) = Fabric\ Loss + Vent\ Loss + Thermal\ Bridge\ Loss \qquad (B1)$$

$$Fabric\ Loss = (U_{wall} \times Wall\ Area) + (U_{roof} \times Roof\ Area) + (U_{floor} \times Floor\ Area) + (U_{opening} \times Opening\ Area) \qquad (B2)$$

$$Vent\ Loss = 0.33 \times Volume \times Air\ Changes\ per\ Hour \qquad (B3)$$

$$Thermal\ Bridge\ Loss = Thermal\ Bridge\ Factor \times (Wall\ Area + Roof\ Area + Floor\ Area + Opening\ Area) \qquad (B4)$$

for 'Thermal Bridge Factor' definition, see C6.

Using the calculated HLP, or a previously calculated HLP from SAP calculations, the monthly heating demand can then be calculated from monthly average ambient and mean internal temperature (MIT), with an allowance made for other heat inputs (gains).

The additional gains (in Watts) included from the SAP 2012 model for space heating per household is a simplified version including only major gains as follows:

$$Solar\ (W) = 0.9 \times Window\ Area \times MVSR \times WT \times Overshading \times Frame\ Factor \qquad (B5)$$

where MVSR = Mean Vertical Solar Radiation, and WT = Window Transmittance

Overshading and Frame Factor are SAP definitions relating to degree of shading of sunlight for the dwelling and a window design factor respectively. See BRE (2013) for full details.

$$Cooking\ Gain\ (W) = 35 + (7 \times N) \qquad (B6)$$

where N = number of occupants

$$Net\ Occupant\ Gain\ (W) = (50 - 40) \times N \qquad (B7)$$

$$Annual\ Electrical\ Demand\ (AED)(kWh) = 207.8 \times (Total\ Floor\ Area \times N)^{0.4714} \times EF \qquad (B8)$$

where, EF is a factor between 1 and 0.67 depending on the use of efficient appliances and behaviour.

$$Electrical\ Gain\ (W) = (1 + 0.157 \times \cos(2\pi(N - 1.78)/12)) \times AED \times 1000\ /\ (24 \times 365) \qquad (B9)$$

$$Annual\ Lighting\ Demand\ (ALD)(kWh) = 59.73 \times (Total\ Floor\ Area \times N)^{0.4714} \times LF \qquad (B10)$$

where, LF is a factor between 1 and 0.5 depending on the proportion of low energy lights used.

$$Lighting\ Gain(W) = (1 + 0.5 \times \cos(2\pi(N - 0.2)/12)) \times ALD \times 1000 / (24 \times 365) \qquad (B11)$$

$$Total\ Gains(W) = \sum Individual\ Gains \qquad (B12)$$

$$Gain/Loss\ Ratio\ (GLR)(W) = Total\ Gains\ /\ HLP\ /\ (MLRT - MAT) \qquad (B13)$$

where MLRT = Mean Living Room Temperature and MAT = Mean Ambient Temperature

$$Useful\ Gains(W) = (1 - \exp(-1.25)\ /\ GLR) \times Total\ Gains \qquad (B14)$$

$$Gains\ Temp\ Rise\ (GTR)(^{o}C) = Useful\ Gains\ /\ HLP \qquad (B15)$$

$$Space\ Heating\ Required\ (kWh) = (HLP \times (MIT - GTR - MAT) \times Hours)\ /\ 1000 \qquad (B16)$$

where MIT = Mean Internal Temperature

Appendix C Building Fabric Selection Basis for Model

C.1 Wall U-Value

For pre-1919 dwellings, solid walls with no insulation improvements are assumed. Only 3% of solid wall UK houses have further insulation measures (DECC, 2013b). In Scotland, the figure given is 11% for 'Solid/Other' wall construction (ScotGov, 2012a). However, this basis can also be used for any modern building with solid walls and is therefore not directly applicable.

For dwellings built between 1919 and 1976, the original wall U-value basis of 1.7 (EST, 2004) is assumed to have been improved to an average value of 0.9, based on a typical improvement to 0.7 using cavity wall insulation (BRE, 2008). In Scotland, 66% of pre-1983 houses that have cavity walls have been insulated (ScotGov, 2012a). The value is higher for social housing due to associated energy efficiency regulations, therefore a conservative value of 0.9 has been used as community heating is likely to be focused in this area.

Using similar logic a value of 0.7 is selected for housing in the 1976-1983 period based on a 1.0 uninsulated (EST, 2004) and 0.54 insulated U-value (BRE, 2008). After 1983, insulation was a mandatory requirement and no further improvements over the original value are expected.

Post-2007, the minimum 'backstop' and 'nominal' U-values are taken from the Building Regulations (ScotGov, 2013f).

The 'zero carbon' and '70% ZCH' future updates are estimated based on a 'zero carbon' Code 6 compliant test project (EST, 2011a) and an intermediate basis between the 2014, and 'zero carbon' requirement. These are further defined in 3.4.

C.2 Roof U-Value

The 2011 Scottish House Condition Survey (ScotGov, 2012a) shows that only 6% of social housing and 16% of private dwellings have less than 100mm of loft insulation. The average is slightly less than 200mm for private dwellings and slightly over 200mm for social housing.

A typical depth of 200mm roof insulation is predicted for all dwellings giving a U-value of 0.2 (EST, 2004). This is assumed to be valid for all housing ages and types up to 2002, when more stringent requirements take effect.

Post-2002, the minimum 'backstop' and 'nominal' U-values are taken from the Scottish Building Regulations (ScotGov, 2013f).

The 'zero carbon' and '70% ZCH' future updates are estimated based on a 'zero carbon' Code 6 compliant test project (EST, 2011a) and an intermediate basis between the 2014, and 'zero carbon' requirement. These are further defined in 3.4.

C.3 Opening/Glazing U-value

For simplicity the analysis assumes that all openings in a dwellings have the same U-value. In general, U-values for doors and windows of a similar age are consistent, and the door opening area is typically much smaller.

Up-to-date statistics on the extent of full double glazing in Scotland are unavailable. Latest data for England shows that 85% of social housing and 72% of private housing have full double glazing, with only 10% and 9% respectively having no double glazing at all (DCLG, 2012). Data from 2004, showed that England and Scotland had similar levels of full and partial double glazing (Utley and Shorrock, 2008), and this trend is assumed to have continued. Scottish data from 2006 showed that the majority of houses without any double glazing are pre-1919 housing, 37% vs 13% average (ScotGov, 2008).

For pre-1919, c.70% double glazing is expected giving an average U-value of 3.6 (3.1 if double glazed, 4.8 if not (EST, 2004)).

For a 1919 to 2002 dwelling, standard double glazing with a 3.1 U-value is assumed (BRE, 2013).

Post-2003, the minimum 'backstop' and 'nominal' U-values are taken from the Building Regulations (ScotGov, 2013f).

The 'zero carbon' and '70% ZCH' future updates are estimated based on a 'zero carbon' Code 6 compliant test project (EST, 2011a) and an intermediate basis between the 2014, and 'zero carbon' requirement. These are further defined in 3.4.

C.4 Floor U-value

The housing used for the case studies shows an average ground floor area of between 60 and 70 m^2. This gives a typical perimeter to area ratio between 0.45 and 0.5. Assuming the majority of pre-1992 floors are uninsulated, this gives a typical U-value between 0.63 and 0.7, with 0.65 selected, based on the SAP 2012 method (BRE, 2012). This compares to 0.6 from EST (2004), although they admit their estimate is highly building size dependent.

The value of 0.45 for the 1992-2002 period is taken from EST (2004). From 2003 onwards, the value is taken directly from the Building Regulations (ScotGov, 2013f).

The 'zero carbon' and '70% ZCH' future updates are estimated based on a 'zero carbon' Code 6 compliant test project (EST, 2011a) and an intermediate basis between the 2014, and 'zero carbon' requirement. These are further defined in 3.4.

C.5 Air Infiltration

Consistent and reliable data on air changes per hour is difficult to source. Testing of traditional Glasgow tenements with double glazing has shown a 17 ach^{-1} @ 50 Pa level, which is equivalent to 0.85 ach^{-1} under ambient (@ 0Pa) conditions (JGA, 2013). (ach^{-1} = air changes per hour)

For 1919, a value of 1.0 ach^{-1} is used to account for the smaller proportion (c.70%) of properties that have double glazing from this period. This is equivalent to the SAP 2012 assumption of 25 $m^3/hr/m^2$, if air tightness is unknown in older building (BRE, 2013).

For 1919-1992, 0.85 ach^{-1} is used which is consistent with the 100% double glazing assumption (BRE, 2013).

For 1992-2002, limited information is available. A value of 0.7 ach^{-1} has been used in line with the Biomass Decision Support Tool (BDST) (Carbon Trust, 2013).

For 2003-2010, a value of 10 $m^3/hr/m^2$ is used, based on the English Building Regulations requirement from 2006 (PlanningPortal, 2013), equivalent to 0.5 ach^{-1} at ambient conditions. Again as per BDST.

For 2011, an air permeability rate of <7 $m^3/hr/m^2$ is stipulated in the Scottish Building Regulations (ScotGov, 2013f). This is equivalent to an air change rate of 0.3 ach^{-1} at ambient conditions.

The minimum recommended air infiltration rate without all-house ducted Mechanical Ventilation with Heat Recovery (MVHR) system is 5 $m^3/hr/m^2$, equivalent to approximately 0.25 ach^{-1} at ambient conditions (ZCH, 2012). This is the level expected for the 'zero carbon' house using passive or small intermittent fans without a full MVHR system.

For a Passivhaus a value of 0.03 ach^{-1} is selected based on the Passivhaus standard (BRE, 2012).

C.6 Thermal Bridge Factor

Thermal bridging accounts for increased heat transfer in buildings at joints between elements, and around openings. A thermal bridge factor (TBF) is applied depending on the degree to which this heat loss has been reduced by the building element and joint design.

As per SAP 2012 (BRE, 2013), where no specified design or improvement is used or expected, a factor of 0.15 W/m^2K should be used. This is assumed for all buildings up to 2007.

An improved value of 0.08 W/m^2K can be assumed for building built with Accredited Construction Details (ACD), 0.04 if with Enhanced Construction Details (ECD) (EST, 2009), or a full calculation can be made as per SAP 2012 (BRE, 2013).

For 2008-2010, partial use of ACD compliant design is assumed, with an average TBF of 1.0.

For the 2010 and 2014 Building Regulations 'nominal' fabric cases, a 100% ACD compliance value of 0.08 is selected.

For the '70%ZCH' and 'zero carbon' 'nominal' fabric cases, a 100% ECD compliance value of 0.04 is selected.

Values for the 'backstop' fabric levels from 2010 onward are higher as shown in Table 2.

C.7 Window Solar Energy Transmittance

In addition to thermal transmittance, another key factor for window design is the solar energy transmittance factor. This value is the proportion of normal incident radiation that passes through the window to heat the room. As per SAP 2012, this varies from 0.85 for a single glazed window to 0.57 for a triple-glazed window with soft, low-e coating (BRE, 2013). No single glazed windows are assumed for any age of house. Gradual improvement from standard (0.76) to soft, low-e coating (0.63) double glazing is predicted up to 2015-2018 (backstop) level, with triple glazing (0.57) assumed beyond that level.

Appendix D Scottish Average Occupancy Analysis

The following section details a review of Scottish average household occupancy data.

D.1 Number of Occupants

Simple analysis of Scottish Census data shows that in 2001 there were 2.27 people per household, falling to 2.19 in 2011. Average house size data is not yet available for 2011, but was 4.75 habitable rooms (not inc. bathrooms, storage etc.) in 2011 (Scrol, 2013). The 2007-2008 Scottish Housing Survey (UKDS, 2013) shows an average number of bedrooms of 2.66. Therefore, on average, there are approximately 0.46 people per habitable room and 0.82 people per bedroom in Scotland.

Data from the 2009-2011 Scottish Housing Condition Survey (ScotGov, 2012b) shows that over 45.7% of social housing is 1-person and 28.0% is 2-person. This compares to 26.0% and 39.7% for private housing, presumably based on the difficulty for single people to afford to rent or buy alone.

Data based on income bands (NRS, 2013a) corroborates this with an increasingly high percentage of 1-person households at lower income levels. It also shows lower median habitable room numbers at lower income levels, but not to decimal place accuracy so it is difficult to use this data usefully.

Statistics from the Scottish Federation of Housing Associations (SFHA, 2013b) shows that 29% of Housing Association properties are bedsit/1-bed properties, 45% are 2-bed, and 22% are 3-bed. This highlights that the available stock does not currently match needs, particularly as the data suggests that the majority of 2-person households are co-habiting. New developments may address this discrepancy with a higher proportion of smaller properties so care needs to be taken if this is the case.

The impact of the social housing occupancy penalty (the 'bedroom tax') introduced in 2013, has also yet to be understood. This may increase general occupancy but the discrepancy between available house size and household size may restrict this (SFHA, 2013b).

Without statistically verifiable data at finer detail, the figure of 0.46 per habitable room is used to generate a 'Scottish Average' occupancy basis for the model. (Census data is available at very small geographical resolution (Scrol. 2013) that would allow this estimate to be improved for specific locations). For a mixed tenure area of a significant size this should be a reasonable assumption, but less useful for smaller, single tenure developments.

D.2 Number of Children

In Scotland, the average number of children per household is 0.49 (Scrol, 2013). To obtain a reasonable assumption of number of children per house size, it is assumed that each house has one main adult bedroom and that above 4 bedrooms, 4 occupied bedrooms are assumed. This gives an approximation of 0.30 children per non-main bedroom up to 3 (based on average of 2.66 bedrooms).

For children under 5 years of age, the 2001 census gives a total of 225,470 applicable households out of 2,191,250 (Scrol, 2013). (Updated results from the 2011 census are not yet available). The model therefore assumes 10.3% of households have a child under 5. As for total number of children, it is expected that 1-bed households have no children. Therefore the proportion of 2+ bed properties with children under 5 increases to 14.5%.

D.3 Pensioner (OAP) Occupancy

Detailed 2001 Census data has 31.2% of Scottish household with a least one pensioner (Scrol, 2013). The figure from the smaller 2009-1011 SHCS survey (ScotGov, 2012b) is 31.5%. This increase is consistent with the recently published 11% increase in over 65s between 2001 and 2011 (NRS, 2013b). Unlike for children, a reasonable assumption of the likelihood of a pensioner being present with house size is difficult. It is therefore assumed that there is a 31.5% chance of a pensioner being present in all dwellings, unless the location (as per Glenshellach) is clearly unsuitable for older residents or housing is designated for pensioners only.

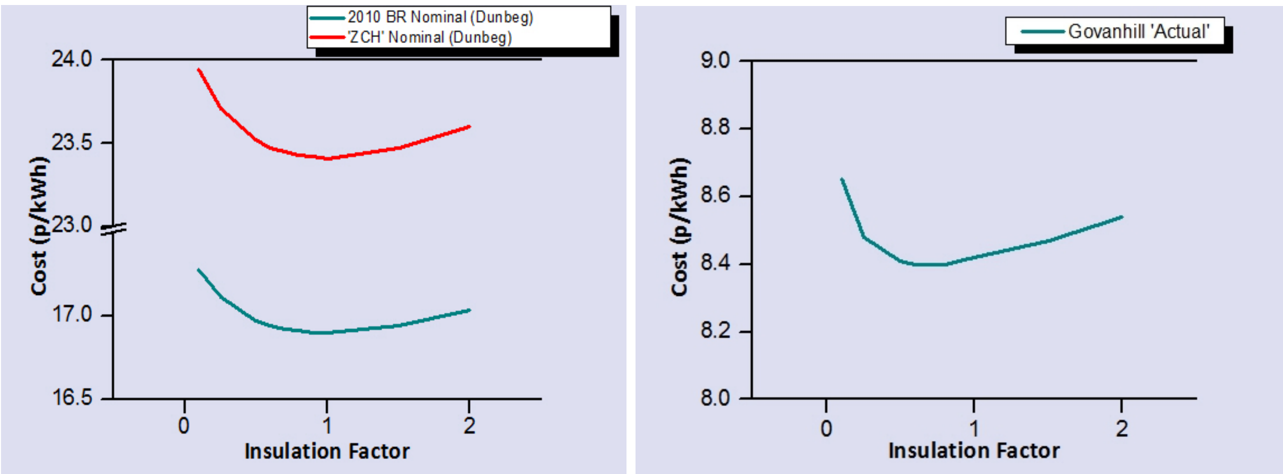
Appendix E Optimum Insulation Thickness Analysis

Increasing piping insulation thickness reduces heat loss but increases installed pipe cost. There should therefore be an optimum thickness that reduces lifetime cost to a minimum. As outlined in 2.2.2, piping is typically available with three insulation levels, 'standard', 'plus', and 'plus-plus'. The following analysis was undertaken to confirm the most effective insulation level for the analysis.

Assuming installed cost varies linearly with diameter in proportion to the 10% difference between 'standard' and 'plus' sizes, it can be shown that for the Dunbeg case study (max pipe size = 40mm), the impact of lifetime cost on the balance between construction and heat loss costs is relatively small up to 'plus' size (see Figure E1a). However, the optimum value is around the 'standard' insulation level. There is also no difference in the optimum thickness due to the reduction in demand between 2010 and 'zero carbon' housing basis, assuming no line size changes are possible.

For the Govanhill case study model, which is a mix of 160mm and 90mm single pipes, the optimum insulation level was slightly less than the 'standard level' but the cost impact is negligible (see Figure E1b).

Figures E1a and E1b show the consolidated results of this analysis. Insulation factor is based on factoring insulation layer thickness based on 1.0 for 'standard' insulation, and is not directly comparable to actual sizes, such as 'plus'. For 'twin' pipe, 'plus' is approximately 2.1, and for 'single' pipe approximately 1.5.



Figures E1a and E1b: Cost impact of different pipe insulation factors for Dunbeg and Govanhill

In all cases the 'standard' insulation level is the optimum available thickness. This has therefore been used as the basis for all modelling analysis undertaken.

Appendix F Radiator Sizing Method

The following section details the radiator sizing method used for the costing of additional heating system surface area requirements for lower temperature networks. See 2.2.3 and 6.1 for lower temperature system analysis.

Radiator pricing taken from several sources can be approximated by £0.2/W capacity at a 50°C delta T (20°C room temp). For the model a standard 50°C delta- T system is modelled to have zero cost for a new-build and the appropriate integration cost for existing housing. An additional cost is added based on the following equation to reflect the additional capital cost of a low temperature system:

$$Low\,Temp.\,Heating\,Cost\,Adder\,(\pounds)=(Peak\,Heat\,Demand\,(W)\times 1.25)\times(\pounds\,0.2)\times MAF \quad (F1)$$

The mean temperature of the radiator system is set to be the mean temperature of the heat network for simplicity. The zero-cost baseline is set to be a 80/60°C system with 70°C mean temperature and 50°C (70-20°C) delta-T between radiators and room (as per BS EN 442 (BSI,2003)). Installed radiator capacity is calculated to be 25% higher than peak demand to allow for heat-up, spare capacity, and uprating of other minor components. The area correction factor (MAF) converted from BS EN 442 heat output factors is determined as follows:

Delta-T (C)	BS EN 442 Factor	Model Area Factor (MAF)
50	0.798	0.0
45	0.700	0.14
40	0.605	0.32
35	0.512	0.56
30	0.423	0.89
25	0.338	1.36
20	0.256	2.12

Table F1: Radiator size factors for various delta-T values based on BS EN 442