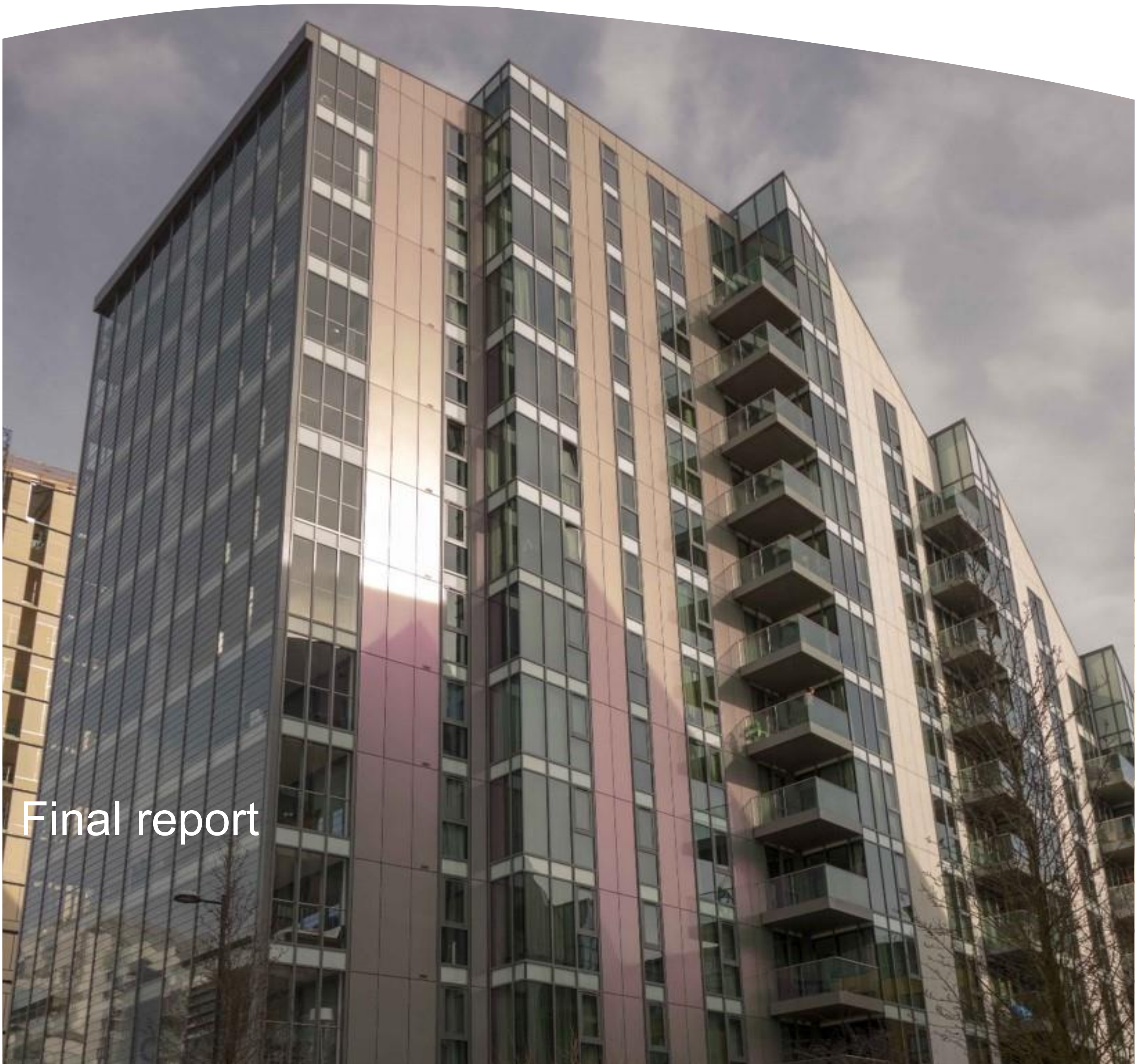
Department of Energy & Climate Change

Heat Pumps in District Heating



Final report

Heat Pumps in District Heating

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This study was undertaken for DECC by Element Energy and Carbon Alternatives.

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1. Executive Summary

Context, objectives and methodology

The government's Strategic Framework for Low Carbon Heating in the UK identifies heat networks as an important element of the decarbonisation of heat in buildings. However, to realise significant emissions reduction using district heating, the heat in the networks must be provided from low carbon sources. As the electricity grid also decarbonises, this presents a potential opportunity to use heat pumps to deliver heat from sources to networks and from networks to buildings.

This study explores the ways in which heat pumps can be integrated into heat networks, to understand which types of scheme could be economically and environmentally beneficial in a UK context. The approach combines data collection from existing schemes across Europe with modelling of promising schemes for the UK. A wide range of existing schemes have been studied and the suitability of heat pump technology for new and existing network designs investigated. In conjunction, a simulation model of heat pumps in district heating has been developed and used to gain insight into the relative benefits of different types of network, heat pump technology and ancillary heating plant. The results are presented in this report in terms of the cost premium of each scheme compared to a conventional district heating network, the CO_2 emissions reduction, and the cost of CO_2 saved.

Data collection and case studies

The integration of heat pumps in heat networks is relatively new in the UK; however, elsewhere in Europe successful schemes have been running for over a decade. Through interviews with scheme operators and a literature search in several languages, data were gathered from more than 50 operational schemes to capture the range of uses of heat pumps in heat networks. This information was supplemented by a second strand of data collection focussing on heat pump technology and its level of readiness to provide heat to/deliver heat from networks. To understand this, interviews were carried out with heat pump manufacturers and installers in the UK and Europe.

A summary of findings from the data collection is highlighted below:

1) Scheme types can be classified by the role of the heat pump: delivering heat to a network, or from a network, or both:

    - A common setup involves the retrofit of a large-capacity heat pump into an existing network, either alongside existing conventional heating plant or integrated with the conventional plant to provide heat recovery. The networks usually operate above 70°C and the heat pump sink temperature is often below the network temperature to increase heat pump efficiency. A large range of heat sources are used, and some larger schemes use different heat sources at different times of year.

- New build networks serving thermally efficient buildings, as can be found in small-scale developments in the UK, are able to operate at lower flow temperatures, thus increasing the efficiency of heat pumps providing heat to the network. Hot water can be provided either using separate systems, or using the network for preheating and electric immersion or booster (micro) heat pumps to further raise the temperature.
- Schemes exist in which the network operates at even lower temperatures – as low as 10-20°C. This temperature is then increased within the buildings, using small heat pumps using the network as a heat source and providing space heating and hot water. Although the cost of these schemes can be high due to plant requirements, these schemes are advantageous in terms of the reduction in thermal losses along the network.

2) Each of the above three types of scheme can be made more economically favourable if cooling demand is also present:
    - Cooling is sometimes the driver for installing a heat pump as opposed to other technologies.
    - Where heating and cooling loads are balanced either simultaneously or over a year, this presents the opportunity for a number of efficient heat pump/heat network scheme types, using either one common network with reversible heat pumps, or connecting heat pumps between a heating network and a cooling network.

3) Success of each scheme type is context specific
    - Economically viable schemes are found at sites/in countries where electricity price is favourable compared to other heating fuels.
    - There is no one ‘best’ scheme type for a UK context; each presents advantages and disadvantages.

From the data collection, four schemes of potential relevance for the UK were selected for further investigation as case studies:

- Helsinki city centre: a large high temperature network into which a 82 MW heat pump was retrofitted;
- Wandsworth Riverside, London: an aquifer thermal energy storage system using heat pumps for space heating and cooling in a new development of apartments;
- Duindorp, Netherlands: a novel low temperature network connected to a new development of apartments, each with its own heat pump;
- Brooke Street, Derbyshire: a ground source heat pump and heat network retrofitted to a small number of homes in an off-gas area.

Development of a simulation model

A flexible model has been developed and populated with data to enable different heat pump in district heating scheme types to be explored.

The user sets up a scheme combining thermal demand from a group of buildings with supply from a heat pump/network system, with the option of also setting up a counterfactual network with no heat pumps for comparison. The model contains a range of customer archetypes, including both domestic and non-domestic buildings, and area archetypes, which can be combined in various proportions in order to define the heat load on the network and key network design parameters, such as the lengths of heat pipe, number of connection points and so on. The scheme is evaluated over a certain lifetime, to allow for evolution of fuel and carbon price and decarbonisation of the electricity grid. The model then uses an hourly simulation algorithm to dispatch heat to the network and to the buildings, and to calculate key outputs including:

- Price of heat, p/kWh
- Scheme Total Cost of Ownership (TCO)
- CO_2 emissions over the scheme lifetime
- Seasonal coefficient of performance (COP) of heat pumps

The data collection exercise highlighted the importance of treating cooling along with heat demand and this functionality is integrated into the model. The technologies which can be incorporated together to supply the demand are shown below.

Category	**Heating**	**Cooling**
Heat sources and types of central heat pumps	• Water source • Ground source	• Water-source HP • Ground-source HP
Central additional plant	• Gas-CHP, Gas boiler • Oil-CHP, Oil boiler • Biomass-CHP, Biomass boiler	• Gas absorption chiller • Oil absorption chiller
Central storage	• Thermal storage (hot)	• Thermal storage (cold)
Building-integrated HP (using network as heat source)	• Water source for space heating and DHW • Water source for DHW only (micro heat pumps)	• Water source for space cooling
Additional heat sources	• Waste heat • Solar thermal	• None
Building-integrated additional plant	• Electric immersion heater	• Electrical chiller

Analysis using the model

The model was used to explore a number of potential scheme configurations that are relevant to the UK. Four scenarios were derived for detailed analysis, based on characteristics of existing schemes across Europe:

- **Scenario 1**: large-scale, high temperature network with a central heat pump serving existing non domestic buildings (where the counterfactual is based on gas CHP);
- **Scenario 2**: medium-scale, low temperature network with a central heat pump and building-integrated heat pumps, serving new build flats (where the counterfactual is based on gas CHP);
- **Scenario 3**: small-scale, medium temperature network with a central heat pump, serving new build flats, where the network serves space heating directly and DHW is provided by electric immersion heating (where the counterfactual is based on gas boilers);
- **Scenario 4**: small-scale, medium temperature network with a central heat pump, serving new build flats, where the network serves space heating directly and DHW is provided by building-integrated heat pumps (where the counterfactual is based on gas boilers).

Three pieces of analysis were undertaken using these scenarios:

- How does the performance of each heat pump scheme compare to a gas-based counterfactual in each scenario?
- How do the heat pump schemes in the above scenarios compare to one another when used to serve the same heat demand?
- Are there promising types of heat pump in district heating scheme in which the cost can be brought down to a level comparable to a conventional district heating scheme without heat pumps?

Key findings

Alongside a decarbonising grid, integrating heat pumps into district heating offers large CO_2 emissions reduction potential

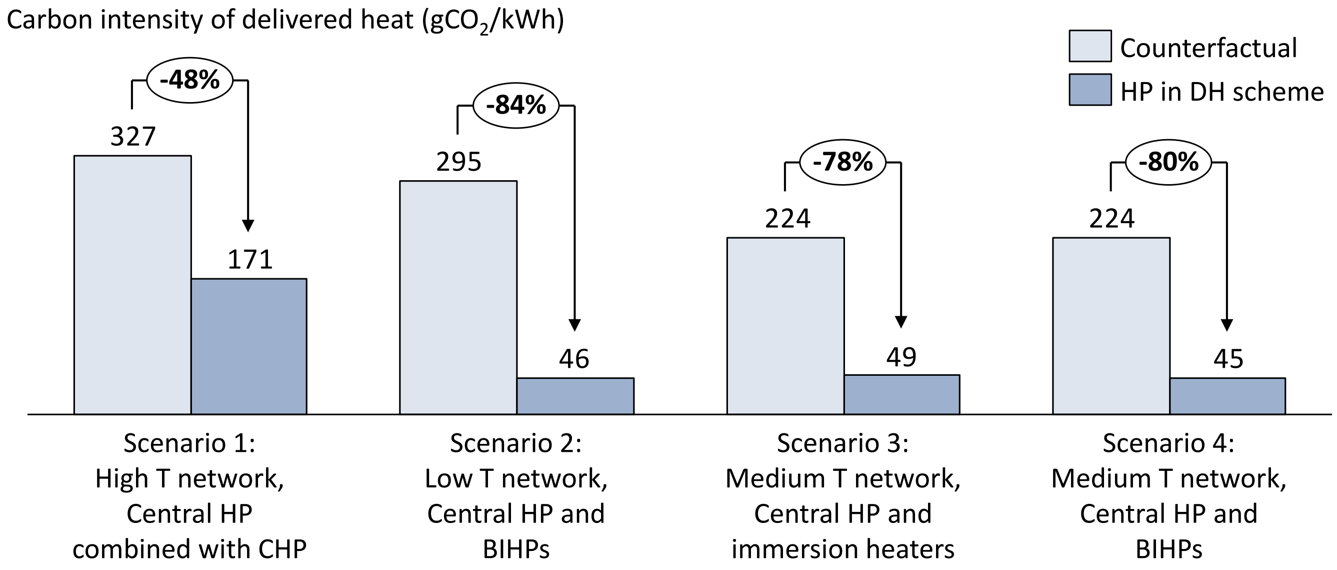
The scenario analysis undertaken using the model showed that incorporating heat pumps into district heating schemes has the potential, in the context of a rapidly decarbonising electricity grid, to offer large CO_2 savings relative to a counterfactual of district heating based on either gas-CHP (for large schemes) or gas boilers (for small schemes). Assuming the current trajectory towards low carbon electricity generation, we found CO_2 savings versus the counterfactual scheme in the range 48-84% across the four core Scenarios, as shown in Figure 1[1].

As may be expected from simple thermodynamic arguments, we showed that the CO_2 savings are greater where the following scheme characteristics are combined:

- Heat pumps provide a larger fraction of the heating
- Heat pumps operate with a lower source-sink temperature difference, leading to increased efficiency
- Network thermal losses are lower, typical for lower temperature networks

As a result, we have found that of the various configurations studied, low or medium-temperature networks based entirely on heat pumps offer the greatest CO_2 savings potential.

Figure 1: Comparison of the carbon intensity of delivered heat for the counterfactual[2] and the HP in DH scheme for each of the four Scenarios studied (using the Central sensitivity assumptions).



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[1] The four core Scenarios describe district heating schemes serving a range of different areas/buildings, from a large-scale area of existing mixed-use buildings to a small-scale, new residential development. Therefore, the counterfactual scheme is in general different in each case.

[2] The counterfactual is based on gas CHP for Scenarios 1 and 2, and gas boilers in Scenarios 3 and 4.

A number of promising scheme types are identified for specific situations

Analysis on ways to increase the cost-effectiveness of heat pumps in heat networks yielded several promising solutions:

- In schemes in which there is CHP installed as part of the heating strategy, the use of heat pumps powered by CHP electricity and also to recover waste heat from CHP operation leads to running cost potentially being brought down enough to offset the increased capital cost associated with the heat pumps.

- In schemes in which there is scope to lower the network temperature (i.e. when supplying thermally efficient buildings), doing this is beneficial, with the majority of the benefit being attributed to enhanced heat pump performance as opposed to reduced network losses. A limiting factor for lowering the network temperature is the temperature at which DHW is supplied; if the network temperature, serving the space heating, is lower than the DHW supply temperature then additional heating plant is needed to upgrade it for DHW provision. In contexts where demand is relatively low, however, then this can be a cost-effective solution.

At current costs, the price of heat is likely to be significantly higher for district heating schemes incorporating heat pumps

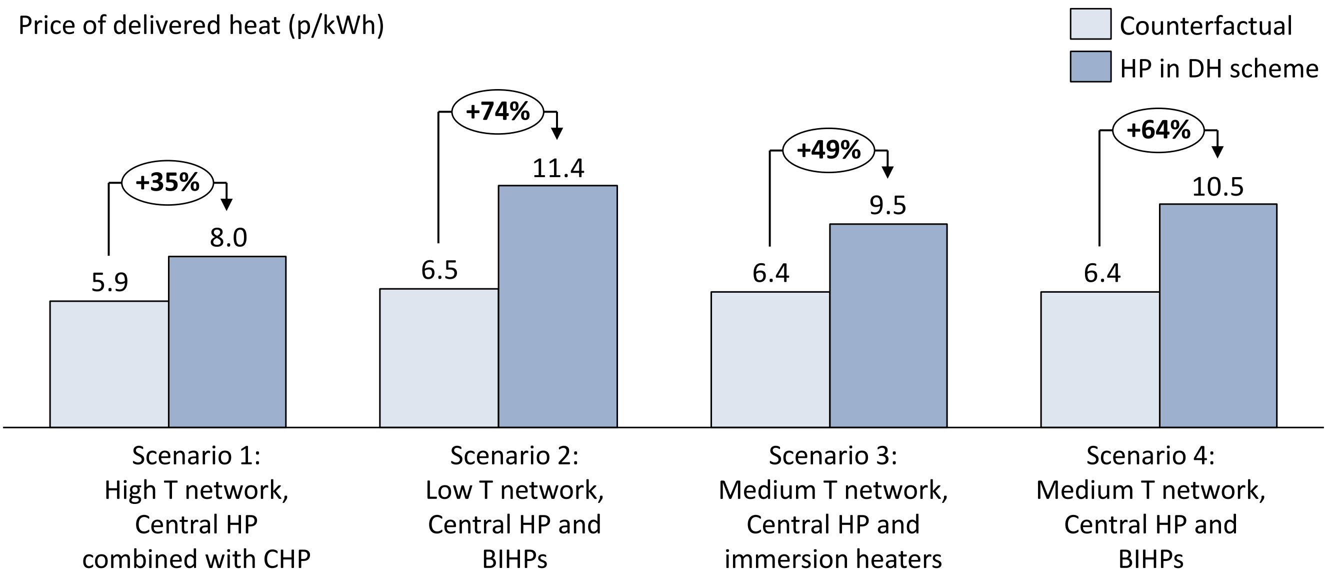
However, we have found that at current costs, heat pump in district heating schemes are likely to provide heat at a higher cost than the counterfactual gas-based district heating schemes.

As shown in Figure 2, the premium for the price of heat for district heating schemes incorporating heat pumps is in the range 35-74%. The main reasons for this include:

- High capital cost of heat pumps (particularly MW-scale heat pumps)
- High electricity price compared to gas price, projected to continue over the next few decades
- Lost revenue from electricity sales when compared with schemes involving gas-CHP
- Higher capacity of heating plant required (versus gas-based district heating) where building-integrated heat pumps serve the peak demand in individual dwellings
- Higher network costs (versus gas-based district heating) where low temperature networks require larger diameter pipes (assuming conventional pipe materials are used)

It is important to note that heat pumps bring potential additional benefits that may shift the economic balance in their favour compared to the counterfactual. In particular, the ability to provide cooling as well as heating has been found to be a key driver of the use of heat pumps in heat networks.

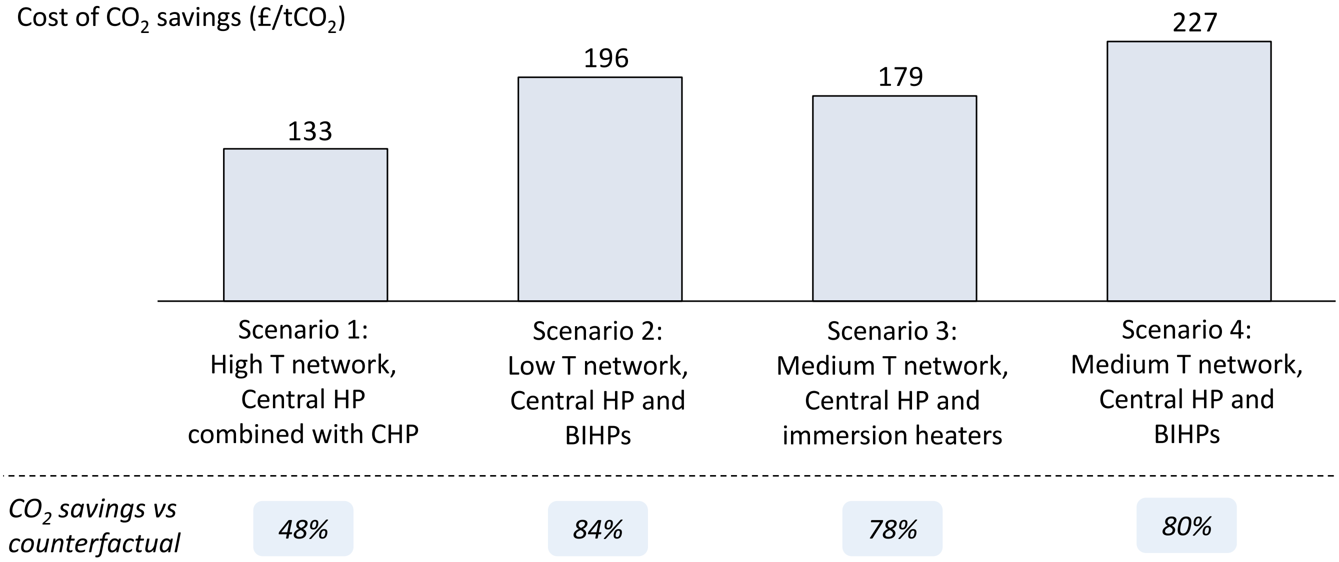
Figure 2: Comparison of the price of heat for the counterfactual and the HP in DH scheme for each of the four Scenarios studied (using the Central sensitivity assumptions).



The optimal scheme design will depend on the balance between cost and environmental objectives

In the four core Scenarios studied, we have found the cost of CO_2 savings for heat pump schemes versus the counterfactual to lie in the range £133-227/tCO_2, as shown in Figure 3. This suggests that if the large CO_2 savings promised by heat pumps are to be achieved, there will need to be a continuation of financial support for renewable heat and/or interventions to ensure a high effective price of carbon emissions.

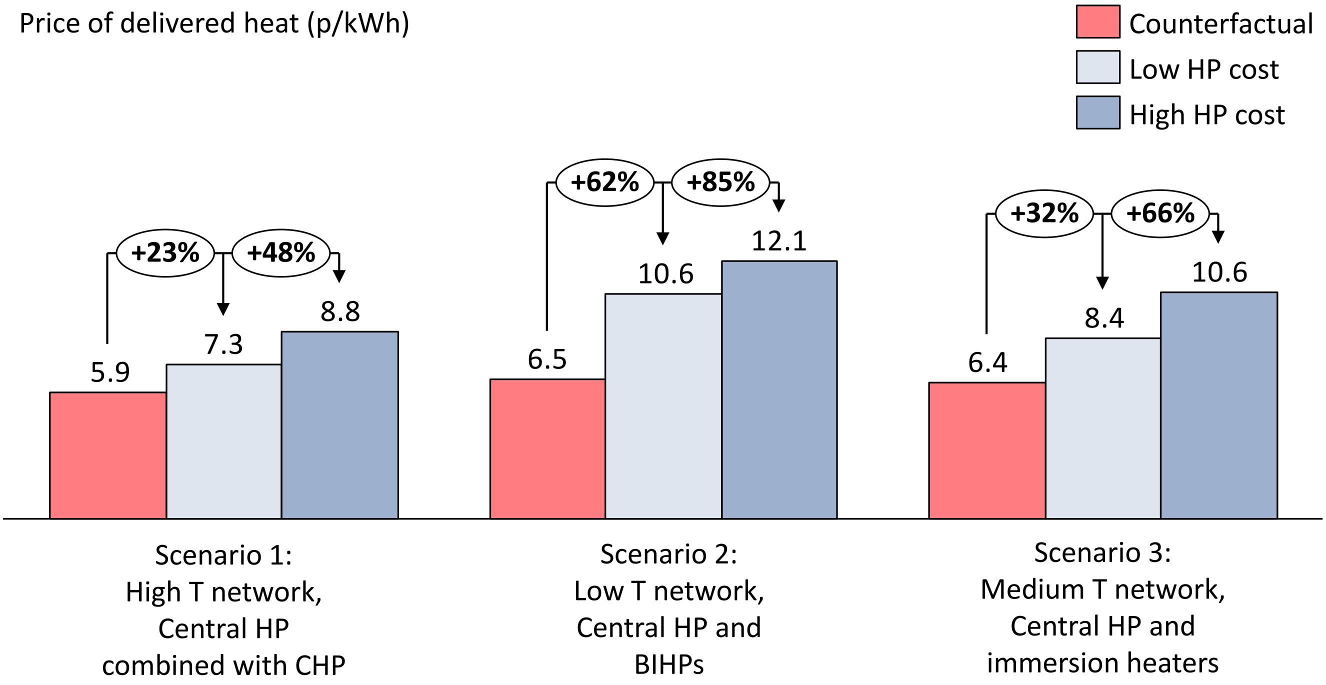
Figure 3: Cost of CO_2 savings of the HP in DH scheme versus the counterfactual for each of the four Scenarios studied (using the Central sensitivity assumptions).



The cost of large heat pumps carries significant uncertainty, and has a large impact on the price of heat

Due to the low number of operational schemes, there is significant uncertainty around the cost of large, bespoke (MW-scale) heat pump systems. We have therefore studied the impact of varying the cost of the large-scale centralised heat pump in our core Scenarios 1, 2 and 3. The range of Central HP costs studied is based on the range of costs gathered through our data collection exercise and industry consultation. Over this range, as shown in Figure 4, the premium for the price of heat versus the counterfactual scheme varies widely in each Scenario.

Figure 4: Impact on the price of delivered heat of varying the assumptions on the cost of the Central HP in Scenarios 1, 2 and 3.



Further deployment experience for heat pumps in district heating would reduce uncertainty around costs, and would be likely to lead to a reduction in costs through learning-by-doing. A detailed examination of the prospects for such future cost reductions is, however, beyond the scope of this study.

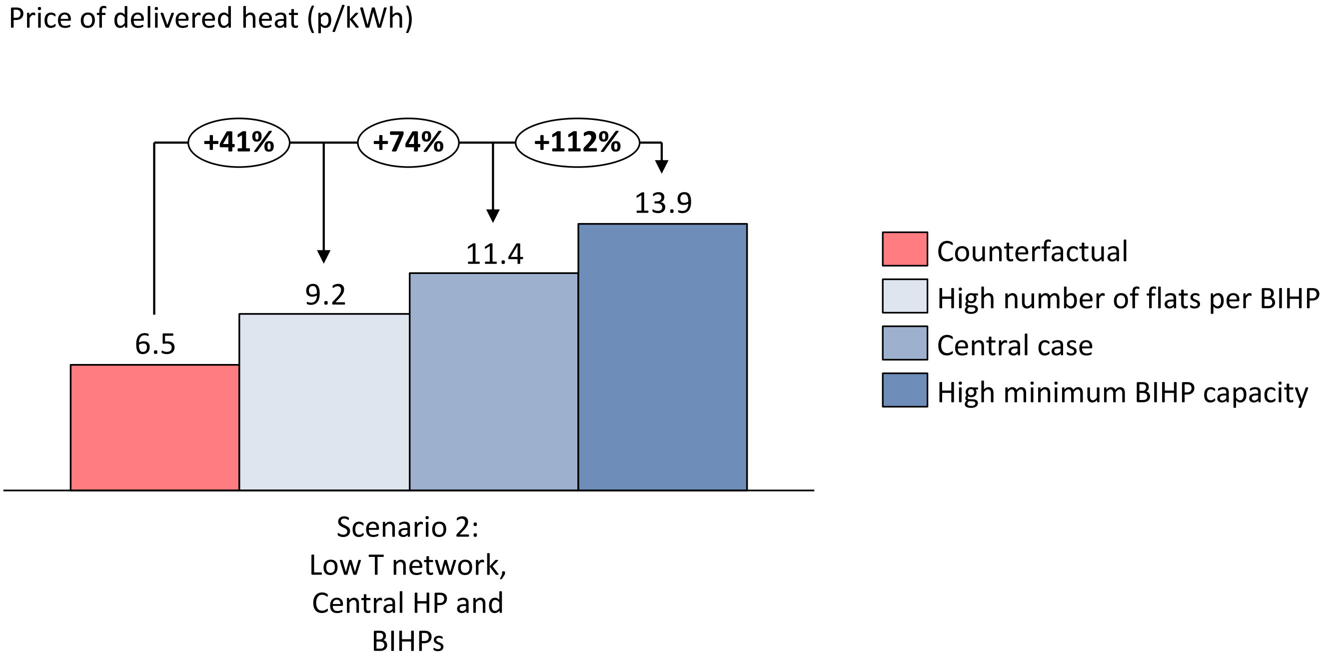
For schemes incorporating building-integrated heat pumps, the scheme design and operation will have a large impact on the price of heat

We have identified a number of important design decisions for schemes incorporating building-integrated heat pumps using heat networks as their source. Due to the relatively high cost of the heat pumps, equipment sizing is a key consideration. Using a separate heat pump to meet the heating and hot water demand in each dwelling – in the case of a residential development – is likely to entail significant oversizing outside times of peak demand unless substantial thermal storage is also installed. In the case of a development of new flats, in Scenario 2, we have studied the impact of installing either a 3 kW_{th} heat pump (the Central case) or a 6 kW_{th} heat pump (the High minimum BIHP capacity case). As shown in Figure 5, the price of heat premium under the High minimum BIHP capacity assumption increases to 112%, from 74% in the Central case.

On the other hand, it may be possible to reduce costs by serving multiple flats with a single heat pump to take advantage of the diversity of demand as well as the reduced cost on a per kW basis of larger heat pumps. Figure 5 shows the impact on the price of heat of serving a whole block of 40 flats with a single heat pump (the High number of flats per BIHP case); the premium on the price of heat versus the counterfactual falls to 41%.

Schemes involving large numbers of building-integrated heat pumps are also likely to entail additional operational and management issues, since heat pump operation cannot be optimised with respect to the rest of the system, unlike in the case of a central HP managed by a scheme operator. Experience from our Case Studies also suggests that building tenants are likely to use building-integrated heat pumps in a non-optimal way, further impacting on scheme performance.

Figure 5: Impact on the price of delivered heat of varying the assumptions on the number of flats served by each BIHP, and on the minimum BIHP capacity per flat in Scenario 2.



The optimum heat pump in district heating scheme design is strongly dependent on site-specific issues

In addition to our core Scenarios, which each compare a certain heat pump in district heating scheme configuration with a gas-based counterfactual, we compared a range of heat pump in district heating scheme configurations directly for two ‘Demand cases’:

- Demand case A: new buildings: small flats with low temperature space heating emitters. We investigated low, medium and high temperature networks for this demand case.
- Demand case B: existing buildings: commercial premises with conventional radiators. We investigated low and high temperature networks for this case, since medium temperature networks cannot provide high enough temperature heat for space heating.

A comparison of the total cost of ownership (TCO) and CO_2 intensity of heat for the relevant scheme configurations incorporating heat pumps for Demand case A is shown in Figure 6. It can be seen that, in this case, the ‘High T network with Central HP’ configuration is the most cost-effective, due predominantly to the high cost of installing building-integrated heat pumps (and immersion heating) in individual flats in the other configurations. Figure 7 presents the corresponding comparison for Demand case B. In this case, the ‘Low T network with Central HP and BIHPs’ configuration is more cost-effective. This is largely due to the high cost-effectiveness of installing building-integrated heat pumps to serve large non-domestic buildings, in which demand is more diversified than in individual dwellings.

As these two ‘Demand cases’ demonstrate, the most suitable heat pump in district heating configuration for a given site will be strongly dependent on a range of site-specific issues and design choices, as explored in greater detail in the body of this report.

Figure 6: Summary of TCO and CO_2 intensity of heat for the four HP in DH configurations studied for Demand Case A, a small-scale, new residential development.

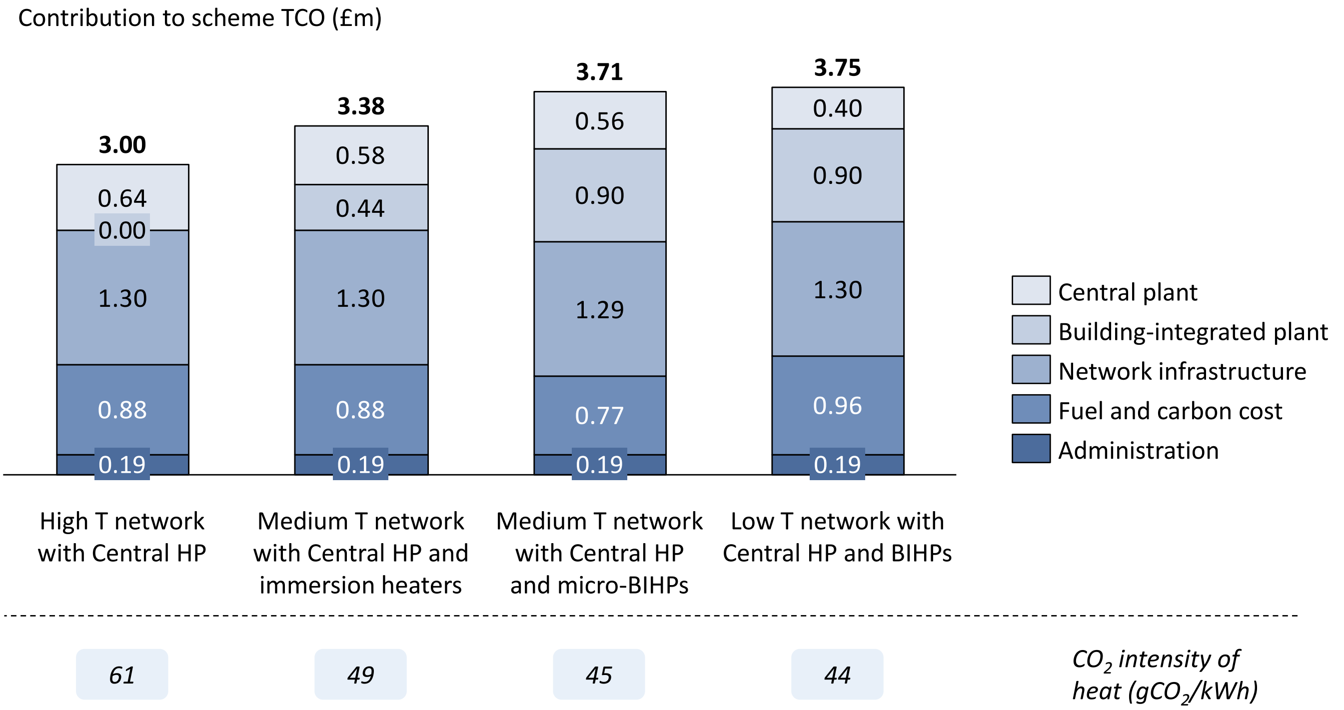
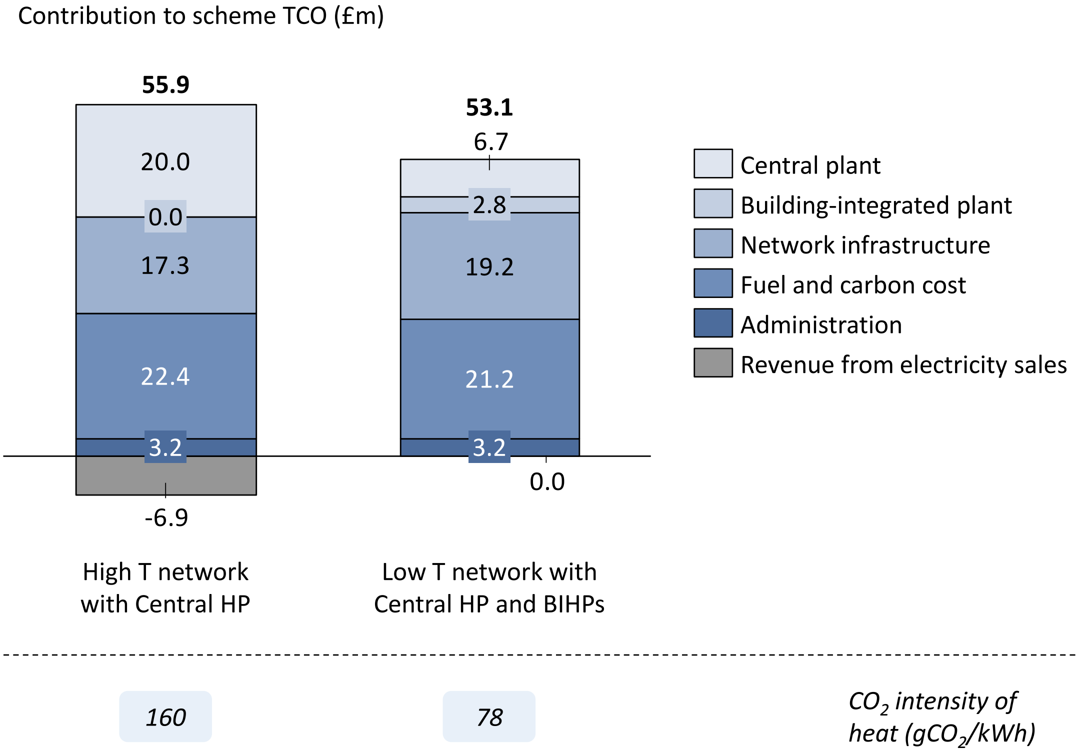


Figure 7: Summary of TCO and CO_2 intensity of heat for the two HP in DH configurations studied for Demand Case B, a large-scale mixed-use development of existing buildings.



2. Introduction

Context

The heat sector accounts for nearly half of all energy consumed in the UK and, of that heat, the great majority is used for space heating, hot-water and cooling in buildings. At present, most of this heating demand is met by the combustion of natural gas. According to the government's Carbon Plan[3], which sets out the scale of the challenge associated with meeting the UK's 2050 carbon emissions reduction target, the emissions from buildings will need to be reduced to near zero by 2050, implying almost complete decarbonisation of the heating sector. In response to this challenge, government has developed a Strategic Framework for Low Carbon Heating in the UK[4], which sets out a framework for solving the problem of drastically decarbonising the heating sector, while also providing secure supplies of affordable heat to support a growing economy.

One of the recognised pathways for delivery of low carbon heat is the shift away from natural gas toward electrified heating systems and a decarbonised electricity grid. In parallel with increasing electrification of heat supply, the strategic framework also recognises the potential for district heating networks to play a key role in delivery of low carbon heat to large parts of the UK's building stock particularly within dense urban areas. Heat networks can be considered an enabling technology and therefore only provide part of the solution. The challenge is to identify long-term sustainable sources of low carbon heat that can be coupled to heat networks in a cost-effective fashion in order to deliver an affordable, low carbon supply to end-users.

Heat pumps have potential to bridge across these two strands of the Strategic Framework for Low Carbon Heat. They are at the forefront of the strategy for electrification of heat and also promise to provide the means of integrating renewable heat with district heat networks, delivering low carbon heat supply into areas where the practicality of alternative, building scale low carbon options can be constrained by issues such as lack of space, access, air quality issues and so on. Adoption of large-scale heat pumps linked to district heat networks is also complementary with further strands of the low carbon heat strategy, such as increasing utilisation of low-grade heat sources, such as heat rejected from industrial facilities and thermal power stations and potentially also nuclear power stations.

Current penetration of heat networks in the UK is very low, with only around 2% of current heat demand in the building stock served by heat networks[5]. The majority of those heat networks that do exist are supplied heat by gas-fired combined heat and power (CHP) technology. However, in line with the objectives of the strategic framework for low carbon heat, DECC is providing financial support to stimulate greater adoption of heat networks, for instance through the Heat Network Delivery Unit (HNDU), which supports local authorities through the early stages of heat network development, from opportunity identification, through technical design and business planning, to the point of investable projects.

In parallel with these activities, DECC now wishes to better understand the role that heat pumps can play alongside heat networks, to deliver low carbon heating over the long-term. This report

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[3] HM Government, 2011. *The Carbon Plan: Delivering our low carbon future*

[4] DECC, 2012. *The future of heating: A strategic framework for low carbon heat*

[5] AECOM, 2015. *Assessment of the Costs, Performance, and Characteristics of UK Heat Networks*, Report for DECC

summarises research undertaken on existing and potential future schemes integrating heat pumps in heat networks, and implications for their role in UK low carbon heat strategy.

Objective

The purpose of this research is to investigate, from a UK perspective, the scenarios in which heat pumps can be integrated into heat networks, and to determine the performance of such schemes in terms of cost, energy and CO_2 emissions.

There is potential for heat pumps to be integrated into heat networks in a variety of configurations. Several examples operational in the UK or Europe are given below:

- Retrofitting a heat pump into an existing district heating scheme to provide a low carbon source of heat to the network;
- Using a low temperature heat network in conjunction with distributed heat pumps in buildings, to increase the temperature at or near the point of use;
- Linking buildings using a network which can be used as a heat source or heat sink for reversible heat pumps in each building, for high efficiency heating and cooling.

Given the range of possible scheme types, it is paramount to understand how heat pumps and heat networks could be integrated most effectively, since this presents a number of challenges. In particular, the high operating temperatures of conventional heat networks and the relatively low temperature of available heat sources can lead to low efficiencies. However, innovative approaches to overcoming these challenges have been developed, including the use of multiple heat pumps operating over smaller temperature ranges to improve efficiency, the seasonal use of heat pumps to raise the temperature of water sources in the winter, the use of new high temperature refrigerants and the redesigning of heat networks to operate at lower temperatures.

The aim of this study is to understand under which circumstances the use of heat pumps in district heating may be advantageous compared with the use of conventional fossil fuel-based heating plant, and which configurations of heat pumps in district heating are likely to be most appropriate for different types of district heating schemes in the UK. The approach is described below.

Approach

The study combines insights from existing schemes of heat pumps in heat networks with analysis using modelled schemes. The different aspects of the project, and how these link together, are described below:

- *Data collection: existing schemes and heat pump technology:* An appropriate starting point for this research was existing schemes in which heat pumps are already used in heat networks, across Europe and the UK. The first task consisted of collection of technical data from a large range of schemes (> 50), to ascertain the range of configurations (in this report, a *configuration* describes how the system is set up, in particular the role of the heat pump and the temperature of the network). Furthermore, to understand the technical aspects of heat pump design for suitability in heat networks, a consultation was undertaken with heat pump manufacturers and installers.
- *Case studies:* From the data collection, four schemes of potential interest for the UK were identified and investigated in more detail, in terms of the factors critical to success and lessons learned from their implementation.

- *Modelling and sensitivity analysis:* A bespoke model was created, populated from the data collection above, and used to simulate a range potential scheme types, to investigate economic and environmental costs and benefits of different configurations in a systematic way. Sensitivity analysis was undertaken to explore the key variables upon which success of certain configurations may depend. Scenarios were compared to one another and to conventional heat networks without heat pumps, and promising scheme types were identified.

Definitions

For the purposes of this report, the following definitions are adopted throughout:

- District heating/heat network: this consists of either:
    - Two or more distinct buildings connected to a single heat source
    - One building in which there are more than ten individual customers connected to a single heat source.[6]
- Central heat pump: a heat pump which provides heat to a heat network as opposed to a building directly,
- Building integrated heat pump (BIHP): a heat pump whose source is a heat network, and which provides heat to the space heating, DHW and/or cooling circuits
- Series additional plant: conventional heat sources in series with a heat pump, i.e. which use the heat output of a heat pump as their inlet
- Parallel additional plant: conventional heat sources in parallel with a heat pump, i.e. which operate independently of any heat pumps

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[6] Definition taken from DECC, 2013. Summary Evidence on District Heating Networks in the UK.

3. Data collection and Case studies

Data collection

The aims of this activity were two-fold: to explore the breadth of existing schemes of heat pumps in heat networks, and to derive inputs and appropriate architecture to inform development of the model. The data collection exercises carried out were as follows:

- A literature review and scheme operator consultation were undertaken to produce a dataset of existing schemes. Existing schemes across Europe and North America were studied and follow up data requests sent to the operators of those which were judged to be relevant to the UK.
- A separate consultation of heat pump manufacturers was undertaken to obtain more detail on available technologies and ways in which they could be integrated into networks.

Below, key insights from these exercises are presented.

Insights from literature survey and scheme operator consultation

Existing schemes are categorised here in terms of their network temperature, as 'high temperature' (network suitable for conventional space heating emitters in existing buildings and domestic hot water (DHW), 'medium temperature' (network suitable for providing underfloor heating but not necessarily DHW) and 'low temperature' (network unable to directly provide space heating and DHW without a further heat pump using it as a heat source).

High temperature networks (70°C+)

While there is a lack of examples of heat pumps in high temperature networks in the UK, precedents for successful high temperature schemes can be found in several Scandinavian countries. Most consist of a central heat pump retrofitted into an existing network. This often means that the heat pump delivers heat at high temperatures and consequently sub-optimal efficiencies or coefficients of performance (COPs); on the other hand the marginal cost and disruption of retrofitting a heat pump to an existing network are both low.

The heat pumps are usually not the only, or even the greatest capacity, heat source within these schemes. Where possible, they are connected to the flue of CHP plant to carry out further heat recovery once conventional condensing and heat recovery processes have been undertaken. The heat pump then boosts heat from, for example, 50°C to 90°C. Alternatively, several Danish schemes combine heat pumps with large scale solar thermal generation and inter-seasonal heat storage. At the start of winter the heat from the store, at around 90°C, can directly be used in the heat network. As the store temperature decreases over the heating season, a HP is used to increase the temperature of the heat in the store before it is incorporated into the network.

For any network which is a heat sink for a central heat pump, reducing the network temperature as far as possible not only results in lower thermal losses along the network but also means that heat pumps are more readily integrated. Denmark's so-called '4th generation district heating'[7] programme is taking advantage of these twin benefits when designing new heat networks to operate at supply temperatures of around 50°C.

Where cooling networks are co-located with heating networks, heat pumps can provide an even greater benefit than when integrated into one or the other, by simultaneously providing coolth and rejecting heat. This is explored in more detail in the context of a large-scale system in Helsinki in the Case Studies section.

Medium temperature networks (40-70°C)

Several variations of medium temperature networks are operational in the UK and elsewhere. These are normally smaller scale than the high temperature networks described above, due to the required presence of a group of relatively new, energy efficient buildings with underfloor heating or low temperature radiators. However, a minority of medium temperature networks are found in existing buildings which have been retrofitted with low(er) temperature radiators.

Two UK implementations of medium temperature networks are as follows: One London scheme of 10 new build (Code for Sustainable Homes level 6) houses uses a 55°C network serving both space heating and DHW. Since DHW is not stored, this does not pose a problem for legionella growth. Another London scheme at Wandsworth Riverside, featured in the Case Studies section, uses a 45°C network for space heating, separate from a second (gas boiler based) system to serve the DHW demand.

Cooling is also a feature of medium temperature networks, especially if the heat is sourced from aquifers, in a configuration known as ATES – Aquifer Thermal Energy Storage. ATES systems are common in the Netherlands where aquifers are prevalent; this is less so in the UK. The systems can yield high heat pump COPs: as heat is removed from the aquifer over the winter, it is pre-cooled ready for summer; and as heat is rejected into the aquifer over summer, it is pre-heated ready for the winter. This setup is effective where a cooling load exists, to minimise the net heat taken from the aquifer over a year. Where there is higher heating demand than cooling, the aquifer can be regenerated using dry air chillers which reject heat to the ground, but this has an energy and environmental cost.

A further benefit of ATES systems located in areas of particularly high cooling demand is reduction of the Urban Heat Island effect, through rejecting heat deep into the ground instead of the air. In the UK, aquifers are not as common as elsewhere in Europe. However, if they are located in areas of particularly high heat and cooling demand (e.g. one scheme in the City of London[8])..

Low temperature networks (10-30°C)

The final type of scheme considered here is low temperature networks, with distributed heat pumps in buildings using the network as their heat source. This type of scheme minimises heat losses from the network, which is at or slightly above ground temperature. That is, carrying out the majority of the heating as close as possible to the point of demand results in less opportunity for heat loss. Another advantage of this type of scheme is the potential to provide heating and cooling from the same low temperature network. This is further explored in the next section.

Examples of low temperature networks with building integrated heat pumps are limited. One technical consideration is the close control of the network temperature to avoid the return side

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[7] http://www.4dh.dk/

[8] http://www.gienergy.net/downloads/casestudies/One_New_Change%20-%20GI_Case_Study.pdf

freezing. One scheme in the Netherlands (described in full in the Case Studies section) uses seawater at 18°C as a heat source in summer, using a heat exchanger between the sea and the network. In winter, the sea is at 6°C, too cold to use in a network. Therefore a central heat pump increases the temperature to 11°C, at which point the heat is used in the network. Individual heat pumps in each building then take heat from the network and boost its temperature to that required for space heating and DHW.

Insights from HP manufacturer consultation

We interviewed a number of heat pump manufacturers and installers to discuss the technical challenges and opportunities of two main types of integration of HPs in heat networks: central HPs providing heat to networks, and networks used as the source for building integrated HPs. Insights from selected key topics are highlighted below.

What suitable heat pump products are available, and to what extent are they bespoke?

- **Large capacity HPs** (100kW to > 1MW) are manufactured by a number of organisations. They can be bespoke, although not necessarily: some solutions suitable for heating/cooling networks are also suitable for other applications such as industrial production plants[9].
  If heat demand is very high and units large enough are not available on the market, multiple off-the-shelf smaller units can be connected in parallel. This can in fact be a preferable solution to one large unit, for several reasons. Firstly, there is increased resilience if a unit fails, secondly there is the ability to switch some units off at times of lower demand and thirdly there is flexibility to run some heat pumps in heating mode and some in cooling mode at any particular point in time (providing a separate cooling network exists). This approach is also often adopted in larger commercial buildings.
  Multi-stage HPs can increase the efficiency of raising the temperature of heat, by using heat recovered from one stage as a heat source for another stage.

- **Building integrated water-to-water HPs** using a low temperature network as their heat source are also currently available. These are essentially the same product as standard ground source heat pumps, without an individual ground loop.
  For groups of non-domestic buildings in which there are simultaneous heating and cooling loads, building integrated HPs with low temperature networks can be an effective means of essentially carrying out heat recovery from one building to another, via a common loop from which some buildings can take heat and into which other buildings can reject heat. This can work well when heating and cooling loads are balanced, and is a feature of the Kingston Heights installation in London[10].
  For dwellings, there also exist reversible heat pumps for heating and cooling, which can be used in conjunction with reversible emitters to provide heating in winter and cooling in summer. If cooling demand is low, products exist which use the network for free cooling, using the HP to provide pumping energy but not active cooling.

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[9] Examples include the Friotherm Unitop 22 system, http://www.friotherm.com/en/products/unitop-22/

[10] CIBSE Case Study: Open Water Source Heat Pump Development, January 2014, http://www.cibse.org/Knowledge/Case-Studies/CIBSE-Case-Study-Kingston-Heights

- **DHW-only HPs** are produced by a small number of manufacturers; these normally use the return flow of a medium temperature space heating network as the heat source. This higher source temperature (usually around 25°C) can yield a much higher COP for DHW production than that from a conventional GSHP or ASHP. The use of DHW-only HPs is not yet widespread.

What are the technical barriers to using central heat pumps in high temperature networks?

There are some situations in which central heat pumps are not compatible with high flow and return temperatures. Otherwise promising high temperature refrigerants, such as CO2, require a large temperature differential on the ‘hot side’ of the heat pump to operate; typical return temperatures are therefore too high to provide this. Alternatively, situations can arise in which the heat pump cannot increase the temperature of the return flow, since the latter is hotter than the sink temperature of the heat pump. In such networks, either the heat pump must switch off and wait for the return temperature to fall, or a means of lowering the network return temperature must be implemented. The latter can include rejecting heat either as waste, or into a lower temperature network if there are for example new build properties nearby.

How is HP performance affected by seasonality?

There are two main seasonal factors which could affect heat pump efficiency, especially for central heat pumps using natural heat sources. These factors are decreased heat demand in summer potentially leading to part load operation, and variation in source temperature (of water sources or air) through the year leading to lower COPs in winter.

Although part load operation does decrease heat pump efficiency, large capacity heat pumps are likely to have variable speed compressors and are able to ramp down, typically to 10-20% capacity. Systems in which multiple smaller units are cascaded may have fixed speed compressors but are able to turn off one at a time to create a similar effect.

Regarding source temperature variation, a useful feature of some central heat pump installations is the flexibility to connect to different heat sources at different times of year to use the highest available source temperature. For example, the Helsinki scheme explored in more detail in the Case Studies section uses seawater in summer and heat from sewage in winter.

Both the part load problem and source temperature problem can be solved using hybrid systems. These are the large scale equivalent to hybrid domestic heat pump installations: a boiler covers the full load during the coldest hours of the year, a boiler and heat pump work together during the remainder of the heating season, and the heat pump provides all of the demand during warmer periods. The capital cost associated with purchasing more capacity than is necessary to cover peak demand may be justified by the additional resilience provided should some of the plant fail or require maintenance.

Case studies

Four of the schemes identified in the data collection process were explored in more detail to create a set of case studies. These were chosen to cover a range of demand types (new build vs existing), network temperatures (high, medium, low), installation types (heat pump installed after or at same time as network) and heat sources.

- **Helsinki, Finland:** large city centre scheme with central water source (seawater, sewage) heat pumps retrofitted in existing heating and cooling networks
- **Wandsworth, UK:** residential development with central heat pumps in heating and cooling networks using an ATES system, with separate DHW provision.
- **Derbyshire, UK:** residential development with central ground source heat pumps in a heat network providing space heating and DHW, in an off-gas area.
- **Duindorp, The Netherlands:** large city centre scheme with a central water source (seawater) heat pump, a low temperature network and building-integrated heat pumps.

From the data collection exercise above, technical parameters for each scheme had already been obtained. Follow up research was then carried out by contacting and interviewing either the scheme operator or client in each case. The aim was to gain qualitative insights about how the scheme was functioning in practice and how transferable each one would be across the UK.

Each scheme is presented below, before drawing out some general findings across the schemes.

Helsinki, Finland

Helsinki has a well established district heating and cooling network, supplying 90% of the city's heat demand and an increasing proportion of cooling demand, and covering a range of customer types. Although the heat network is mostly heated by gas-fired CHP and the cooling network by absorption chillers, new plant such as heat pumps and storage can be and are being integrated. In 2006, 84 MW of heat pump capacity (in 5 individual units) was integrated into the existing system, covering 4% of the network's total heat and 33% of total cooling.

The heat pumps' sources, sinks, source temperatures and sink temperatures vary seasonally:

- In winter, heat is recovered from sewage and used to preheat the district return flow from 50°C to 62°C. This is lower than the network temperature, but in this way the heat pump can run more efficiently. All cooling is provided directly from sea water (free cooling), so the heat pumps are not used for this.
- In the summer the heat pumps operate to meet the cooling loads, with the heat extracted from the cooling network being used to heat the heating network to the summer operating temperature (88°C). Heat from the cooling network that is in excess of the heating network heat demand is rejected into the sea.

The Helsinki scheme is an example of economically viable and technically successful integration of heat pumps in heat networks. It operates without any grants or subsidies, although it should be noted that this is partly due to a set of factors that are not entirely applicable to the UK. These include the limited availability of natural gas in Finland, the prevalence, experience and knowledge of district heating systems which lead to lower capital and operating costs, and the demand for district cooling networks. Regarding this last factor, the benefit of the heat pump is maximised due to the co-location of heating and cooling networks, in which it carries out effective heat recovery. In the UK there are currently far fewer existing high temperature heat networks to connect heat pumps to, and even fewer combined heating and cooling networks. However, there is potential for new networks to integrate heat pumps in this way. Furthermore, from the industry consultation undertaken as part of this study, the use of heat pumps in heat recovery from sewage is currently being considered in the UK.

Wandsworth, London

Wandsworth Riverside Quarter is a development of apartments on the banks of the Thames in south-west London. The development will provide 504 apartments and substantial commercial and leisure space when fully built out, the first apartments were occupied in 2013. An Aquifer Thermal Energy Storage (ATES) system has been installed in Phase 1 of the development, providing both space heating and cooling to the mixed-use buildings. Heat supply for domestic hot water and heat pump back up comes from gas boilers and a gas CHP.

The ATES scheme consists of three heat pumps coupled to an aquifer below the site via an open-loop system of boreholes. The heat pumps supply a peak cooling capacity of 2.25 MW and a heating peak output of 1.2 MW. The aquifer warms over the summer due to the injection of the waste heat from the cooling loads, leading to better heat pump performance in winter. In the winter the aquifer is cooled as heat for the space heating is drawn out, and this cooling of the aquifer means the summer cooling COPs are higher - or under ideal design conditions the aquifer is cool enough to directly cool the chilled water. Space heating is supplied at 45°C.

Where the geology is suitable and regulatory consent can be obtained, the technical potential of schemes similar to the Wandsworth ATES installation is high. ATES systems can achieve very good COPs where there are heating and cooling loads approximately in balance over a year. Furthermore, the function of the ATES as a heat sink means that no heat rejection plant is needed for the building cooling system – a useful benefit is in dense city locations, especially as it has become increasingly common for building occupants to make use of the roof space where such heat rejection plant was typically put.

The capital cost for the Wandsworth scheme was high (around £2 million for 500 flats) – however, in areas of high property value this cost is viewed as inevitable for obtaining planning permission. Due to the interseasonal heat recovery leading to more ideal heat pump source temperatures, ATES systems should have low operating costs. Achieving maximum efficiency requires the building heating and cooling systems to be designed to allow the ATES to yield its full potential. This requires a good understanding of system optimisation and good attention to detail.

There are many successful ATES schemes in Holland and Belgium. ESCO operators are actively seeking opportunities for application of the ATES approach in mixed use buildings in the UK. Installations in areas of mixed domestic and commercial buildings could optimise the balance of heating and cooling loads.

Brooke Street, Derbyshire

Brooke Street is an off-gas grid area on the edge of a rural village in South Derbyshire. A small heat pump in district heating installation was carried out in 2012 to serve 18 existing local authority flats (built in 1982), to replace individual electric heaters in each flat.

The replacement of the previous heating system was carried out due to residents' complaints about the high cost and poor control of electric storage heaters. The council was interested in exploring renewable energy solutions, and obtained a RHPP grant to help fund the capital cost of the installation. Building fabric insulation was improved where possible as part of the project.

The installation consists of three ground source heat pumps using 28 boreholes, coupled to a common ground loop. The heat pumps supply heat at 55°C to a network, sufficient for space heating through low temperature radiators. The network is raised to 60°C for a period every night to heat the DHW cylinder and remove Legionella risks. However, the previous electric showers were not replaced, so the DHW cylinder does not serve these and hence DHW demand is low.

This scheme is the only one of the case studies involving retrofit of not just central plant/network but also components within homes. It is therefore useful to consider the process.

A couple of years on, the residents are very satisfied with the new system. There were however a number of problems at the start. The project caused more upheaval in and around the flats than the council had first envisaged, one reason being that other maintenance work needed to be brought forward, and another being that the short time period in which the grant needed to be spent meant that the scheme of works could not be planned for minimum disruption.

Residents initially did not understand how to best operate their new heating and DHW systems, leading to higher operating costs than anticipated. It has also taken time for the council to consider how best to charge for the cost of operating the system, in terms of how the fixed and variable costs are passed through to the residents.

The above challenges do not concern the technical design of the scheme. Indeed, there is good technical potential for energy and CO_2 savings from heat pumps in heat networks in off-gas grid areas such as this one, where the previous heating system is direct electric resistance heating or storage heaters. However, one consideration arising from this type of system is how to effectively heat and store DHW in schemes using medium temperature networks. In the Derbyshire scheme, the heat pumps boost the DHW tank temperature from 55°C to 65°C once per day, leading to high standing losses from DHW tanks. This raises the question of whether the magnitude and frequency of the heating boost are necessary and whether legionella regulations could be addressed using a more efficient solution. Similar schemes in the Netherlands heat the DHW from the network directly at 55°C.

Duindorp, Netherlands

The scheme at Duindorp is relatively complex, with high capital costs due to the need to purchase and install the central heat pump, the network and the distributed heat pumps. Furthermore, the operating costs are also high. The operator of the Duindorp scheme commented on the significant commitment arising from being responsible for the efficient operation of 789 distributed heat pumps. Commonly, a key benefit of district heating for housing providers is the reduction in maintenance responsibilities within flats/houses, where getting access can be time consuming. The Duindorp setup loses this benefit.

Using seawater as the heat pump heat source has also been implemented in the UK (at Portsmouth International Ferry Terminal), however in the UK scheme the central heat pump produces high temperature heat directly. Although it poses challenges (corrosion, filtering and restriction of inlet and outlet points by growth of seaweed) it could be a promising solution for heat networks by the coast.

General findings

From the above range of configurations, no single system emerges as the most promising for use in the UK. Instead, it has been found that each system is associated with a set of advantages and disadvantages, many of them relating to technical potential with certain types of heating/cooling demand in certain geographical areas. The relative benefits and drawbacks to each option are presented in Table 1.

Table 1: Benefits and drawbacks of the HP in DH scheme configurations explored in the case studies

Configuration	Advantages	Disadvantages
Large central HP in high-temperature DH network with additional heating plant	• HP can be controlled by scheme operator, and its use can be optimised as part of the larger heat supply system. • Existing buildings with traditional heating systems can be connected without changes to their heating systems. • It is relatively easy to extend the scheme to more buildings. • If the return temperature is low enough, the heat pump can be used for initial heating of the return flow with the remainder carried out by conventional plant, leading to high heat pump COPs.	• The network may run at an unnecessarily high temperature for some buildings. • Heat pumps may therefore deliver to a high temperature sink, entailing a lower COP than would have been the case if operating temperature were lower. • High distribution losses
Central HP in medium temperature network serving space heating	• High COPs can be achieved due to lower network temperatures than those above.	• The network temperature may be too low to be used directly for DHW demand. • Therefore either a parallel system for provision of DHW is required, or a means of raising the network temperature locally at the point of demand.
Central HP in medium temperature network with Aquifer Thermal Energy Storage (ATES)	• The inter-seasonal storage of heat and coolth can significantly improve the heat pump COPs. • With appropriate design of building cooling systems a significant part of the cooling load can be supplied directly from the aquifer. • When used with weather compensation controls, the heat pump performance can be further improved by only delivering hottest flow temperatures on the coldest days and coolest chilled water when the cooling demands are greatest.	• Requires the presence of an aquifer. • Requires a cooling load. If none is present, it requires use of dry air coolers or similar technology to regenerate the ground. • No ideal option for the provision of DHW. For new build residential properties where the DHW is a significant proportion of the overall heat load this is a problem, as an alternative low carbon heat source still needs to be found.

Central heat pump, low temperature distribution network and building-integrated heat pumps	• If the heat pumps are run efficiently, this configuration is an efficient manner of delivering heat (i.e. low network losses). • Low capital costs for the very low temperature DH network. The use of uninsulated plastic pipe is possible – much cheaper than insulated steel DH pipe. • Cooling can be offered to the customers from the same network.	• High capital cost, since the system requires a central HP and distributed HPs as well as the network. • To achieve maximum energy and CO2 savings, not only must the central HP and network be operated efficiently, the building-integrated heat pumps must also. However, the scheme operator has little control over how the building integrated heat pumps are used, and maintaining a large number of BIHPs is costly.

4. Model development and methodology

Purpose of the model

A bespoke, technology-rich simulation model has been developed for this study.

The purpose of the model is to allow a user to set up and simulate a wide range of potential HP in DH scheme configurations. The model then evaluates the environmental and economic performance of each scheme over a certain (user-defined) lifetime. This allows the user to explore the relative benefits of different types of scheme. A selection of the key performance metrics that the model is able to provide is given in Table 2.

Table 2: Key performance metrics determined by the simulation model (illustrative list).

Category	Key performance metric	Unit
Energy	Primary energy consumption	MWh/yr
	Heat generated	MWh/yr
	Heat delivered to consumers	MWh/yr
	Thermal losses	MWh/yr
	Pumping losses	MWh/yr
	Overall system efficiency on primary energy basis	%
CO_2 emissions	CO_2 emissions (ETS and non-ETS)	tCO_2/yr
Economic	Capex – plant and infrastructure	£
	Opex – plant and infrastructure	£/yr
	Opex – fuel spend	£/yr
	Total cost of ownership (TCO)[11]	£
	Price of delivered heat to consumers[12]	p/kWh

Scope of model

A wide range of HP in DH scheme configurations can be simulated

A key requirement of the simulation model was to allow a wide range of potentially relevant scheme configurations to be studied, so that the most appropriate scheme configuration for a given area can be identified. The variations in scheme design shown in Table 3, as identified through our industry consultation exercise and literature review, are included within the simulation model.

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[11] The TCO includes all costs associated with heating plant, network infrastructure, fuel and carbon costs (cost of traded emissions only), revenue from electricity sales and administration costs. Costs are discounted over a scheme lifetime of 20 years. The build year is 2018 for all scenarios shown in this report, and all TCO values are calculated using a discount rate of 10%, unless otherwise stated. It is assumed that all equipment has a lifetime of at least 20 years, such that no replacement costs are incurred.

[12] The price of delivered heat is defined here as (Total cost of ownership)/(Total heat delivered to consumers over the scheme lifetime). No profit margin is accounted for; that is, we assume here that the price of heat charged to consumers is equal to the cost to the scheme operator of delivering that heat.

Table 3: Aspects of scheme design included in the simulation model

Aspect of HP in DH scheme design	Variations included within the model
Supply technologies and heat sources	• See **Error! Reference source not found.**
HP configuration	• Central HP feeding a DH network • Building-integrated HPs fed by a DH network • Both a Central HP and building-integrated HPs
Energy end-use served	• Space heating only • Space heating and hot water • Space heating, hot water and cooling
Network temperature	• Network temperature is a flexible user-defined variable, covering unheated, medium and high temperature networks
Fraction of peak demand met by Central HP	• Additional heating plant to boost the temperature of the water supplied by the central HP ('series' additional plant) • Additional heating plant supplying the network separately ('parallel' additional plant)
Central thermal storage	• Capacity of central thermal storage is a flexible user-defined variable

Figure 8 illustrates schematically the range of schemes that can be simulated within the model. Any configuration of scheme combining the above aspects of design can be represented by this general scheme configuration diagram by removing certain components, increasing or decreasing the contribution of each component and by specifying the heat pump source and sink temperatures, the network flow and return temperatures and the space heating and hot water emitter temperatures. Table 4 summarises the supply technologies and heat sources included in the simulation model.

Figure 8: General configuration diagram for HP in DH schemes, as explained in the main text.

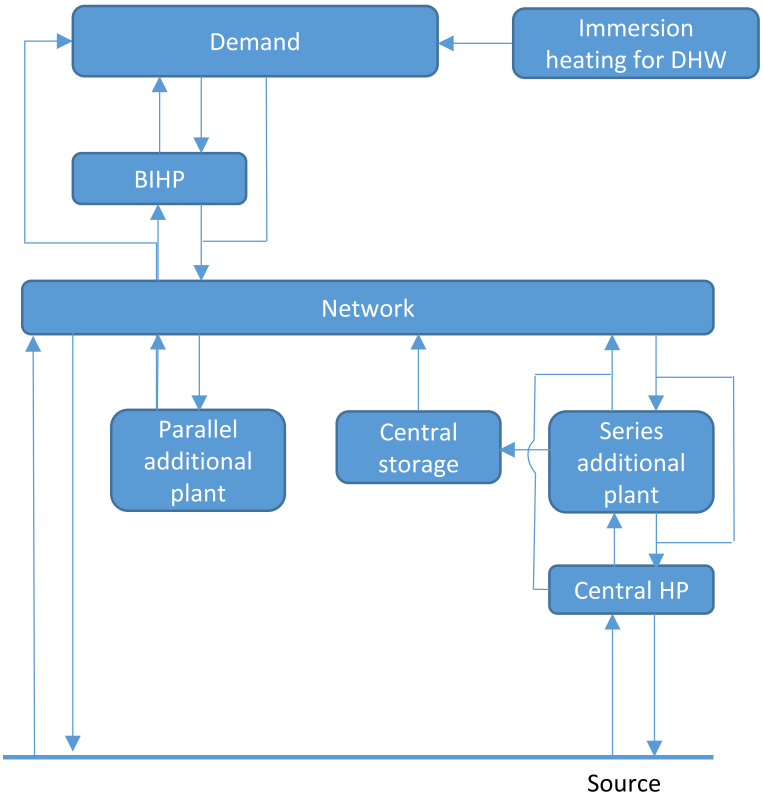

Table 4: Supply technologies and heat sources included in the simulation model by category

Category	**Heating**	**Cooling**
Central HP	• Water-source HP[13] • Ground-source HP	• Water-source HP • Ground-source HP
Building-integrated HP	• Water-source HP	• Water-source HP
Additional heat sources	• Waste heat • Solar thermal	None
Central additional plant	• Gas-CHP, Gas boiler • Oil-CHP, Oil boiler • Biomass-CHP, Biomass boiler	• Gas absorption chiller • Oil absorption chiller
Building-integrated additional plant	• Electric immersion heater	• Electrical chiller

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[13] We consider both open- and closed-loop water-source heat pumps, with various water sources. This is specified further within each scenario.

Overview of key inputs and aspects of the methodology

The model includes highly flexible heat demand characteristics

The user is able to define in detail the characteristics of the heat demand through the specification of the consumers served and of the nature of the area in terms of heat density. A summary of the range of consumers included within the model is given in Table 5. This includes a range of non-domestic building types, as well as typical house types. Since the cost of DH is strongly dependent on heat density, the model allows the user to explore the impact of varying the thermal efficiency level of the buildings served. For each building type a thermal efficiency level of 'existing' or 'new' is defined, to reflect the typical level of thermal efficiency in the existing stock and the efficiency level required by the Target Fabric Energy Efficiency rate that will be required for all new build homes as part of compliance with building regulations.

For each consumer, the model provides the following default data, which can be modified by the user if desired:

- Total floor area and building footprint;
- Hourly space heating, hot water and cooling demand profiles and total annual demand;
- Length of 'service' pipe required to connect to the distribution network.

The user can also define the heat density characteristics of the area being served. The physical size of the network – the length of transmission and distribution pipe required – can be specified either through pre-defined area types or by directly entering the pipe lengths. The pre-defined area types are defined by the following attributes:

- 'Plot ratio' – the ratio of the footprint of buildings within the area to the total area covered by the scheme;
- Length of distribution and transmission pipe required per km^2 of total area covered by scheme.

The plot ratio allows the total area covered by the scheme to be derived from user input data relating to the number of consumers enclosed by the scheme (of which only a fraction may be connected) and the floor area data. The length of distribution and transmission pipe can then be derived.

Table 5: Consumers types included in the simulation model

Sector	Building type	Thermal efficiency level
Domestic	Terraced Semi-detached Detached Flat	Existing New
Non-domestic	Office Retail Hotel Restaurant/public house Leisure centre Hospital School	Existing New
Industrial	Industrial building	Existing New

Cost and COP of heat pumps are key data points

An important aim of the study was to be able to model heat pump performance within the particular setup of each modelled scheme, as opposed to defining seasonal performance factor exogenously. The chosen methodology was to obtain COP data for a range of refrigerants over a range of source and sink temperatures, and implement a lookup function in the model to select the appropriate COP each hour of the year. It was also important to capture the interaction between the anticipated higher cost of heat pumps to traditional heating plant and their increased energy/exergy efficiency.

Data on both cost and COP of heat pumps were difficult to find, and in both cases it is evident that a large range of values exist. We therefore describe here how values were chosen or constructed, and which sources were used. For the purpose of the analysis in this report, we have carried out sensitivity analyses to determine the impact of uncertainty in the cost and COP assumptions in the model, with the range of input data based on our findings from the data collection exercise.

Costs of large capacity heat pumps were obtained from two existing schemes, both of which allowed disaggregation of component and installation costs. These were set as the ‘low’ cost scenario since literature indicated that many existing installations were much more expensive, possibly due to the bespoke nature of certain schemes or at least the fact that many were the first of their kind. Costs of water-to-water building-integrated heat pumps were also obtained from industry consultation.

To allow heat pump performance to be modelled and compared across a range of operating conditions, it was necessary to obtain a relationship between COP, source temperature and sink temperature. Upon recommendation from a heat pump manufacturer during the industry consultation, an online software tool was used (‘Select 7’, by Copland/Emerson Climate Technologies) which yielded rated COPs for each source and sink temperature achievable with a particular refrigerant.

The software did not perform the same function for cooling, so tables from manufacturer literature were used to construct the COP as a function of source and sink temperature.

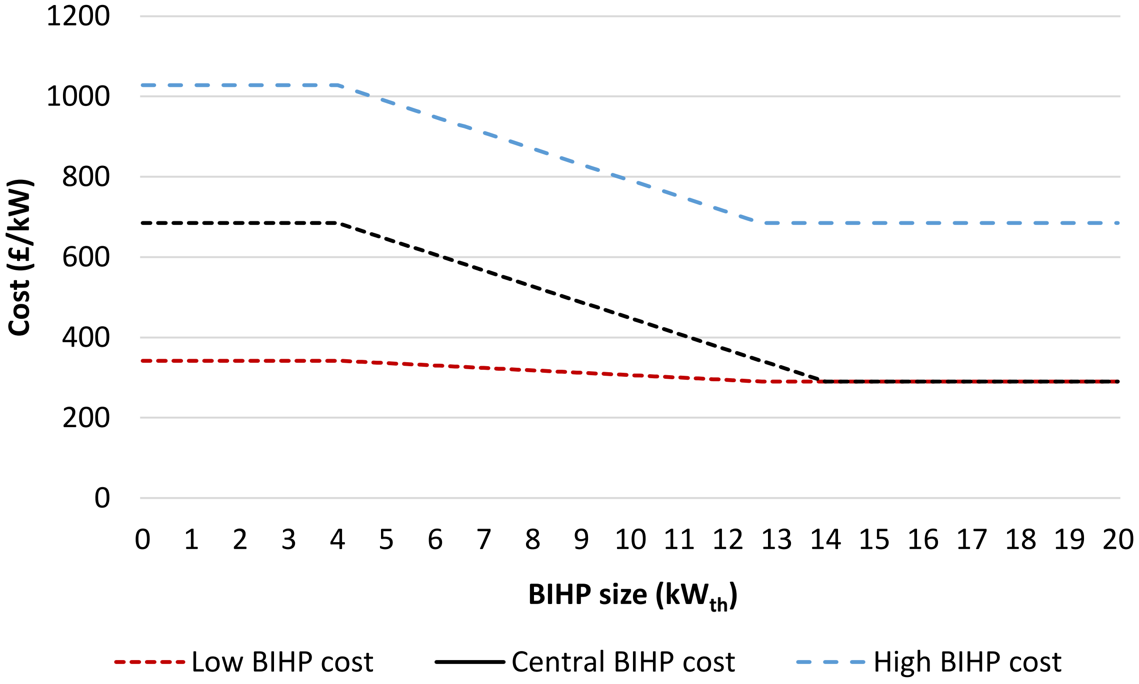
The results from the above were used as central scenarios. Generally, the high and low scenarios for COP were defined using the same online tool, by taking COP values for a sink temperature 5ºC higher or lower than the sink temperature of interest. However, for the ‘high’ scenario for central heat pumps, performance data from an established scheme at Drammen, Norway which incorporates a central high temperature heat pump was used. In this scheme, the use of a multi-stage heat pump with efficient heat recovery led to high COPs being achieved. This was therefore incorporated into the modelling as an indication of the potential performance of the HP in a high COP scenario.

Table 6 presents a selection of example input data on heat pump cost and COP. We note that the cost of building-integrated heat pumps depends on the capacity of the heat pump; Figure 9 shows the dependence of the cost of building-integrated heat pumps on heat pump capacity in the Central case, and for the Low and High sensitivities. Heat pump COP is strongly dependent on the source and sink temperatures, which are variable in the model. Table 6 therefore provides COP values for typical source and sink temperatures.

Table 6: HP cost and COP data resulting from the data collection exercise used in sensitivity analyses

Category	Unit	Low	Central	High
Cost – central HP (incl. installation)	£/kW	500	1500	2500
Cost – water-to-water building-integrated HP (excl. installation)	£/kW @ 6kW	303	606	909
COP – central HP	COP @ 10°C source, 70°C sink	1.5	2.21	3.6
COP – water-to-water building-integrated HP	COP @ 10°C source, 45°C sink	3.86 (from increasing sink T by 5°C)	4.53	5.31 (from decreasing sink T by 5°C)

Figure 9: Graph showing the Low, Central and High cost assumptions for building-integrated heat pumps.



It can be seen from Table 6 and Figure 9 that, for the majority of the sensitivity assumptions, the cost presented for the central heat pump is greater than that for the building-integrated heat pump on a per kW basis. This may be surprising given that, as shown in Figure 9, the cost of building-integrated heat pumps decreases with increasing capacity on a per kW basis. There are three factors contributing to this:

i. The building-integrated heat pumps do not, in this context, require any pipework, trenches or boreholes, as they connect directly to the network. In contrast, the cost of the central heat pumps includes the pipework required to connect to the source of heat (for the data shown, this is a source of water).

ii. As indicated in Table 6, the cost presented for the central heat pump includes installation, whereas the cost for the building-integrated heat pump does not. The cost of installation for the building-integrated heat pump is accounted for separately, together with the installation of the other building-level infrastructure, including the heat interface unit and the heat meter.

iii. The building-integrated heat pumps under consideration are ‘off-the-shelf’, whereas the central heat pumps are currently bespoke pieces of equipment; it may be expected that the cost of central heat pumps will decrease through learning-by-doing as more projects of this type are implemented.

Hourly simulation methodology

The simulation methodology allows a high degree of interaction between model parameters

In this section we highlight a number of key aspects of the approach and the implications for the results derived. We also comment on the limitations of the simulation model in its current form.

The model is based on an hourly energy balance simulation and a simple dispatching algorithm[14]. The simulation includes a merit order for dispatching heat, such that the HP is prioritised. However, the user is able to stipulate that the HP does not run at times of high electricity price, and a minimum ramp-down fraction which switches off the HP if demand is too low.

As such there is a high degree of interaction between model parameters. For example:

- Building-integrated plant is sized according to the peak heat demand (using minimum equipment sizes where appropriate);
- Network pipe sizes are calculated based on the peak heat demand and the amount of heat that can be extracted from the network based on the associated flow and return temperatures;
- Network thermal losses are calculated based on the pipe sizes and the associated network flow and return temperatures;
- Heating plant is sized based on the peak network heat demand, accounting for network thermal losses and the presence of central thermal storage, where available.

The interactions above are potentially important in a comparison of two different HP in DH schemes, given the wide range of design options. For example, a low temperature network brings the advantage of reduced thermal losses relative to a high temperature network, leading to reduced fuel consumption and reduced heating plant capacity requirements. On the other hand, low temperature networks typically involve a smaller difference between network flow and return temperatures than high temperature networks, since the return temperature cannot drop too close to the freezing point. This means that, typically, a greater mass of water needs to be transported around the network, requiring larger diameter pipes and leading to higher infrastructure costs.

Limitations of the model

We highlight here a number of limitations of the model. Options for further enhancing the model's functionality are discussed in the Further Work section.

- The network flow and return temperature used in the model are exogenous inputs; that is, the system is not reactive (in terms of flow rate and temperature) to changes in heat demand as a real network would be. One implication of this above is that poor management of the system is not accounted for; in real schemes, increasing return

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[14] Implementation of a complex dispatching algorithm, optimising dispatch of heat from a heat pump or other plant based on a wider set of criteria, is beyond the scope of this study.

temperatures, if uncorrected, can lead to heat pumps unable to deliver heat above the network return temperature and therefore not heat up the network.

- Similarly, heat source temperatures are exogenously defined. This means that the cooling process of aquifers and boreholes over the heating season, and their heating up over the cooling season, is not represented in the model. The model is better-suited to heat sources which can be assumed to be infinitely replenishable, such as a river or sea.
- Although the heat source temperature can vary in the model, the heat pump sink temperature is fixed. This means that the model does not include the option of lowering the sink temperature in winter to achieve a higher COP, which some real schemes may opt to do.
- Cooling is included in the model in several forms: individual chillers, a separate network, and from the same network as the heating. However, in the latter two cooling types, the data collected was insufficient for detailed treatment. A benefit of using heat pumps for simultaneous heating and cooling is the ability to provide heat to a heat network whilst rejecting coolth into a cooling network. This is not represented in the model.

Model Validation

The results of an exercise to validate key aspects of the modelling are presented in Appendix 2.

5. Comparison of heat pump in district heating scenarios with conventional heat networks

Introduction to the analysis chapters

The model described in the previous section was used to carry out three pieces of analysis, each involving modelling heat pumps in district heating in a number of scenarios. A ‘scenario’ refers to a configuration of equipment (e.g. central heat pump with gas CHP) combined with a particular type of heat demand (e.g. existing non-domestic buildings). The analysis is presented in Chapters 5, 6 and 7 and focuses on the following questions:

- Chapter 5: How does the performance of each heat pump scheme compare to a gas-based counterfactual in each scenario?
- Chapter 6: How do the heat pump schemes in the above scenarios compare to one another when used to serve the same heat demand?
- Chapter 7: Are there promising types of heat pump in district heating scheme in which the cost can be brought down to a level comparable to a conventional district heating scheme without heat pumps?

Scenarios studied and research questions

The objectives of the analysis are to examine a range of HP in DH scheme configurations potentially relevant to the UK; to assess under which circumstances the integration of HPs into DH networks could be advantageous; and to elucidate the key technical factors which are likely to determine the performance of the scheme in terms of cost, energy consumption and CO_2 emissions.

Based on our review of existing schemes, we have chosen four scenarios potentially of relevance for the UK:

1. Large-scale high temperature heat network retrofit with a central heat pump serving existing non-domestic buildings
2. Medium-scale low temperature heat network with a central heat pump and building-integrated heat pumps serving a new residential development
3. Small-scale medium temperature heat network with central heat pump supplying a new residential development
4. Small-scale medium temperature heat network with a central heat pump and hot water-only building-integrated heat pumps serving a new residential development

We will examine the potential of HP in DH in the UK through sensitivity analyses for each scenario

Within each scenario, we undertake a series of sensitivity analyses to determine the impact of a number of key variables on the cost, energy and CO_2 performance of the system. The sensitivity analyses are intended to reflect both:

- *Variations in the scheme design*, such as the heat density of the area being served by the network, the fraction of the overall scheme demand to be served by the HP, and the space heating emitter temperature;
- *Uncertainty in the input data*, such as the HP cost, the HP COP and the future electricity price.

Through the sensitivity analyses for these four scenarios, we will therefore effectively examine a wide range of potential HP in DH schemes. This will allow an understanding to be gained of the scheme designs most likely to be successful in the UK; the heat load characteristics most likely to be suitable; and the likely requirements in terms of HP cost and fuel prices.

In this section, we focus on a comparison of the performance of the HP in DH schemes with an appropriate counterfactual. The counterfactual for this study is defined as a high temperature network based on gas CHP for large-scale networks and on gas boilers for small-scale networks. We will also make a comparison of the HP in DH schemes with other competing options, such as building-level gas boilers.

Scenario 1: Large-scale heat network retrofit with a central heat pump serving existing non-domestic buildings

Description of scenario

The key characteristics of Scenario 1 are summarised in Table 7, and shown schematically in Figure 10. We model Scenario 1 as a large central HP, in combination with gas CHP plant in series and parallel to increase temperature and capacity respectively, supplying heat to a large-scale high temperature network. The HP is a water-source heat pump, and its source is a river whose temperature is assumed to be 10ºC all year round. The network serves the space heating and hot water demand of a set of existing non-domestic buildings including offices, shops and restaurants[15]. Operational examples of schemes similar to this scenario include Drammen (using a fjord as the heat source) and Helsinki.[16]

The counterfactual for this scheme, as summarised in Table 7, is an identical network supplied entirely by a gas CHP plant.

Full details of the scenario, including all assumptions and input data, can be found in the accompanying technical assumptions document.

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[15] We note that in all scenarios described in this report, whether serving new or existing buildings, in both the HP in DH scheme and the counterfactual, the cost of the network infrastructure is included in full in the analysis.

[16] Helsinki also includes a cooling load, which this scenario does not.

Figure 10: Schematic illustration of HP in DH scheme in Scenario 1

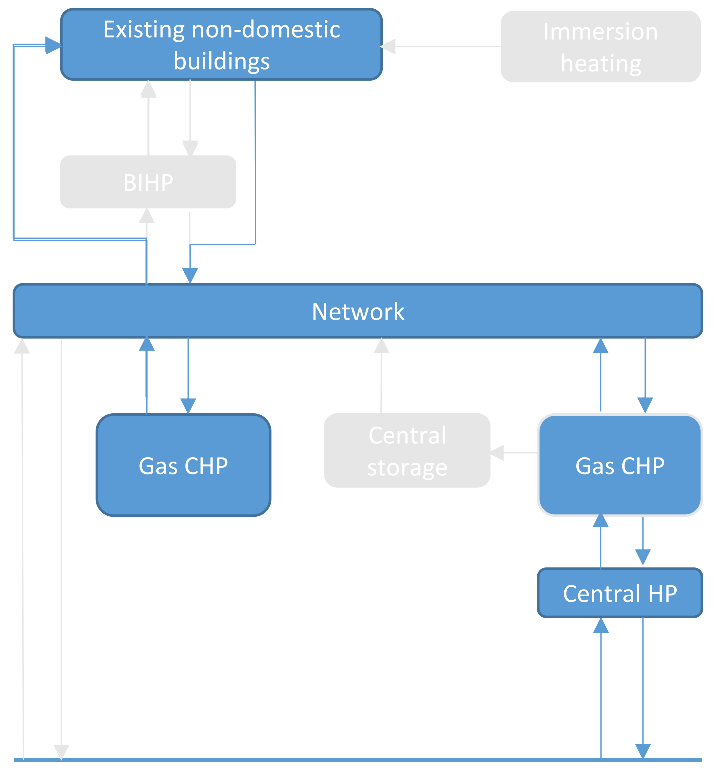

Table 7: Summary of key characteristics of Scenario 1

		HP in DH scheme	***Counterfactual***
Description of scheme and buildings served		Large-scale scheme serving a variety of existing non-domestic buildings (heat density varied in a sensitivity)	
Heating	Heat source (source T)	River (10ºC)	None
	Central HP type (HP sink T)	WSHP (70ºC)	None
	Building-integrated HP type	None	None
	Central conventional plant	Gas CHP in parallel and series	Gas CHP
	Building-integrated conventional plant	None	None
	Network flow/return temperature (ºC)	80/60	80/60
	End-uses served by network	Space heating and DHW	Space heating and DHW
Cooling		No cooling demand treated	

Key parameters for sensitivity analysis

Table 8 details the sensitivity analyses carried out for Scenario 1. In this scenario, the network and demand-side are identical in the HP in DH and counterfactual scheme. The only difference between the schemes is the nature of the plant supplying the network. Whether the HP in DH scheme is advantageous over the counterfactual depends upon whether the higher efficiency of the central HP relative to the conventional plant leads to fuel savings which compensate for the (typically) higher capital cost of the HP. Since this scenario involves the incorporation of a HP into a high temperature network, we consider the potentially important option of using conventional plant in series with the HP, in order to allow a lower HP sink temperature and achieve a higher HP efficiency.

Table 8: Summary of sensitivity parameter values used in Scenario 1

Sensitivity	Low	Central	High
Cost of Central HP (£/kW$_{th}$)	500	1,500	2,500
COP of Central HP (at 70ºC sink T)	1.5	2.2	3.6
% of peak demand served by HP and series gas CHP	10	50	90
HP sink T (ºC)	50	70	-
Fuel prices	DECC fuel price scenarios (see Appendix 1)		
Scheme heat density (kWh/m^2)	-	125	200

Central HP cost

For this scenario, the input data assumptions on the cost of the central HP are of great importance. Given the small number of operational HP in DH schemes, as described in Section 3, we have been able to collect only limited data on the cost of large HPs. Therefore, the range of central HP costs defined by the sensitivity reflects the likely range of real values based on our data collection exercise and industry consultation. Nonetheless, we emphasise the central HP cost as one of the key uncertainties in the input data assumptions, and suggest that it should be reviewed as further data becomes available.

Central HP COP

Similarly to the Central HP cost, limited data is available on the COP of large HPs. The range of central HP costs defined by the sensitivity reflects the likely range of real values based on our data collection exercise and industry consultation.

Fraction of the peak demand provided by the Central HP and series Gas CHP

The performance of the HP in DH scheme relative to that of the counterfactual is also expected to be dependent upon the fraction of the peak demand provided by the HP. As this fraction increases, there is a tendency for over-sizing of the HP, with the HP only operating at full capacity for a small fraction of the year. Since the capital cost per (kW_{th}) of the HP is, in the Central case, greater than that of conventional plant, this will tend to penalise the HP in DH scheme relative to the counterfactual. Use of thermal storage is one way to reduce the HP capacity required and address this issue. In this section, however, we do not include thermal storage, in order that the effect of changes in the fraction of the peak demand provided by the HP can be directly observed.

HP sink temperature

As shown in Figure 10, there is the possibility to employ conventional plant (in this case, a Gas CHP) in series with the central HP. Using such additional series plant allows the HP sink temperature to be reduced, thereby increasing the efficiency of the HP.

As the HP sink temperature reduces, the contribution of the series Gas CHP, which is typically less efficient than the HP, increases. Whether a reduction in the HP sink temperature is economically beneficial therefore depends upon whether the reduction in fuel spend in the HP is outweighed by the increase in fuel spend in the series additional plant.

Electricity and gas prices

We also study the effect of different fuel price scenarios. Since HPs typically consume electricity[17], while the counterfactual is typically based on gas, the relative price of electricity and gas is expected to have a large impact on the economic performance of the HP in DH scheme relative to the counterfactual. We have studied this effect using DECC's fuel price scenarios[18]. We note that we have used internally consistent fuel price scenarios; that is, where gas prices are higher, electricity prices are also higher.

Scheme heat density

Finally, we also present the impact on the price of heat of increasing the heat density of the development being served by the network. While this will affect the HP in DH scheme and the counterfactual in the same way, this will serve to illustrate the importance of high heat density in determining the viability of a DH network in place of distributed heating plant such as individual gas boilers.

Scenario results and sensitivity to key parameters

Scenario results based on Central sensitivity assumptions

Figure 11 summarises the heat supplied by the various plants and the heat delivered to meet demand over the 20 year scheme lifetime in Scenario 1, using the Central sensitivity assumptions. It can be seen that in the HP in DH scheme, approximately two-thirds of the total heat supplied is supplied by the central HP. Of the 697 GWh supplied, 92 GWh is attributable to network thermal losses, amounting to 13%.

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[17] Absorption heat pumps, based on gas or oil, are not included in the scenarios presented in this report.

[18] Source: Supporting Tables for DECC HMT Supplementary Appraisal Guidance, October 2014.

A number of key performance metrics for Scenario 1 are shown in Table 9. It can be seen that, using the Central sensitivity assumptions, the HP in DH scheme has a higher total cost of ownership (TCO)[19] than the counterfactual scheme based on gas-CHP, at £48m as compared with £36m, representing a premium of 33% versus the counterfactual. Figure 12 presents the breakdown of the TCO for the HP in DH and counterfactual schemes.

It can be seen that the key difference between the HP in DH scheme and the counterfactual is the balance between fuel costs and the revenue from electricity sales from the CHP plant. The higher system efficiency and reduced carbon intensity of the HP in DH scheme results in a 14% reduction in fuel and carbon costs. However, the counterfactual benefits from much higher revenue due to sales of electricity, far outweighing the increased fuel and carbon costs. The cost of the heating plant is similar in the two cases. The cost of the network infrastructure, which includes the transmission, distribution and service pipes, as well as the heat interface units (HIU) and heat meters, is identical in each case.

The price of heat delivered is therefore higher, at 8.0 p/kWh as compared with 5.9 p/kWh. The CO_2 intensity of heat delivered by the HP in DH scheme, at 171 gCO_2/kWh, is much lower than for the counterfactual, at 327 gCO_2/kWh.

The efficiency of heat production on a primary energy basis[20] at 39% for the counterfactual and 54% for the HP in DH scheme, is low in both cases since both schemes involve the production of electricity as well as heat. In the HP in DH case, this also reflects the modest heat pump COP (of 2.2) resulting from the large temperature difference between heat pump source and sink. The efficiency of heat and electricity production on a primary energy basis[21] is 63% for the counterfactual and 57% for the HP in DH scheme. The relatively low value for the HP in DH scheme is a result of accounting for the primary energy associated with the additional electricity produced in the counterfactual case, using the primary energy factor for grid electricity (as explained in Footnote 21).

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[19] The TCO includes all costs associated with heating plant, network infrastructure, fuel and carbon costs (cost of traded emissions only), revenue from electricity sales and administration costs. Costs are discounted over a scheme lifetime of 20 years. The build year is 2018 for all scenarios shown in this report, and all TCO values are calculated using a discount rate of 10%, unless otherwise stated. It is assumed that all equipment has a lifetime of at least 20 years, such that no replacement costs are incurred. No subsidies are assumed for this analysis.

[20] Efficiency of heat production on a primary energy basis is defined here as: (Heat delivered to consumers) / (Primary energy associated with all fuel consumed). This includes the impacts of thermal and pumping losses. The primary energy factor for grid electricity is in all cases the 2015 value, since projections of the grid primary energy factor consistent with the projected grid carbon intensity could not be obtained. Therefore, these values apply only to the case in 2015. A decreasing primary energy factor would favour the efficiency for the HP in DH scheme relative to the CHP-based counterfactual.

[21] Where the counterfactual includes CHP, we make an indicative comparison of the efficiency of heat and electricity production on a primary energy basis between the HP in DH scheme and the counterfactual. We account, in the HP in DH scheme case, for the primary energy input associated with the shortfall in electricity production versus the counterfactual, using the primary energy factor corresponding to grid electricity. The efficiency of heat and electricity production on a primary energy basis then defined as: (Heat delivered to consumers + Electricity generated in the counterfactual scheme) / (Primary energy associated with all fuel consumed and electricity imported). As for the efficiency of heat production on a primary energy basis, in this analysis the primary energy factor for grid electricity is in all cases the 2015 value.

Figure 11: Summary of heat supplied and delivered over the 20 year scheme lifetime for the HP in DH scheme and the counterfactual in Scenario 1.

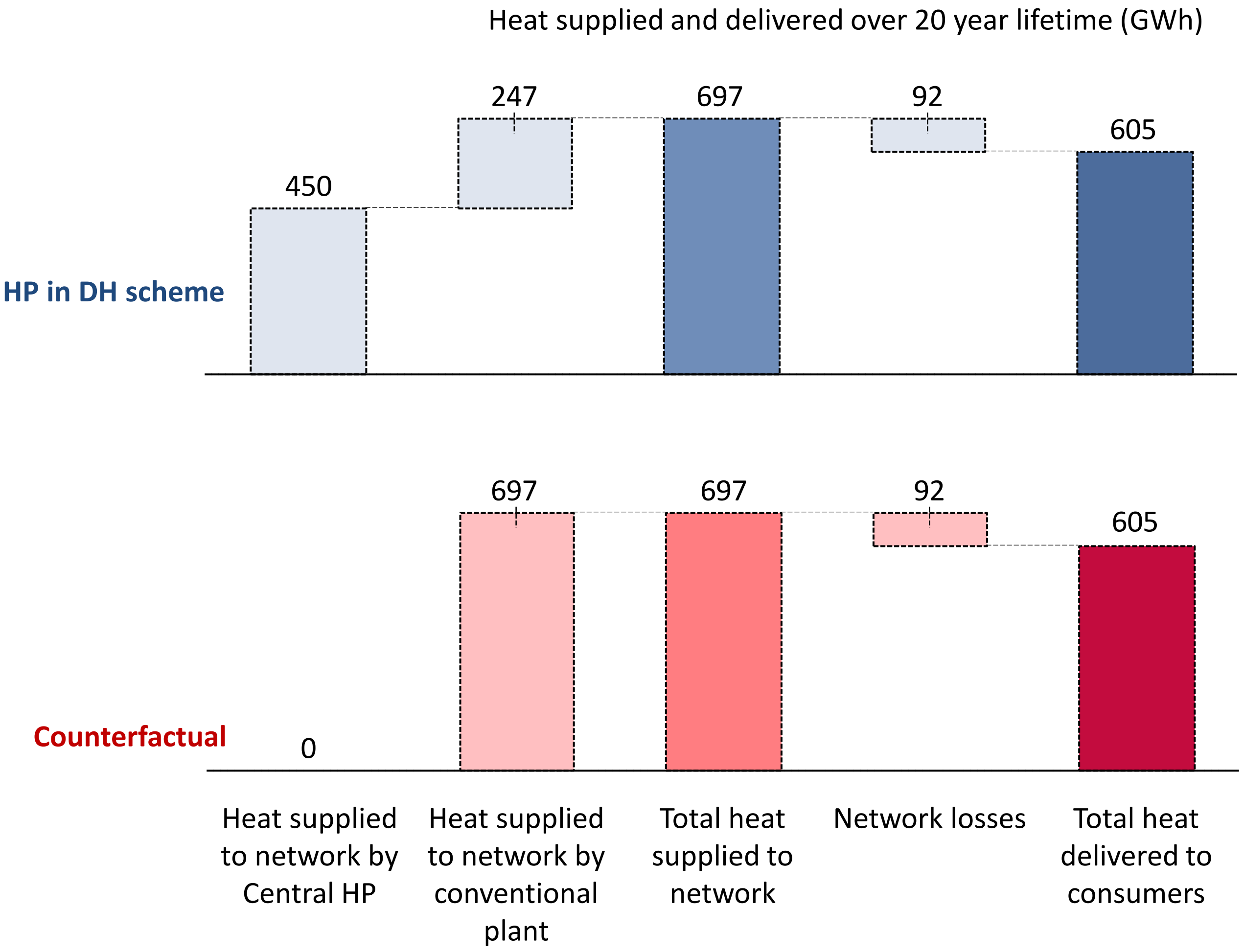

Table 9: Summary of key performance metrics for Scenario 1 using Central sensitivity assumptions

Parameter	***HP in DH scheme***	***Counterfactual***
TCO (£m)	48.4	35.8
Price of heat (p/kWh)	8.0	5.9
CO_2 intensity of delivered heat (gCO_2/kWh)	171	327
Efficiency of heat production on a primary energy basis (2015 value) (%)	54	39
Efficiency of heat and electricity production on a primary energy basis (2015 value)[22] (%)	57	63

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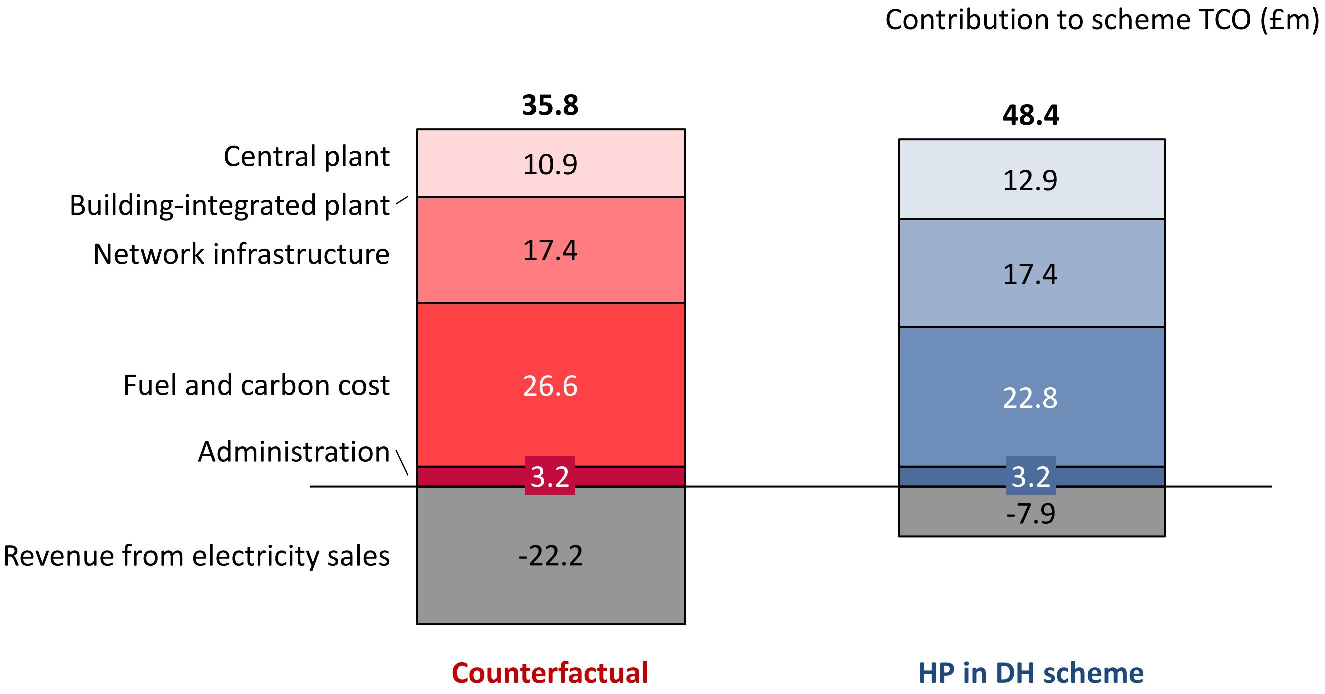
[22] See Footnote 21.

Figure 12: Breakdown of contributions to the TCO for the HP in DH scheme and the counterfactual in Scenario 1.



Sensitivity analysis: Central HP cost

Figure 13 shows the effect of uncertainty in the input data assumptions for the central HP cost. It can be seen that for the full range of the individual sensitivities on HP cost, the HP in DH scheme is less cost-effective than the counterfactual. For the Low HP cost value, the TCO of the HP in DH scheme is £43.9m, representing a premium of 23% versus the counterfactual.

Sensitivity analysis: Central HP COP

Figure 13 also shows the effect of variation in central HP COP. The HP in DH scheme is less cost-effective than the counterfactual in all cases. The High value for HP COP results in a TOC of £43.7m, representing a premium of 22% versus the counterfactual.

The CO_2 intensity of the HP in DH scheme, which varies only with the HP COP, is always significantly lower than that of the counterfactual, in the range 152-194 gCO_2/kWh as compared with 327 gCO_2/kWh for the counterfactual. In the Central case, this corresponds to CO_2 savings of 48%. Over one year, where the total heat delivered in this scenario is 30 GWh, this amounts to annual CO_2 savings of nearly 5 $ktCO_2$.

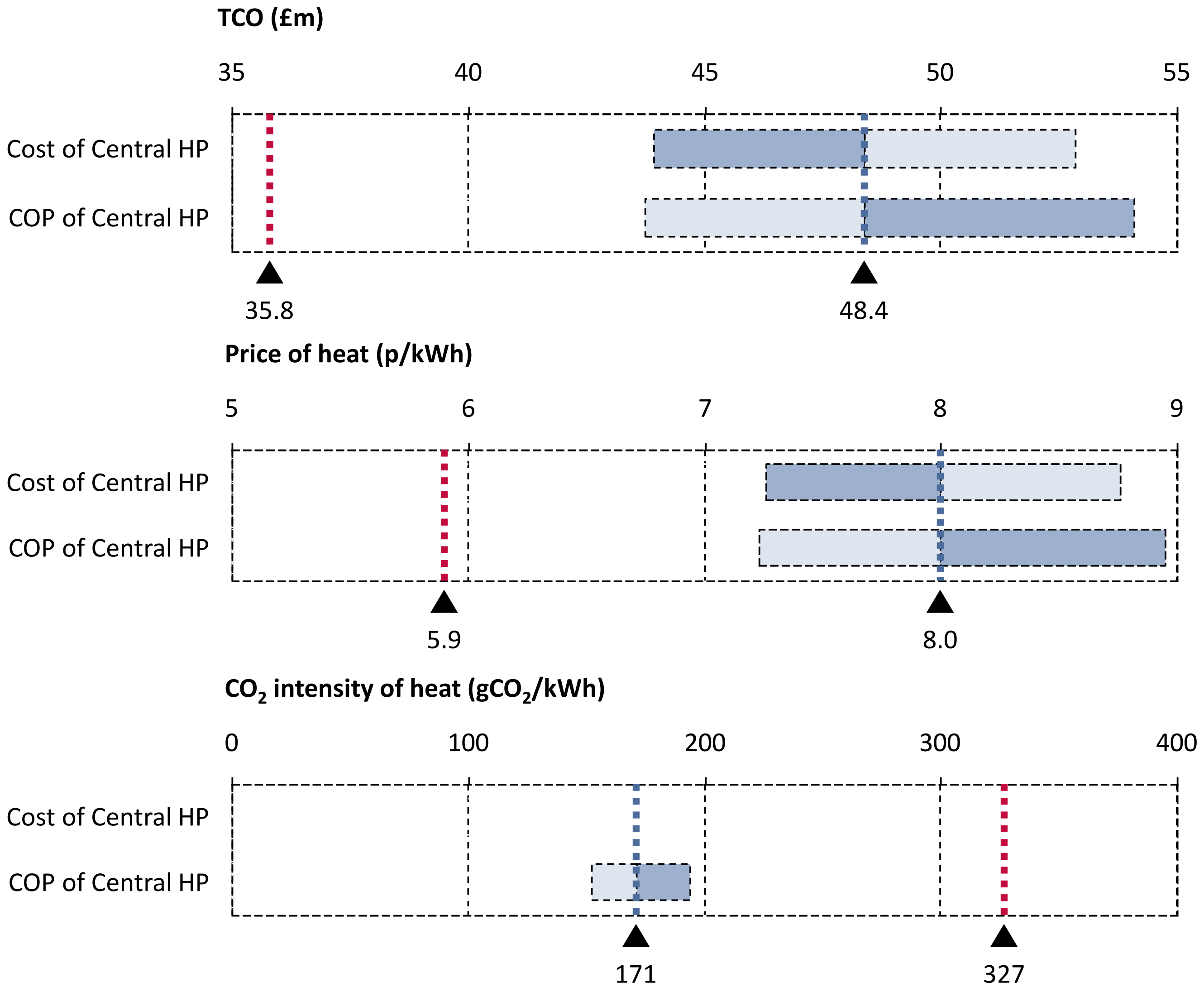


Figure 13: Impact of the Central HP cost and COP assumptions on key performance metrics for Scenario 1. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 8.

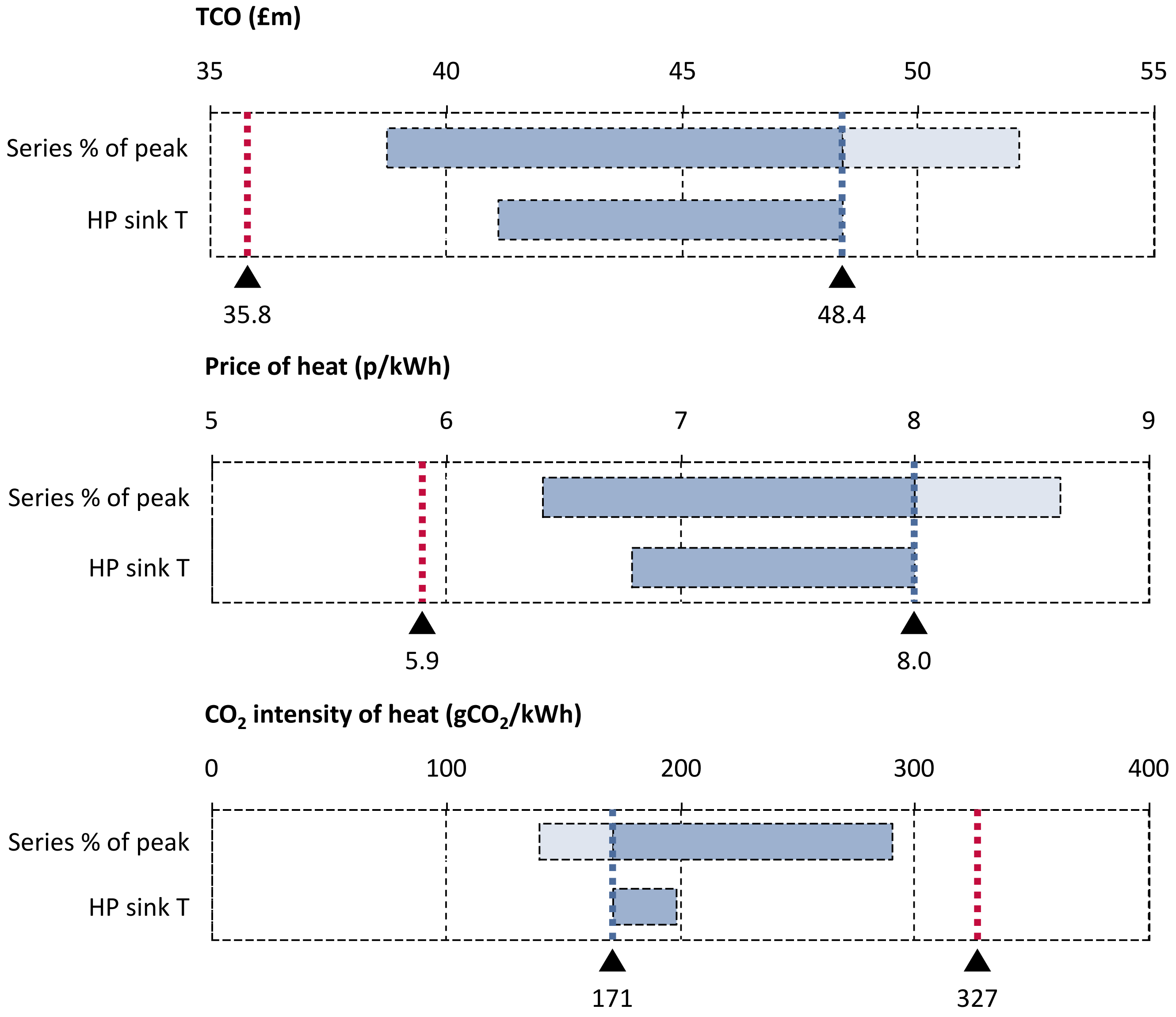
Sensitivity analysis: Fraction of the peak demand provided by the Central HP and series Gas CHP

Figure 14 shows the effect of varying the design of the HP in DH scheme in terms of the contribution of the HP and series gas CHP (relative to the parallel gas CHP). As the fraction of the peak demand provided by the HP and series gas CHP increases from 10% to 90%, the price of heat increases from 6.4 p/kWh to 8.6 p/kWh, as compared with the counterfactual value of 8.0 p/kWh. It can be seen that as the contribution of the HP and series gas CHP increases from 50% to 90%, the carbon intensity of heat is reduced by more than 18% to 140 gCO_2/kWh, while the TCO increases by less than 8% to £52.1m. This suggests that the cost of carbon savings would be significantly lower where the HP contribution is larger. This will be examined later in this section.

Sensitivity analysis: HP sink temperature

Figure 14 also shows the effect of varying HP sink temperature. As the HP sink T is reduced from 70ºC to 50ºC, and the contribution of the series gas CHP increases, the price of heat of the HP in DH scheme is reduced by 15% from 8.0 p/kWh to 6.8 p/kWh. However, the carbon intensity of heat increases by 16% to 198 gCO_2/kWh. The implication for the cost of carbon savings will be examined later in this section.

Figure 14: Impact of the % of the peak demand provided by the HP and series gas CHP, and of the HP sink temperature, on key performance metrics for Scenario 1. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 8.

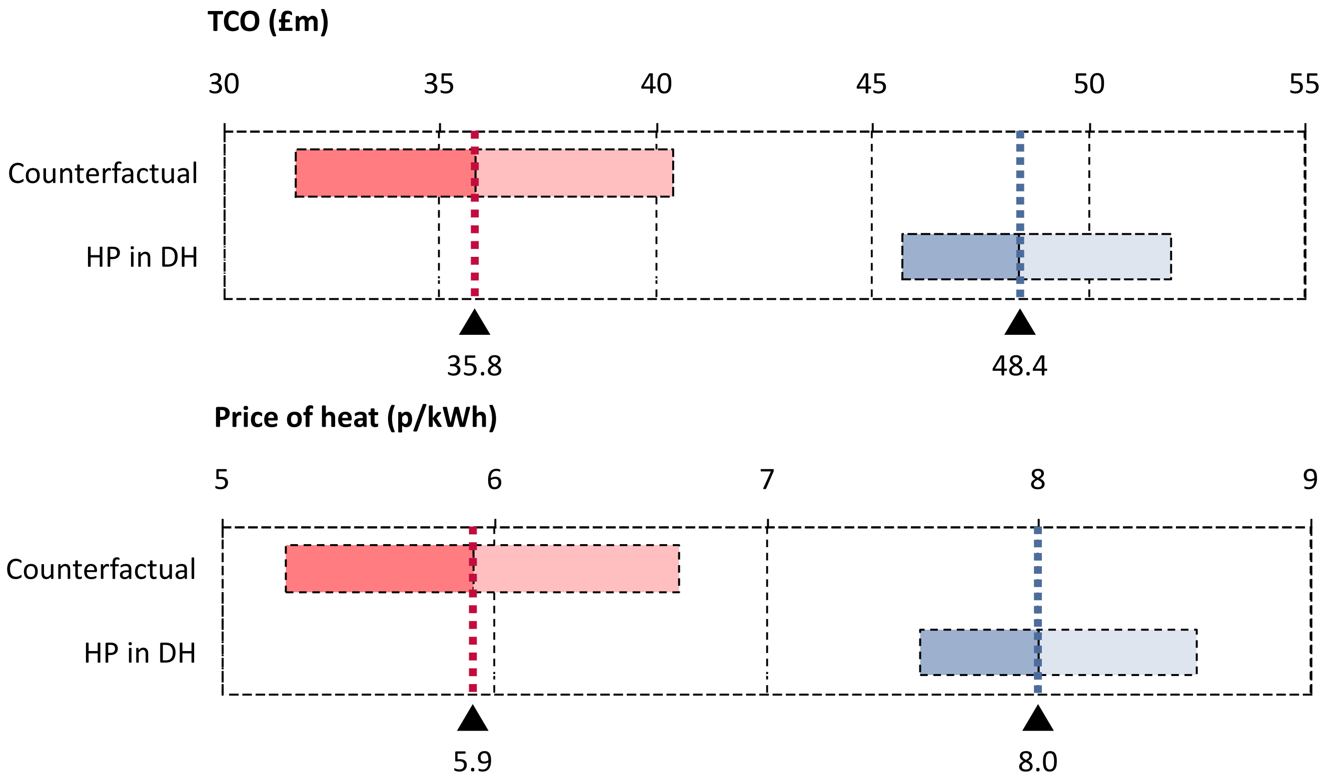


Sensitivity analysis: Electricity and gas prices

The impact of different fuel price scenarios is presented in Figure 15. It can be seen that in each of the Low, Central and High fuel price cases, the HP in DH scheme is less cost-effective than the counterfactual. We note that there is a somewhat higher uncertainty in the cost of the gas-based counterfactual than in the cost of the HP in DH scheme. This reflects the fact that in the

DECC fuel scenarios, there is a greater variation in the gas price between Low and High than in the electricity price.

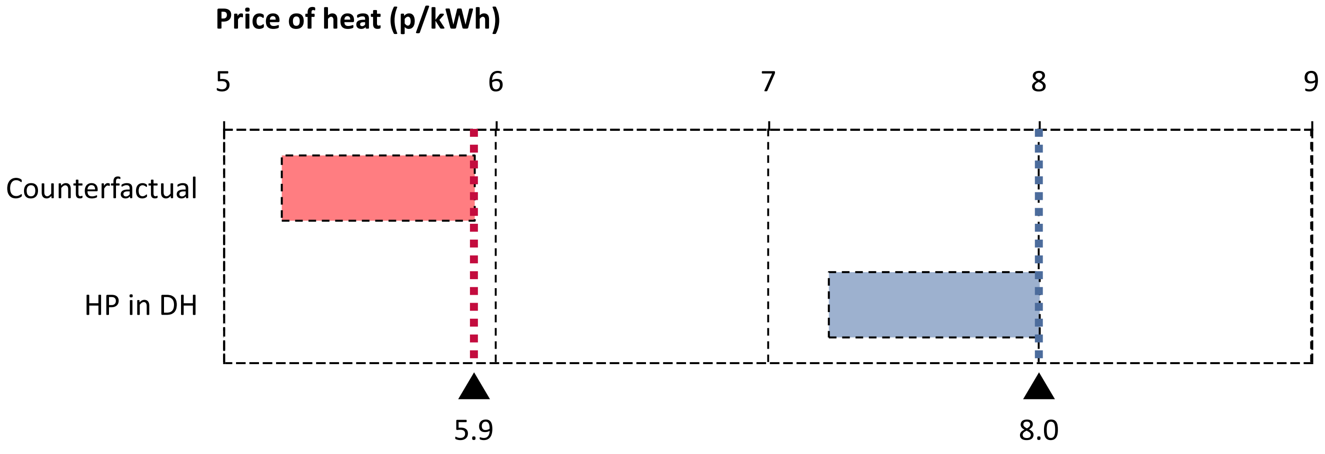
Figure 15: Impact of fuel price scenarios on key performance metrics for Scenario 1. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 8.



Sensitivity analysis: Scheme heat density

Figure 16 shows the impact on the price of heat of increasing the scheme heat density. As shown in Table 8, we have considered the impact of increasing the scheme heat density from 125 kWh/m^2/yr to 200 kWh/m^2/yr, without any change in the physical size of the network (that is, with the same transmission, distribution and service pipe lengths). In the case of the counterfactual, the price of heat decreases by 12% from 5.9 p/kWh to 5.2 p/kWh. In the case of the HP in DH scheme, the price of heat decreases by 10% from 8.0 p/kWh to 7.2 p/kWh. Even higher heat densities are, of course, possible. This serves simply to highlight the importance of the characteristics of the demand to be served by the heat network, relatively independent of the technologies chosen to supply the heat.

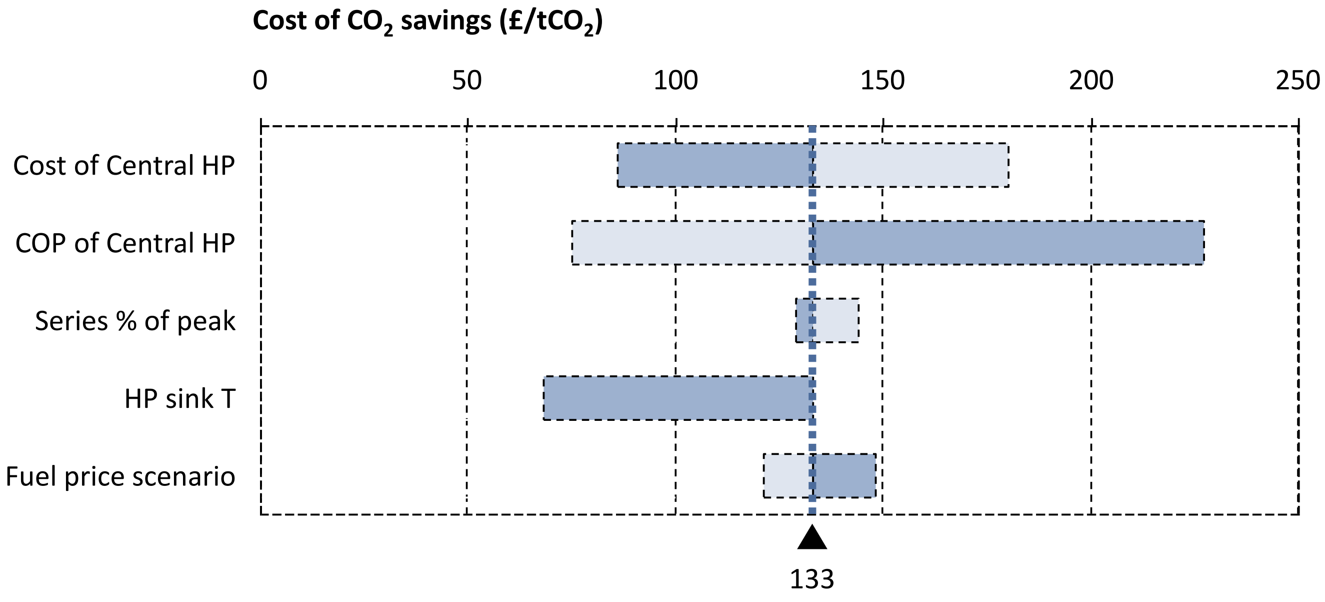
Figure 16: Impact of scheme heat density on the price of heat for Scenario 1. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 8.



Cost of CO_2 savings versus the counterfactual

Figure 17 presents the lifetime cost of carbon savings across the sensitivities described above. The cost is defined as the difference in the TCO of the HP in DH scheme and the counterfactual, divided by the difference in the total lifetime CO_2 emissions. The cost of CO_2 savings, at £133/tCO_2 using the Central sensitivity values, varies between £68/tCO_2 and £227/tCO_2. The lowest cost of carbon savings in this range is achieved by reducing the HP sink temperature from 70ºC to 50ºC. Variation in the COP and cost assumptions for the Central HP also has a large impact on the cost of the CO_2 savings.

Figure 17: Cost of CO_2 savings for various sensitivities for Scenario 3. The thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 8.



Summary of Scenario 1 results

Large-scale high temperature networks supplied by a central HP could be close to cost-competitive with the counterfactual based on gas-CHP

As demonstrated above, the cost-effectiveness of the type of HP in DH scheme represented in Scenario 1 is strongly dependent on the capital cost and COP of the HP. Using the Central HP cost assumptions, where the HP cost is £1,500/kW_{th}, results in a cost premium of 35% versus the counterfactual. Using the Low HP cost assumptions, where the HP cost is £500/kW_{th}, the premium is reduced to 23%. Similarly, in the Central and High HP COP cases, where the COP for a HP sink temperature of 70ºC is 2.2 or higher, the premium for the HP in DH scheme versus the counterfactual is 22-35%. The Low cost and High COP values are figures gathered through our industry consultation exercise that have already been achieved in a real scheme – the Star Refrigeration scheme in Drammen. Whether or not local supply chains will allow the same low cost to be achieved in the UK, and whether this COP value can be readily reproduced by others in the UK, has yet to be proven.

In the Central case, the HP in DH scheme in Scenario 1 delivers CO_2 savings of 48%

The HP in DH scheme described here also delivers large primary energy and carbon emissions savings. Using the Central assumptions, CO_2 savings of 48% are achieved, with a carbon intensity of delivered heat of 171 gCO_2/kWh as compared with 327 gCO_2/kWh.

Even for high heat density areas, a high carbon price will be required for DH schemes of any type to compete with individual gas boilers

It is nonetheless important to note that the price of delivered heat presented here for both the HP in DH scheme and the counterfactual is substantially higher than that expected in the case of individual condensing gas boilers in each building. The price of heat from individual gas boilers, discounted over the time period 2018-2038, can be estimated using the Central fuel price scenario as 4.0 p/kWh for domestic consumers and 3.2 p/kWh for commercial consumers[23]. This higher costs of heat for the DH schemes is largely a result of the network infrastructure required for DH, and applies equally to the counterfactual DH scheme.

We have studied the impact of increasing the scheme heat density from 125 $kWh/m^2/yr$, which is representative of a dense commercial development, to 200 $kWh/m^2/yr$. The price of heat for the HP in DH scheme is reduced from 8.0 p/kWh to 7.2 p/kWh, as the fixed length of network infrastructure is able to serve a higher demand. Nonetheless, it is evident that the DH scheme is unlikely to be able to compete with individual gas boilers without a large price levied on carbon emissions.

HP in DH schemes based on a high temperature network appear to be of high relevance to the UK

In summary, the type of HP in DH scheme described in Scenario 1 – a large-scale high temperature heat network with a central heat pump serving existing buildings – appears to be technically suitable for the UK as a competitive alternative to a gas-CHP based counterfactual.

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[23] Based on a 10 kW boiler, 86% efficient, with a capex of £1,500, an opex of £90 per year, a lifetime of 10 yrs and a load factor of 10%.

The key requirement for this scenario is a source of water, such as a river, sea or aquifer in close proximity to a dense, mixed-use development with high heat demand (typically existing buildings). The cost-effectiveness of this type of HP in DH scheme relative to the counterfactual is strongly dependent on the HP cost and COP achieved; however, evidence gathered from real schemes suggests that the Central sensitivity values can be achieved and even improved upon.

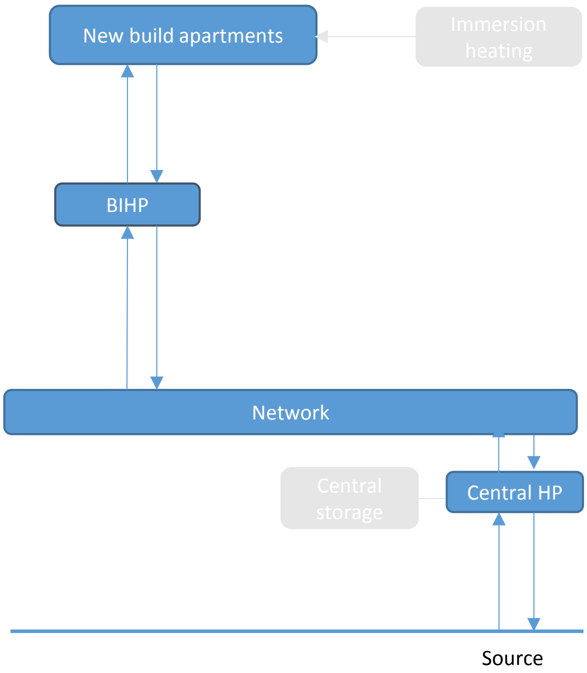
Scenario 2: Medium-scale low temperature heat network with a central heat pump and building-integrated heat pumps serving a new residential development

Description of scenario

The key characteristics of Scenario 2 are summarised in Table 10, and shown schematically in Figure 18. Scenario 2 consists of a large central water-source HP supplying heat to a medium-scale low temperature network, with a sea as the heat source. In winter, the sea is at 3ºC, and the HP delivers water to the network at 10ºC. In summer, when the sea is at 18ºC, the HP does not operate. The network delivers heat to a development of 800 new-build residential flats (arranged in 20 blocks), each with a water-source building-integrated HP (BIHP). The BIHPs then raise the temperature of the water and provide the space heating and hot water demand for the flats. In this scenario, no cooling demand is treated. Operational examples of schemes similar to this scenario include Duindorp (see the Case Studies section) and a scheme in London at Kingston Heights[24].

The counterfactual for this scheme, as summarised in Table 7, is a high temperature network supplied entirely by a gas CHP plant.

Figure 18: Schematic illustration of HP in DH scheme in Scenario 2



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[24] Before the cooling load at Kingston Heights was connected.

Table 10: Summary of key characteristics of Scenario 2

		HP in DH scheme	*Counterfactual*
Description of scheme and buildings served		Medium-scale scheme serving a new development consisting of 800 residential flats (arranged in 20 blocks)	
Heating	Heat source (source T)	Sea (3-18ºC)	None
	Central HP type (HP sink T)	WSHP (11ºC)	None
	Building-integrated HP type	WSHP	None
	Central conventional plant	None	Gas CHP
	Building-integrated conventional plant	None	None
	Network flow/return temperature (ºC)	18/11 (summer), 11/3 (winter)	70/50
	End-uses served by network	Space heating and DHW	Space heating and DHW
Cooling		No cooling demand treated	

Key parameters for sensitivity analysis

Table 11 details the sensitivity analyses carried out for Scenario 2.

Table 11: Summary of sensitivity parameter values used in Scenario 2

Parameter	**Low**	**Central**	**High**
Cost of Central HP (£/kW$_{th}$)	500	1,500	2,500
Cost of BIHPs (£/kW$_{th}$)	342	685	1,028
SH/DHW emitter temperatures (ºC)	30/60	40/60	50/60
Minimum BIHP capacity per flat (kW$_{th}$)	-	3	6
Number of BIHPs serving 800 flats	20 (one per block)	800 (one per flat)	-

Central HP and BIHP cost

As for Scenario 1, since HP cost data is a key assumption with a significant level of uncertainty, we test the performance of the scheme across a range of HP costs, in this case for both central HPs and BIHPs. The range of central HP and BIHP costs shown in Table 11 reflects the likely range of real values based on our data collection exercise and industry consultation.

Minimum BIHP capacity

An important factor in the economics of schemes including BIHPs is the minimum capacity of BIHP which can be installed in each flat. In order to ensure adequate performance, a minimum of 6 kW_{th} of BIHP has typically been installed in each flat (such as for the Duindorp scheme described in Section 3). However, there are now 3 kW_{th} products aimed at providing both the space heating and hot water demand for new, energy-efficient dwellings[25]. Given the demand case in this Scenario of new, energy-efficient flats, we take the case of a minimum BIHP capacity of 3 kW_{th} as our Central case. However, we recognise that this may not be the default case, and that this is likely to require accompanying measures such as the use of low-flow showers and a degree of behavioural change in terms of the management of hot water use. As a sensitivity, we study the impact on scheme cost of varying the minimum BIHP capacity from 3 kW_{th} to 6 kW_{th}.

Number of BIHPs serving 800 flats

As described above, where a BIHP is installed in each flat, a minimum of 3-6 kW_{th} of capacity is required for each flat. If, alternatively, one BIHP is used to serve a larger number of flats, diversity in the demand will lead to a reduced capacity requirement on a per flat basis. Furthermore, as was shown in Figure 9, as the BIHP capacity increases, the cost per kW_{th} decreases. Therefore, there is a strong cost advantage to serving multiple flats with a single BIHP, providing that the required capacity is not so large that there is no longer an 'off-the-shelf' option. In this sensitivity analysis, we consider the case of serving a whole block of 40 flats with a single large BIHP.

Space heating emitter temperature

In Scenario 2, the HP in DH scheme includes a low temperature network, while the counterfactual includes a high temperature network. As presented in Figure 19, a key advantage of a low temperature network is that the thermal losses are greatly reduced. A key disadvantage is that, typically, the power that can be extracted from a fixed mass flow rate of water in the network is lower (as the flow and return temperatures are typically closer), and hence larger diameter pipes are required, increasing the network capital cost. The network temperature also has an impact on the efficiency of the central HP and the BIHPs; all else being equal, raising the network temperature reduces the efficiency of the central HP, and increases the efficiency of the BIHPs. In this study, limitations on the available HP COP data mean that we are unable to study the performance of the HP in DH scheme in Scenario 2 over a range of network temperatures – COP data has been found only for the one network flow temperature used in the Duindorp scheme in the Netherlands.

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[25] See, for example, the Kensa 3kW 'Shoebox' at http://www.kensaheatpumps.com/product/shoebox-2/ (accessed online 16th March 2015).

We are, however, able to study the effect of varying the space heating emitter temperature. The emitter temperature will have an important impact on the BIHP efficiency; the lower the emitter temperature, the more efficient the BIHP will be for a fixed network temperature. This is of interest in relation to new developments. As buildings become more energy-efficient, it becomes feasible to provide space heating using lower emitter temperatures. Space heating emitter temperatures as low as 30-40ºC are now commonly used to heat highly efficient buildings with underfloor heating. The hot water temperature is typically less flexible. In order to reduce the risk of legionella in water systems, hot water is typically stored at temperatures of at least 60ºC. However, typical HPs are able to operate with two sink temperatures to provide space heating and hot water at different temperatures. Accordingly, we study the impact on scheme performance of a range of space heating emitter temperatures.

The same counterfactual, with a network flow temperature of 70ºC, is used for the range of emitter temperature sensitivities.

Scenario results and sensitivity to key parameters

Scenario results based on Central sensitivity assumptions

Figure 19 summarises the heat supplied by the various plant and the heat delivered to meet demand over the 20 year scheme lifetime in Scenario 2, using the Central sensitivity assumptions. It can be seen that in the HP in DH scheme, the full 71.0 GWh of heat supplied is supplied by HPs. Just over half of this heat is supplied by the central HP to the network, and the remainder of this heat is supplied by the BIHPs in raising the temperature of the network water to provide space heating and hot water directly to the buildings. Since the network is low temperature, at 11-18ºC compared with a ground temperature of 12ºC, there are negligible thermal losses. In the counterfactual, the network is high temperature. Therefore, thermal losses are significantly higher, at 5.8% of total heat delivered, and as such the gas-CHP plant is required to supply additional heat to the network.

Several key performance metrics for the Scenario 2 HP in DH scheme are shown in Table 12. In this case, the HP in DH is significantly less cost-effective than the counterfactual. The TCO of the HP in DH scheme is £8.1m, as compared with £4.6m for the counterfactual. Accordingly, the price of heat is higher, at 11.4 p/kWh as compared with 6.5 p/kWh for the counterfactual.

Figure 20 presents the breakdown of the TCO for the HP in DH and counterfactual schemes. It can be seen that the cost of the network infrastructure is the largest single component of the TCO in each case, and is £0.3m higher for the HP in DH scheme than for the counterfactual. This is due to the requirement for pipes of a larger diameter in the low temperature HP in DH scheme, resulting from the smaller difference between flow and return temperature, leading to higher pipe costs. However, the premium for the cost of the heating equipment in the HP in DH scheme versus the counterfactual is even more significant, at £1.6m. The BIHPs contribute the majority of the heating plant cost. Finally, in a similar way to Scenario 1, the reduced fuel and carbon costs of the HP in DH scheme versus the counterfactual are more than outweighed by the loss of revenue from electricity sales.

Since all heat supplied in the HP in DH scheme is supplied by HPs, the carbon intensity and total efficiency on a primary energy basis are much improved relative to the counterfactual. The CO_2 intensity of delivered heat is 46 gCO_2/kWh for the HP scheme as compared with 295 gCO_2/kWh for the counterfactual. This corresponds to lifetime CO_2 savings of 18 $ktCO_2$, at a cost of £196/tCO_2.

The efficiency of heat production on a primary energy basis is 126% for the HP in DH case, reflecting the high COP values for the Central HP (at 11.0) and BIHPs (at 4.1). The efficiency of heat and electricity production on a primary energy basis is 69% for the counterfactual and 71% for the HP in DH scheme. Therefore, even using the 2015 primary energy factor for grid electricity, the HP in DH scheme is expected to bring primary energy savings.

In the following sections, we examine the dependence of these key performance metrics on the parameters shown in Table 11.

Figure 19: Summary of heat supplied and delivered over the 20 year scheme lifetime for the HP in DH scheme and the counterfactual in Scenario 2 using the Central sensitivity assumptions.

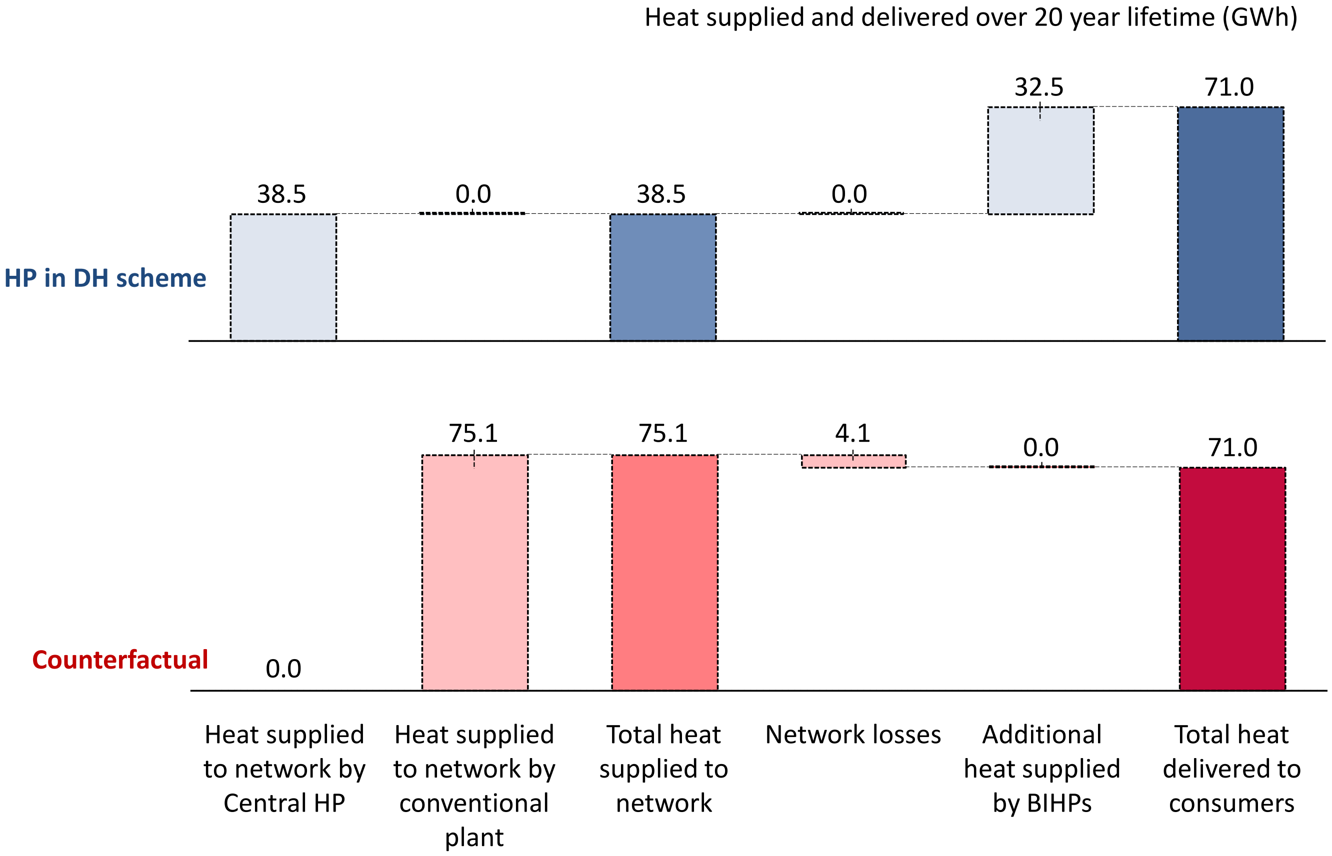
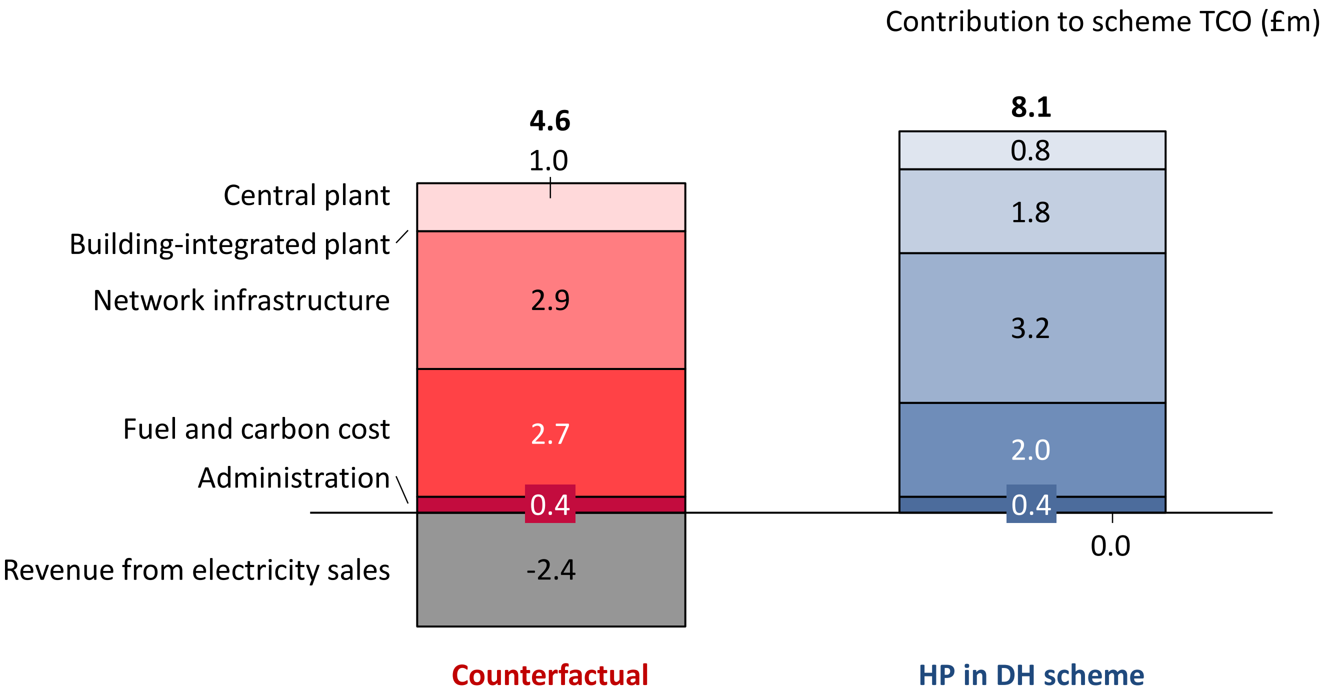


Table 12: Summary of key performance metrics for Scenario 2 using the Central sensitivity assumptions.

Parameter	*HP in DH scheme*	*Counterfactual*
TCO (£m)	8.1	4.6
Price of heat (p/kWh)	11.4	6.5
CO_2 intensity of delivered heat (gCO_2/kWh)	46	295
Efficiency of heat production on a primary energy basis (2015 value) (%)	126	44
Efficiency of heat and electricity production on a primary energy basis (2015 value)[26] (%)	71	69

Figure 20: Breakdown of contributions to the TCO for the HP in DH scheme and the counterfactual in Scenario 2 using the Central sensitivity assumptions.



Sensitivity analysis: Central HP cost

Figure 21 shows the impact of the Central HP cost assumptions on a number of key performance metrics. It can be seen that the TCO of the HP in DH scheme remains significantly higher than the counterfactual across the range of costs considered. The price of heat for the

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[26] See Footnote 21.

HP in DH scheme remains above 10 p/kWh in each case. The CO_2 intensity of delivered heat does not vary with the HP cost data.

Sensitivity analysis: BIHP cost

Figure 21 also shows the impact of the BIHP cost assumptions on the same performance metrics. As for the Central HP cost sensitivity, the price of heat for the HP in DH scheme remains above 10 p/kWh for all BIHP cost assumptions, and thus higher than the cost of the counterfactual.

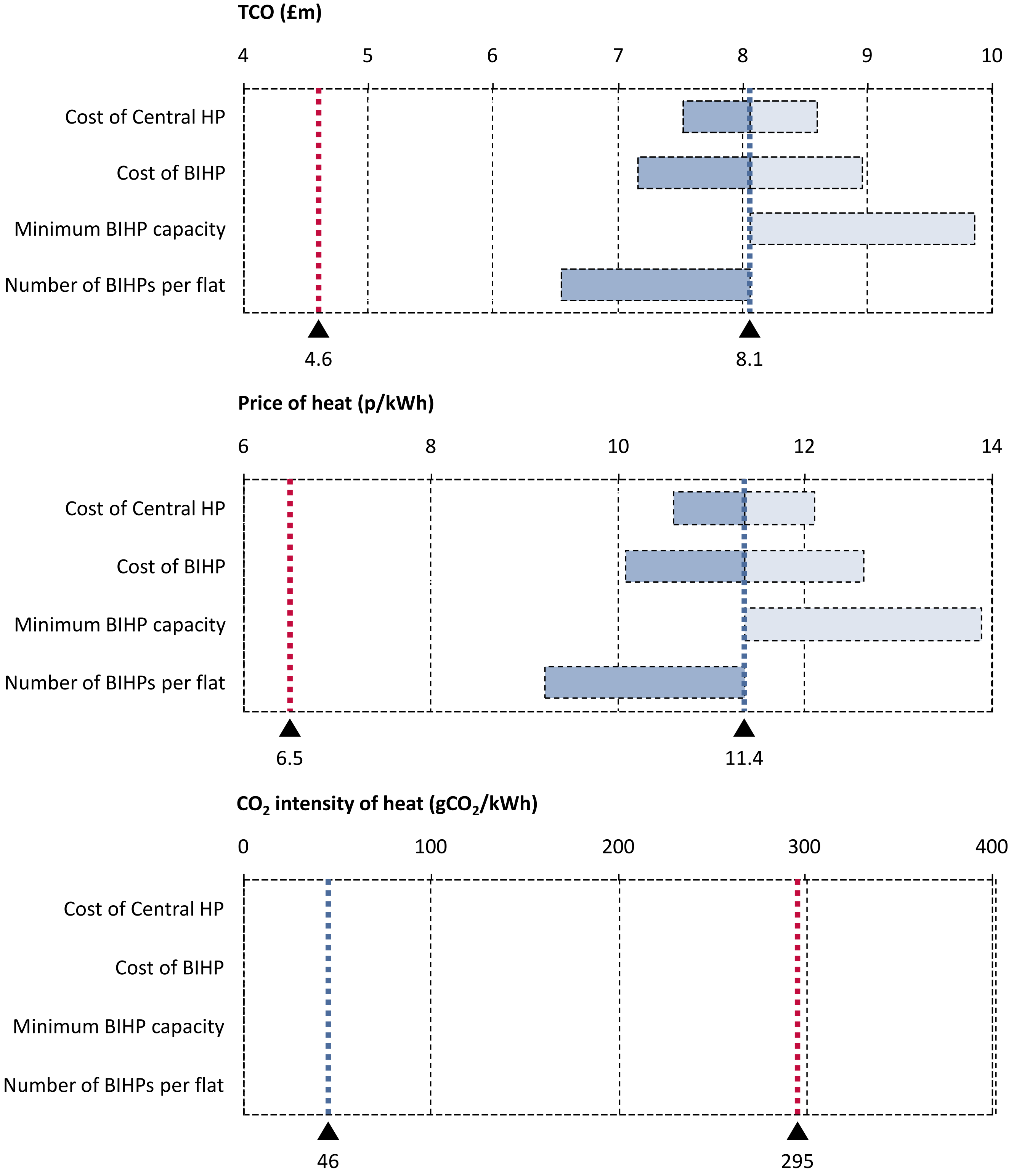
Sensitivity analysis: Minimum BIHP capacity

The BIHP capacity per flat has a large impact on the economics of the HP in DH scheme. Where 6 kW_{th} of BIHP capacity is installed in each flat, rather than 3 kW_{th}, the TCO increases by 22% from £8.1m to £9.9m. In line with this, the price of heat increases from 11.4 p/kWh to 13.9 p/kWh.

Sensitivity analysis: Number of BIHPs serving 800 flats

The number of BIHPs serving the 800 flats also has a large impact on the economics of the scheme. By using 20 large BIHPs to serve each of the blocks of flats, taking advantage of a reduced capacity requirement per flat (due to the diversity of demand) and the lower cost per kW_{th} of larger BIHPs, the price of heat is reduced from 11.4 p/kWh to 9.2 p/kWh, which represents a 42% premium versus the counterfactual.

Figure 21: Impact of the Central HP cost and BIHP cost, capacity and number assumptions on key performance metrics for Scenario 2. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 11.



Sensitivity analysis: Space heating emitter temperature

Figure 22 shows the impact of variation in the space heating emitter temperature on the same key performance metrics. It can be seen that, while there is an impact on the cost of the HP in

DH scheme, with lower emitter temperature leading to a lower TCO and price of heat, the impact is small compared with the difference between the HP in DH scheme and the counterfactual.

The reduction in the price of heat is due to an increase in the overall COP of the BIHP. Across the range of emitter temperatures, the Central HP works between same temperatures (between the source temperature of 3ºC and the network flow temperature of 10ºC, in winter only), such that its COP remains the same. As the space heating emitter temperature reduces from 50ºC to 30ºC[27], however, the BIHP COP increases from 3.6 to 4.6. The increase in system efficiency results in a reduction in fuel spend over the scheme lifetime, from a discounted cost of £2.2m in the High emitter temperatures case to a cost of £1.8m in the Low emitter temperatures case. This results in the relatively modest reduction in the TCO observed in Figure 22.

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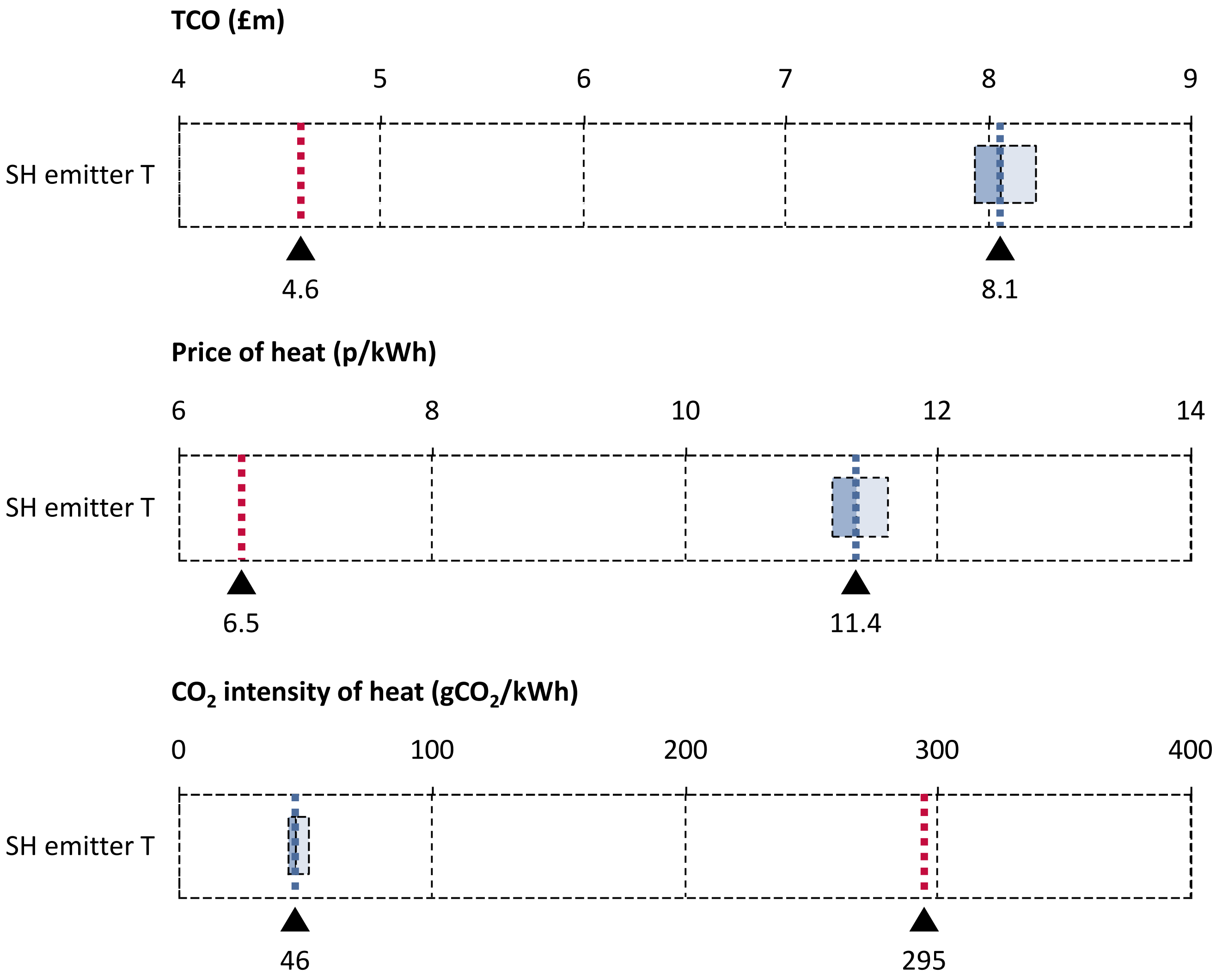
[27] We emphasise that across the range of space heating emitter temperatures studied here, the BIHP continues to provide water for DHW at 60ºC. Typical HPs are able to operate at two sink temperatures to provide space heating and hot water at different temperatures.

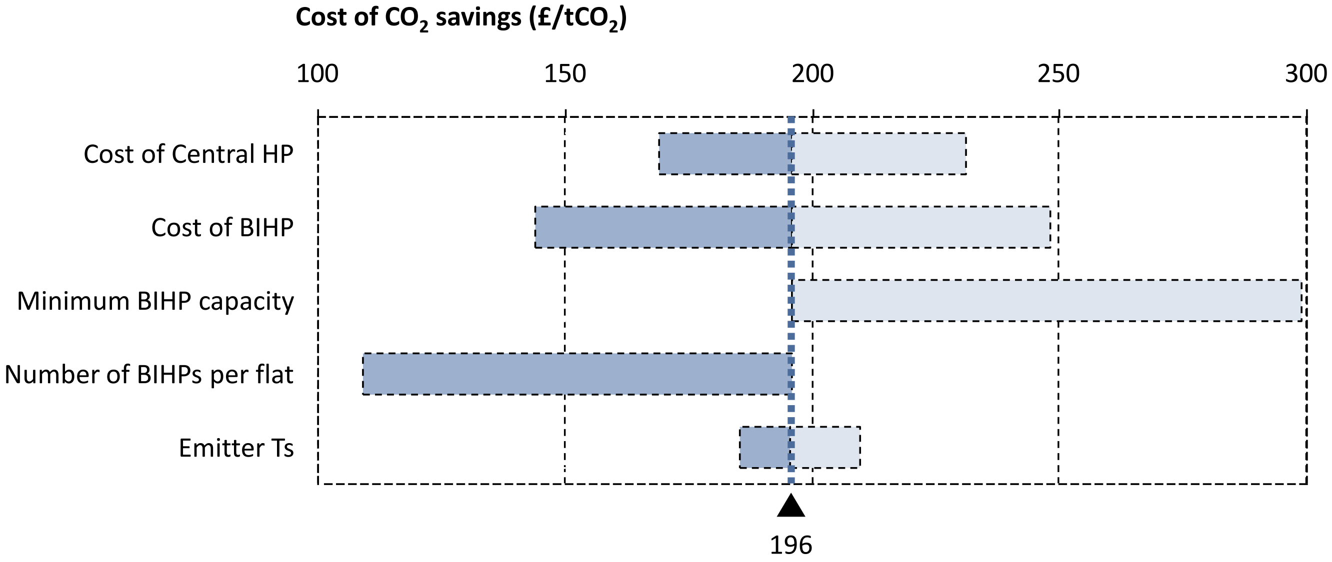
Figure 22: Impact of the space heating emitter temperature on key performance metrics for Scenario 2. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 11.



Cost of CO_2 savings versus the counterfactual

Figure 23 presents the lifetime cost of carbon savings across a number of the sensitivities described above. The cost of CO_2 savings, at £196/tCO_2 using the Central sensitivity values, varies between £109/tCO_2 and £299/tCO_2 across the individual sensitivities. The largest individual impact on the cost of the CO_2 savings relates to the minimum BIHP capacity and the number of BIHPs per flat. This reflects the fact that installing a BIHP in each flat, and sizing it in order to meet an individual dwelling's peak hot water needs, results in significant over-sizing outside these times of peak demand.

Figure 23: Cost of CO_2 savings for various sensitivities for Scenario 2. The thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 11.



Summary of Scenario 2 results

While the energy and environmental performance of the HP in DH scheme in Scenario 2 is excellent, it is likely to be more costly than the counterfactual

On the evidence presented above, the HP in DH scheme in Scenario 2 – a medium-scale low temperature heat network with a central heat pump and building-integrated heat pumps serving a new residential development – is likely to be less cost-effective than the counterfactual high temperature network based on gas-CHP. Where the price of heat for the counterfactual is 6.5 p/kWh, the price of heat from the HP in DH scheme is in the range 9-14 p/kWh.

The key strength of the scheme is in its energy and environmental performance. Since all the heat is supplied through HPs, unlike in Scenario 1 where the Central HP is backed up by gas-based plant, the scheme is highly energy efficient. Furthermore, since the HP in DH scheme is based entirely on electricity it is compatible, in theory, with zero carbon heating. Over the range of space heating emitter temperatures studied here, for a scheme build year of 2018[28], the HP in DH scheme achieves CO_2 savings in the range 83-85% versus the counterfactual. Over the range of individual sensitivities studied above, the CO_2 savings carry a cost in the range £109-299/tCO_2.

Increasing the number of flats served by a single BIHP could make this type of scheme more competitive

Serving multiple flats with a single BIHP can lead to significant cost reductions, taking advantage of a reduced capacity requirement per flat (due to the diversity of demand) and the lower cost per kW_{th} of larger BIHPs. In the Scenario studied here, using 20 large BIHPs to serve

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[28] The scheme lifetime is 20 years, so the savings presented here correspond to the carbon intensity of grid electricity over the period 2018-2038.

each of the blocks of flats, rather than 800 small BIHPs in each flat, leads to a reduction in the price of heat from 11.4 p/kWh to 9.2 p/kWh. This represents a 42% premium versus the counterfactual, making the HP in DH a significantly more competitive option. Given the low carbon intensity of heat for the scheme, the cost of CO_2 savings falls to £109/tCO_2.

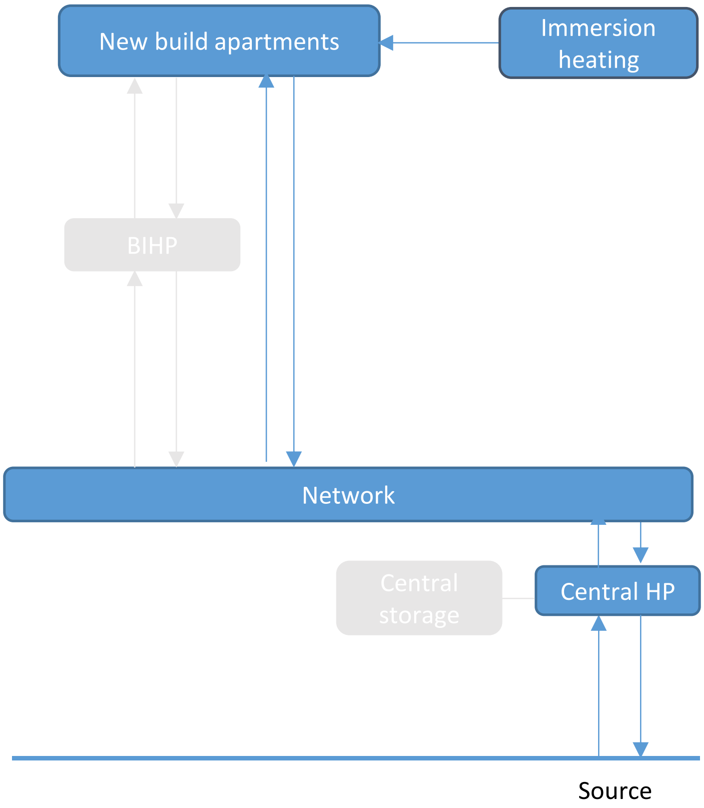
Scenario 3: Small-scale medium temperature heat network with central heat pump supplying a new residential development

Description of scenario

The key characteristics of Scenario 3 are summarised in Table 13 and shown schematically in Figure 24. Scenario 3 consists of a central HP supplying heat to a small-scale medium temperature network, which delivers water at 45ºC[29] to a development of 400 new, thermally-efficient residential flats, arranged in 3 blocks. The central HP is a water-source heat pump, and its source is a river at 10ºC year-round. The network serves the space heating demand of the flats directly. Electric immersion heaters in each flat heat the pre-heated water from the network further to provide the hot water demand. In this scenario, no cooling demand is treated.

The counterfactual for this scheme, as summarised in Table 13, is a high temperature network supplied entirely by a gas boiler. This scheme and the next (Scenario 4) are smaller in scale than the previous two; as such it has been assumed that boilers are likely to be chosen over CHP for the smaller heat networks.

Figure 24: Schematic illustration of HP in DH scheme in Scenario 3



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[29] Note that the network flow temperature varies in the space heating emitter temperature sensitivity for Scenarios 3 and 4.

Table 13: Summary of key characteristics of Scenario 3

		HP in DH scheme	*Counterfactual*
Description of scheme and buildings served		Small-scale scheme serving a new development consisting of 400 residential flats (in 10-storey blocks)	
Heating	Heat source (source T)	River (10ºC)	None
	Central HP type (HP sink T)	WSHP (45ºC)	None
	Building-integrated HP type	None	None
	Central conventional plant (capacity)	None	Gas boiler
	Building-integrated conventional plant	Electric immersion heaters	None
	Network flow/return temperature (ºC)	45/35 (varies with sensitivity on space heating emitter T)	70/50
	End-uses served by network	Space heating and DHW	Space heating and DHW
Cooling		No cooling demand	

Key parameters for sensitivity analysis

Table 14 details the sensitivity analyses carried out for Scenario 3.

Table 14: Summary of sensitivity parameter values used in Scenario 3

Parameter	Low	Central	High
Cost of Central HP (£/MW$_{th}$)	500,000	1,500,000	2,500,000
COP of Central HP (at 45ºC sink T)	3.3	4.5	6.2
Space heating emitter temperature (ºC)	30	40	50
DHW emitter temperature (ºC)	50	60	70
Heat pump technology	Water-source heat pump compared to two types of ground-source heat pump		

Central HP cost and COP

As for the earlier scenarios, we test the performance of the scheme across a range of Central HP costs, as shown in Table 14.

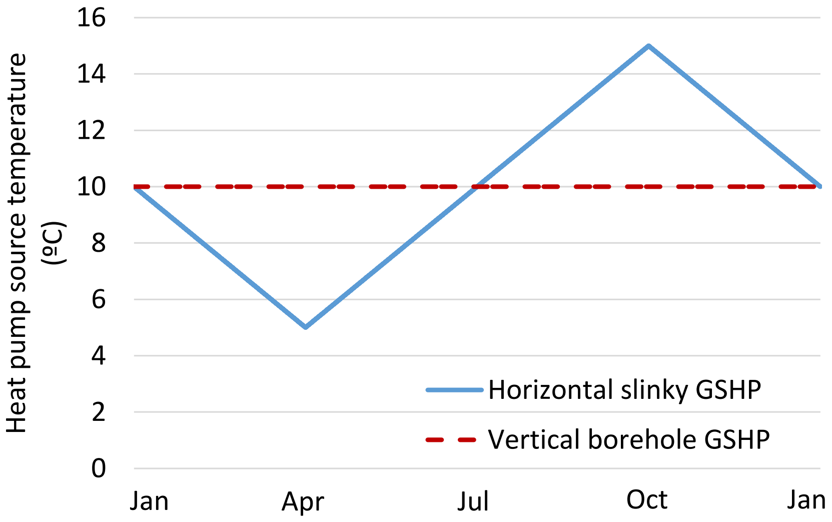
Space heating and hot water emitter temperatures

In this scenario, we examine the possibility of the network providing space heating directly to thermally-efficient new-build flats at a lower temperature than in a conventional DH scheme. In the Central case, the network flow temperature is 45ºC, directly supplying space heating emitters operating at 40ºC. Advantages of using a reduced network flow temperature include a higher COP for the Central HP, and reduced thermal losses from the network. The main disadvantage is the greater requirement for electrical hot water heating within the building. The hot water temperature is therefore also an important factor. While industry guidance means that hot water is typically stored, or at least periodically heated, to above 60ºC, it is possible to deliver water below this temperature. In order to understand the potential cost or benefit to reducing the space heating and hot water emitter temperatures, we examine the performance of the HP in DH scheme over a range of emitter temperatures, as shown in Table 14.

Heat pump technology (water-source or ground-source)

We also make a comparison between heat pump technology, comparing the water source heat pump used in the Central case with two types of ground source heat pump (GSHP) installation, with either a vertical borehole or a horizontal ‘slinky’. Ground temperature and installation cost vary for each of the GSHP installations. Since the model takes ground temperature as an exogenous input, ground temperature profiles were created from simple functions for each of the two GSHP installation types.

Figure 25: Ground temperature profiles used for vertical borehole and horizontal ‘slinky’ GSHP installations.



Based on industry consultation, the costs associated with the groundworks for GSHP systems comprise around 60% of the capital cost for vertical borehole schemes and 40% for horizontal installations. The cost of ground works was therefore added on to the cost of a large WHSP, leading to the costs shown in Table 15.

Table 15: Cost of GSHPs used in the heat pump technology sensitivity in Scenario 3

Cost of HP technology (£/MW_{th})	Low	Central
Central WSHP	500,000	1,500,000
Central GSHP (vertical borehole)	1,250,000	3,750,000
Central GSHP (horizontal 'slinky')	833,333	2,500,000

Scenario results and sensitivity to key parameters

Scenario results based on Central sensitivity assumptions

Figure 26 summarises the heat supplied by the various plant and the heat delivered to meet demand over the 20 year scheme lifetime in Scenario 3. The values shown correspond to the Central sensitivity assumptions; since the network temperature varies with the space heating emitter sensitivity for this scenario, the network losses, and hence heat supplied to the network also varies.

It can be seen in Figure 26 that the thermal network losses are reduced in the HP in DH scheme relative to the counterfactual, as expected given the reduced network temperature. In the HP in DH scheme, the majority of the heat is supplied by the Central HP, with only around 13% of the total heat supplied by the electric immersion heaters in the buildings.

A number of key performance metrics relating to Scenario 3 are shown in Table 16. Using the Central sensitivity assumptions, the TCO of the HP in DH scheme, at £3.4m, is approximately 48% more expensive than the TCO of the counterfactual, at £2.3m. The price of heat is accordingly higher, at 9.5 p/kWh as compared with 6.4 p/kWh for the counterfactual.

Figure 27 presents the breakdown of the TCO for the HP in DH and counterfactual schemes. Again, the network infrastructure is the single largest contribution to the cost, and is slightly higher in the HP in DH scheme due to the lower network flow-return temperature difference and the associated requirement for larger pipes. However, the key difference in cost between the HP in DH scheme and the counterfactual scheme is the cost associated with the heating plant. This reflects the very low cost of the central gas boiler relative to the central HP and building-integrated immersion heaters. This accounts for almost all the difference between the scheme TCO values.

The HP in DH scheme also entails higher fuel costs. This is despite a significantly higher system efficiency. Total efficiency on a primary energy basis is 120% for the HP in DH case as compared with 74% for the counterfactual, amounting to a 38% reduction in primary energy consumption relative to the counterfactual, using the 2015 primary energy factor for electricity. Since a decarbonising grid will mean a decreasing primary energy factor for grid electricity, the primary energy savings would be significantly higher than this when considered over the scheme lifetime. The higher fuel costs associated with the HP in DH scheme therefore reflect the higher price of electricity relative to gas.

Given the higher efficiency and the fact that the system is based entirely on electricity, the carbon intensity is much improved relative to the counterfactual. The CO_2 intensity of delivered heat is 49 gCO_2/kWh for the HP scheme as compared with 224 gCO_2/kWh for the counterfactual. This represents a reduction in CO_2 emissions of nearly 80%, and corresponds to lifetime CO_2 savings of 6 $ktCO_2$ at a cost of £179/tCO_2.

In the following sections, we examine the dependence of these key performance metrics on the parameters shown in Table 14.

Figure 26: Summary of heat supplied and delivered over the 20 year scheme lifetime for the HP in DH scheme and the counterfactual in Scenario 3 using the Central sensitivity assumptions.

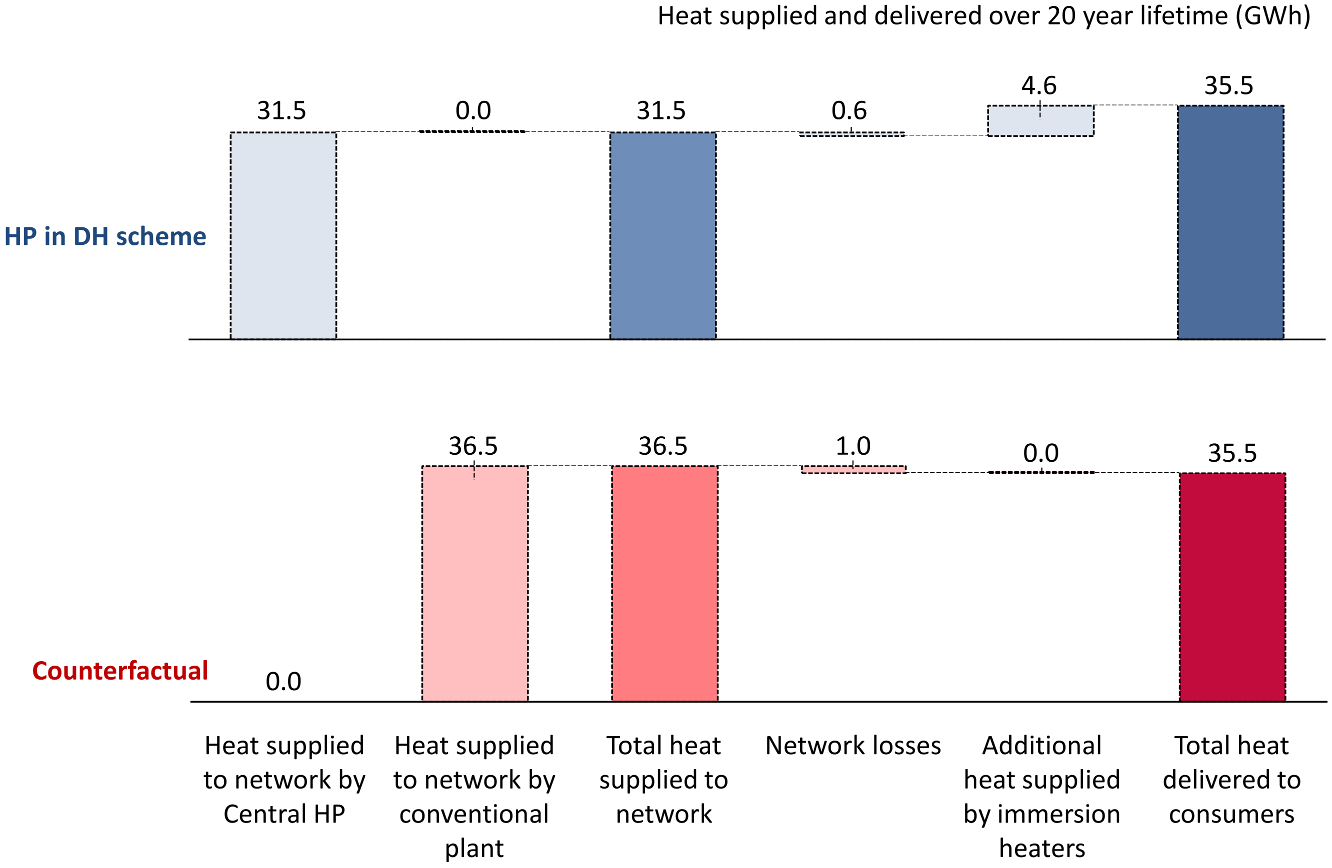
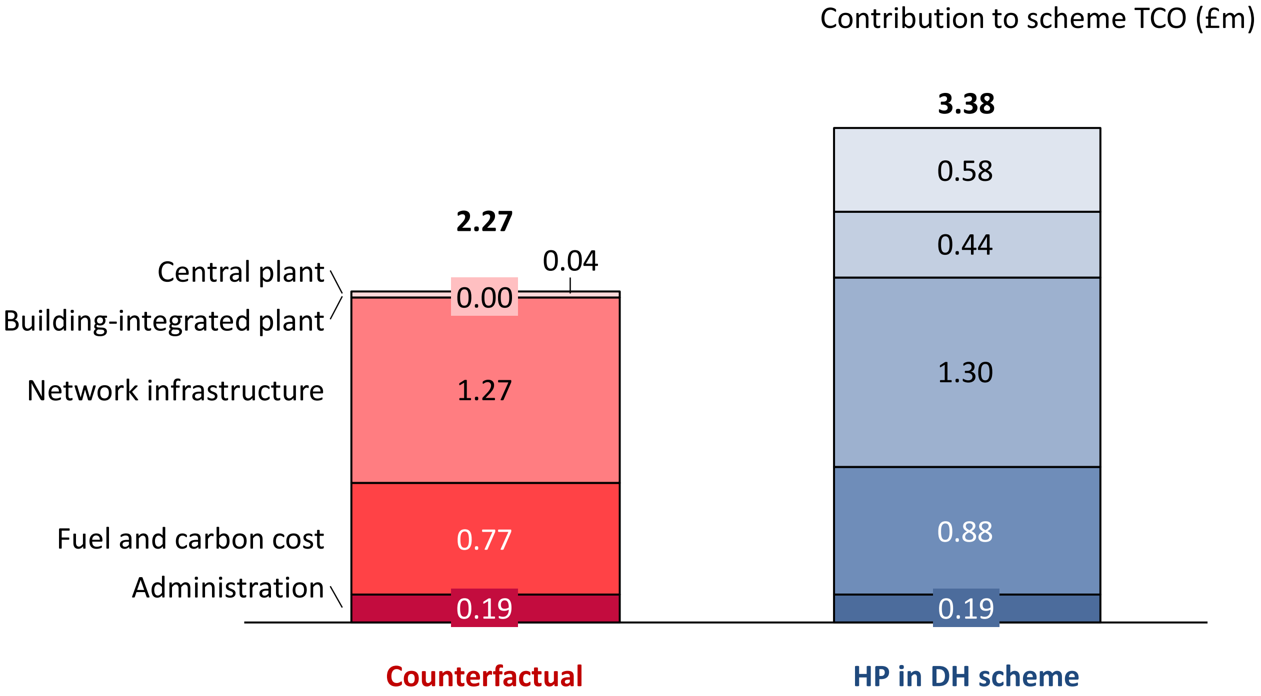


Table 16: Summary of key performance metrics for Scenario 3 using the Central sensitivity assumptions.

Parameter	***HP in DH scheme***	***Counterfactual***
TCO (£m)	3.4	2.3
Price of heat (p/kWh)	9.5	6.4
CO_2 intensity of delivered heat (gCO_2/kWh)	49	224
Efficiency of heat production on a primary energy basis (2015 value) (%)	120	74
Efficiency of heat and electricity production on a primary energy basis (2015 value)[30] (%)	No electricity production	

Figure 27: Breakdown of contributions to the TCO for the HP in DH scheme and the counterfactual in Scenario 3 using the Central sensitivity assumptions.



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[30] See Footnote 21.

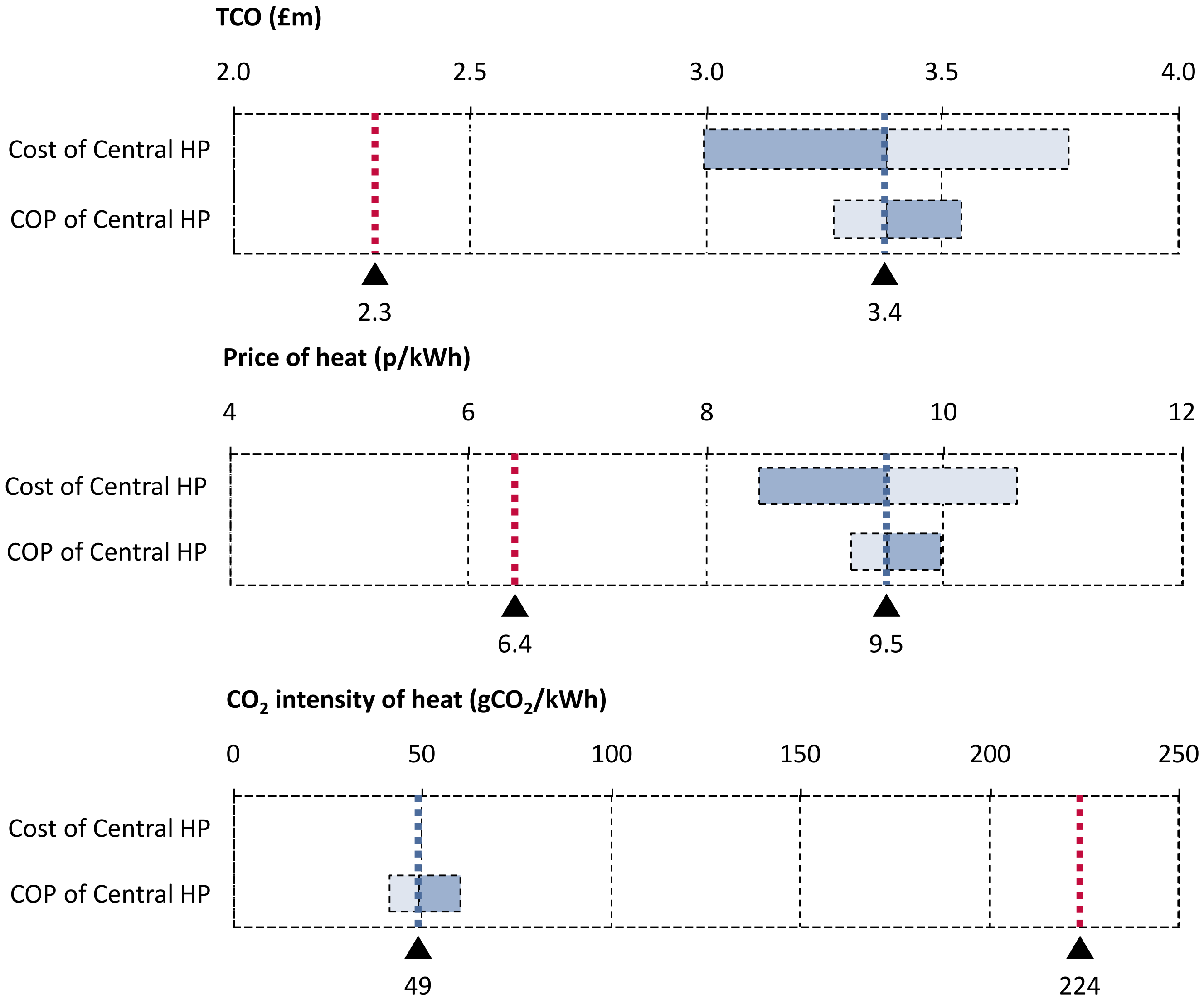
Sensitivity analysis: Central HP cost

Figure 28 shows that over the range of HP cost values studied, the TCO of the HP in DH scheme remains significantly higher than the TCO of the counterfactual. In terms of the price of heat, the premium for the HP in DH scheme ranges from 32%, using the Low HP cost sensitivity, to 66%, using the High HP cost sensitivity.

Sensitivity analysis: Central HP COP

Figure 28 also shows the dependence of the TCO and price of heat on the HP COP. This has a smaller impact than the HP cost, and across the range of COP values the TCO of the HP in DH scheme remains higher than the TCO of the counterfactual.

Figure 28: Impact of the Central HP cost and COP assumptions on key performance metrics for Scenario 3. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 14.



Sensitivity analysis: Space heating and hot water emitter temperatures

Figure 29 shows the impact of variation in the space heating and hot water emitter temperatures on the key performance metrics. While there is an impact on the TCO and price of heat by varying the temperatures, the impact is smaller than the difference between the HP in DH scheme and the counterfactual.

It can be seen that reducing the space heating emitter temperature, and thereby reducing the network flow temperature, results in a slightly higher overall cost. This can be explained by the variation in efficiency of heat production, as shown in Figure 30. It can be seen that a decrease in the space heating emitter temperature from 40ºC in the Central case to 30ºC in the Low case (corresponding to a decrease in the network flow temperature from 45ºC to 35ºC), results in a decrease in the efficiency of heat production from 120% to 114%. This is despite an increase in the Central HP COP from 4.5 to 6.2 and a reduction in network thermal losses from 1.7% to 1.1%. The overall efficiency penalty therefore reflects the increasing contribution of the comparatively inefficient electric immersion heaters, which are required to heat the water an additional 10ºC. Since both the Central HP and the immersion heaters are based on electricity, this results in an increase in total electricity consumption and increased cost.

Figure 29 shows that reducing the hot water emitter temperature from 60ºC to 50ºC (using the Central sensitivity value for the network flow temperature of 45ºC) leads to a reduction in the TCO of the HP in DH scheme. Figure 30 presents the corresponding increase in efficiency of heat production from 120% to 144%. This reflects the reduced contribution of the electric immersion heaters as the temperature ‘boost’ required to provide hot water diminishes.

Figure 29: Impact of the emitter temperatures on key performance metrics for Scenario 3. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 14.

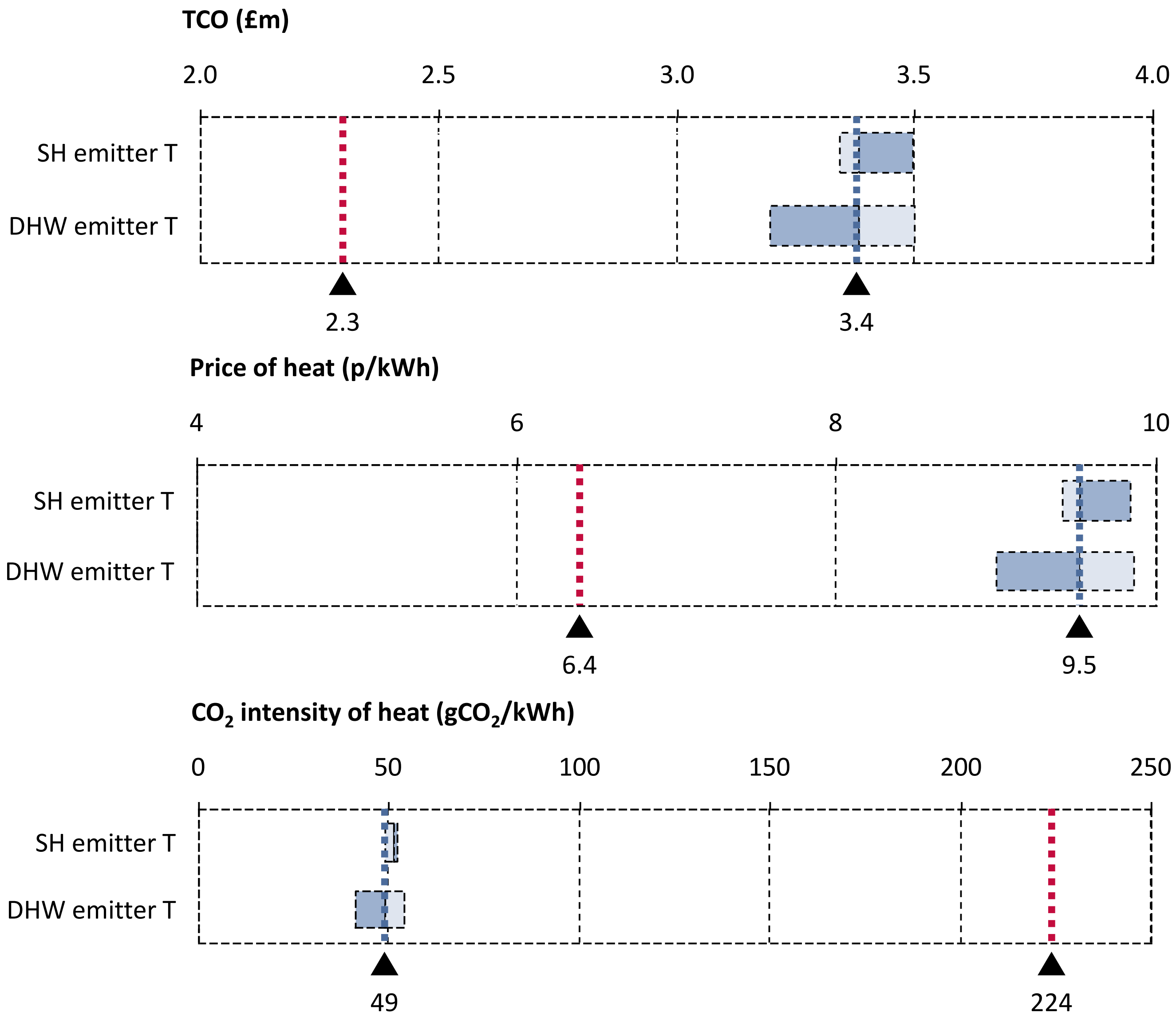
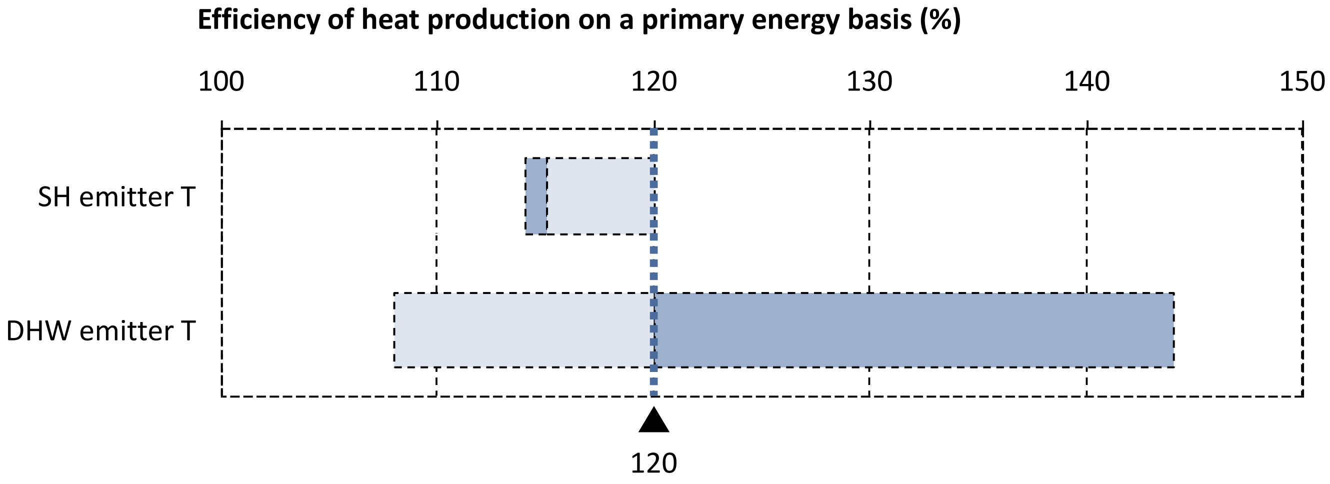


Figure 30: Impact of emitter temperatures on efficiency of heat production on a primary energy basis for Scenario 3. The thick blue line indicates value using the Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 14.



Sensitivity analysis: Heat pump technology

Figure 31 shows the impact on the TCO of replacing the central WSHP with the two types of GSHP. It can be seen that both GHSP types entail a higher cost compared to the WHSP. This is due almost entirely to the additional cost of the groundworks. The increased groundwork cost for the vertical borehole GSHP installation is larger than that for the horizontal 'slinky' installation, as described above. The fuel and carbon costs for the vertical borehole GSHP installation are the same as those for the WSHP, as the vertical GSHP installation experiences the same constant ground temperature. The horizontal GSHP installation has slightly increased fuel costs, a result of the varying ground temperature. For the same reason, the CO_2 intensity of heat, as presented in Figure 32, is slightly higher for the horizontal GSHP installation than for the other cases.

Figure 31: Summary of the TCO for the heat pump technology sensitivity in Scenario 3.

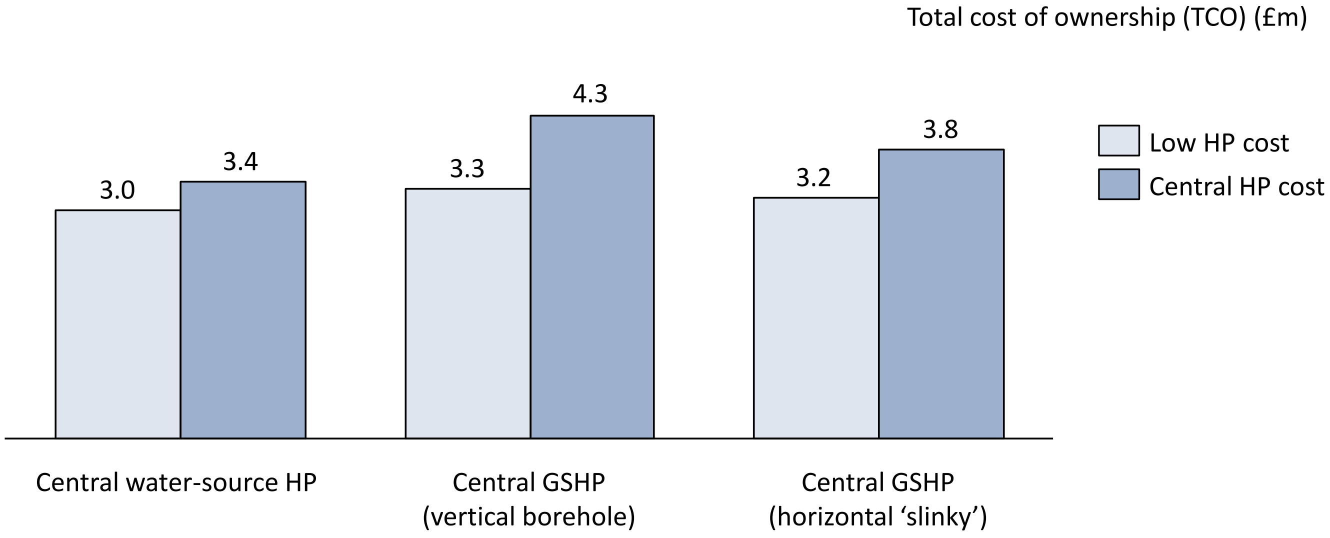
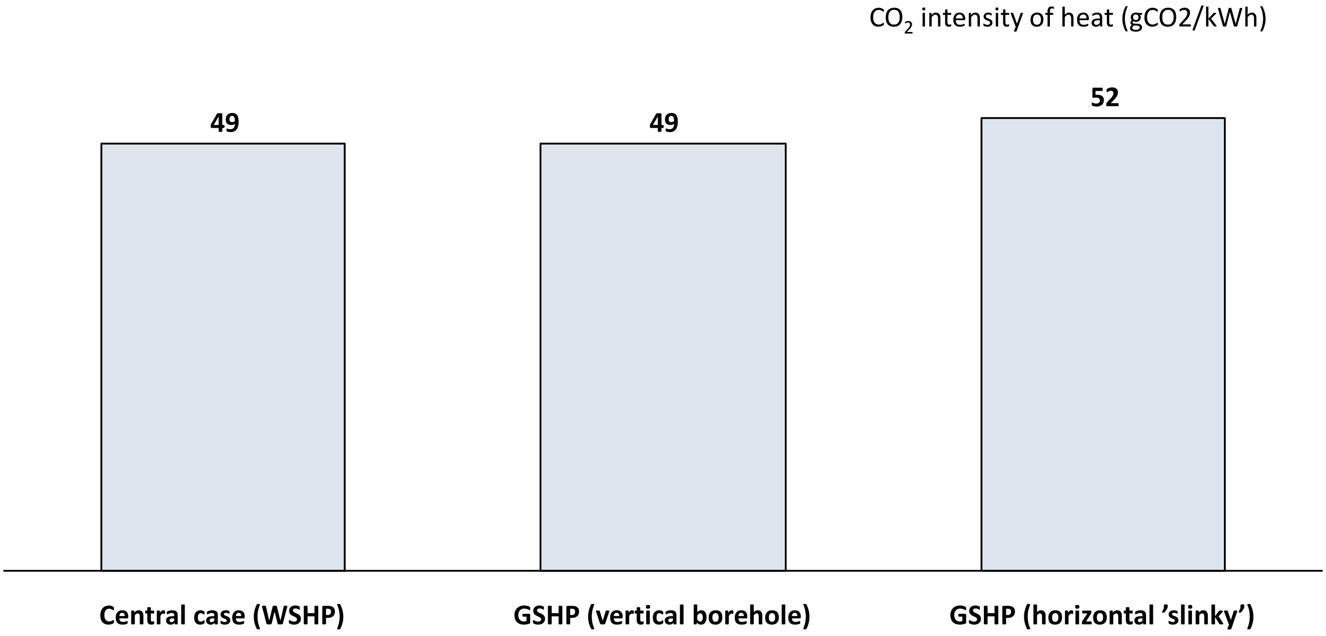


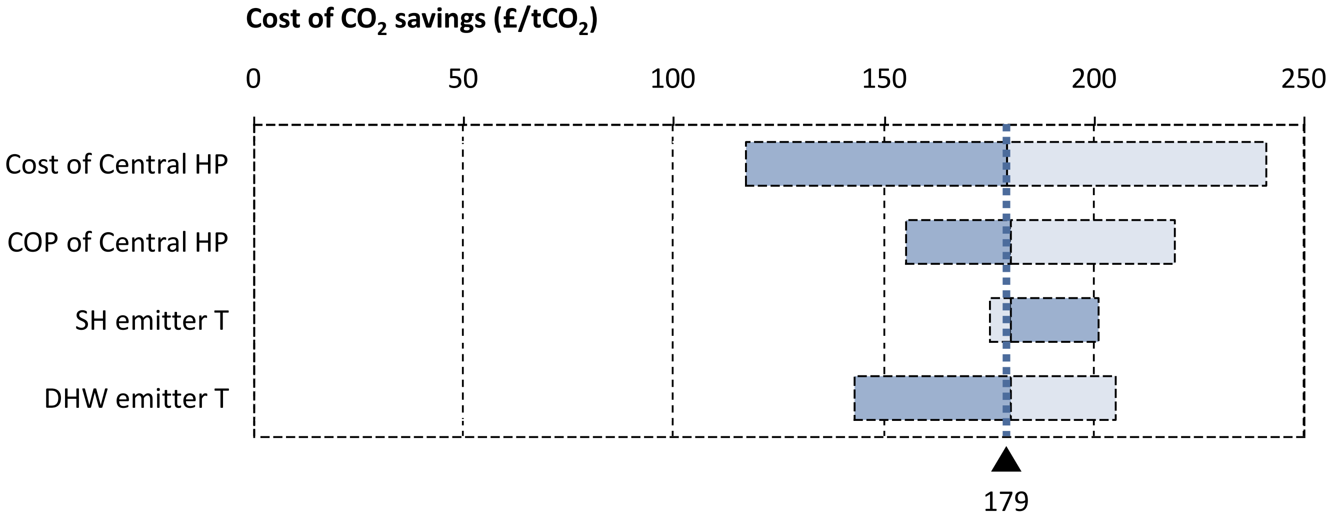
Figure 32: Comparison of CO_2 intensity for the heat pump technology sensitivity in Scenario 3.



Cost of CO_2 savings versus the counterfactual

Figure 33 presents the lifetime cost of carbon savings across the sensitivities described above. It can be seen that the cost of CO_2 savings, at £179/tCO_2 using the Central sensitivity values, varies between £117/tCO_2 and £241/tCO_2. The cost of the Central HP has the largest individual impact on the cost of the CO_2 savings.

Figure 33: Cost of CO_2 savings for various sensitivities for Scenario 3. The thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 14.



Summary of Scenario 3 results

HP in DH schemes based on a medium temperature network provide modest fuel savings versus a gas boiler-based counterfactual, but are limited by the higher cost of the heating plant

The type of scheme presented in Scenario 3 – a small-scale medium temperature heat network with a central HP to provide space heating and electric immersion heaters to provide hot water – is likely to be less cost-effective than the counterfactual high temperature network based on a gas boiler.

The cost premium for the HP in DH scheme, using the Central sensitivity assumptions, is approximately 49%, with the price of heat at 9.5 p/kWh versus 6.4 p/kWh for the counterfactual.

The difference in cost is due predominantly to the higher cost of the heating plant as compared with a gas boiler. In addition, the fuel costs are higher for the HP in DH, due largely to the use of inefficient electric immersion heaters. Reducing the hot water emitter temperature can mitigate this to some extent, with the price of heat decreasing from 9.5 p/kWh to 9.0 p/kWh where the hot water emitter temperature is reduced from 60ºC to 50ºC. This corresponds to a 41% premium versus the counterfactual. A reduction in the cost of the Central HP from £1,500/kW_{th} to £500/kW_{th} would lead to a reduction in the price of heat to 8.4 p/kWh, a 32% premium versus the counterfactual.

This type of scheme could provide large carbon emissions savings in the UK, but at a fairly high cost

The HP in DH scheme described in this scenario achieves CO_2 savings of between 74% and 82% versus the counterfactual. The cost of these savings is £179/tCO_2 using the Central sensitivity assumptions, falling to £117/tCO_2 using the Low HP cost assumption.

If there is no water source accessible, an area of ground or even an underground aquifer could be used as the heat source. This would further increase the cost premium.

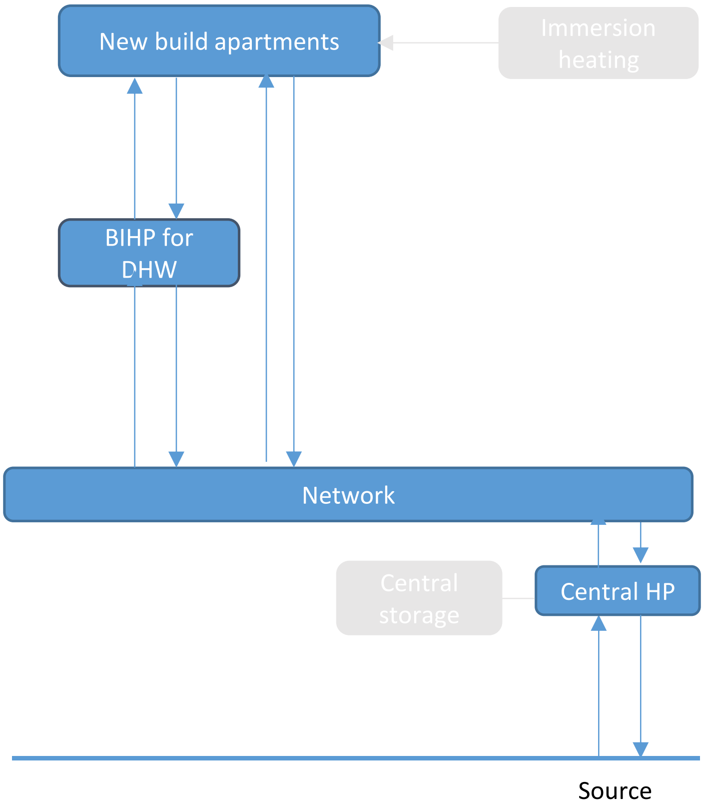
Scenario 4: Small-scale low temperature heat network with a central heat pump and hot water-only building-integrated heat pumps serving a new residential development

Description of scenario

The key characteristics of Scenario 4 are summarised in Table 17 and shown schematically in Figure 34. Scenario 4 closely resembles Scenario 3, in that it consists of a central HP supplying heat to a small-scale medium temperature network, delivering water at 45ºC[31] to a development of 400 new, thermally-efficient residential flats, arranged in 3 blocks. The central HP is a water-source heat pump with its source a river at 10ºC. As for Scenario 3, the network serves the space heating demand of the flats directly. The variation in Scenario 4, however, is that BIHPs raise the temperature of the water to provide the hot water demand, rather than electric immersion heaters. This configuration is of interest given that we identified the requirement to boost the network temperature with electric immersion heaters as a key limitation to achieving competitive cost in Scenario 3.

The counterfactual for this scheme, as summarised in Table 17, is a high temperature network supplied entirely by a gas boiler – this is identical to the counterfactual in Scenario 3.

Figure 34: Schematic illustration of HP in DH scheme in Scenario 4



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[31] Note that the network flow temperature varies in the space heating emitter temperature sensitivity for Scenarios 3 and 4.

Table 17: Summary of key characteristics of Scenario 4

		HP in DH scheme	***Counterfactual***
Description of scheme and buildings served		Small-scale scheme serving a new development consisting of 400 residential flats (in 10-storey blocks)	
Heating	Heat source (source T)	River (10ºC)	None
	Central HP type (HP sink T)	WSHP (45ºC)	None
	Building-integrated HP type	Micro-WSHP	None
	Central conventional plant	None	Gas boiler
	Building-integrated conventional plant	None	None
	Network flow/return temperature (ºC)	45/35 (varies with sensitivity on SH emitter T)	70/50
	End-uses served by network	Space heating and DHW	Space heating and DHW
Cooling		No cooling demand treated	

Key parameters for sensitivity analysis

Table 18 details the sensitivity analyses carried out for Scenario 4.

Table 18: Summary of sensitivity parameter values used in Scenario 4

Parameter	**Low**	**Central**	**High**
Cost of BIHP (£/kW$_{th}$)	133	685	1,000
Number of BIHPs serving 400 flats	3 (one per block)	400 (one per flat)	-
COP of micro-BIHP (at 60ºC sink T)	4.1	5.3	-
SH emitter temperature (ºC)	30	40	45
DHW emitter temperature (ºC)	50	60	65

Since the variation in Scenario 3 from Scenario 4 is the use of a BIHP to provide the hot water demand, rather than electric immersion heaters, we focus here on several sensitivities relating to the BIHP.

BIHP COP

The BIHP included in this scenario is a specialised type of BIHP: a micro-BIHP. Micro-BIHPs are designed to operate over a narrow range of temperatures and at particularly high source temperatures in the range 35-50ºC. This is in contrast to the BIHPs in Scenario 2 which operate at lower source temperatures up to around 20ºC. Therefore, the BIHP COP data in this scenario is different from the data in Scenario 2, being gathered specifically for micro-BIHPs[32].

BIHP cost

We note that since no reliable cost data was found for micro-HPs, the cost data for 'typical' BIHPs were used here. As will be described in this section, the small sample size, which reflects the small number of products on the market, means that there is considerable uncertainty around this data.

Number of BIHPs serving the 400 flats

As in Scenario 2, we consider varying the number of BIHPs used to serve the flats, in order to take advantage of the diversity of demand across a larger number of flats, allowing the use of a smaller capacity of BIHP per flat, and the reduction in cost per kW_{th} of BIHPs as the capacity increases.

Space heating and hot water emitter temperatures

As with Scenario 3, this scenario involves providing space heating directly to thermally-efficient new-build flats at a lower temperature than in a conventional DH scheme, with the aim of increasing the Central HP COP and reducing network losses. In Scenario 3, it was demonstrated that reducing the space heating emitter temperature, and the network temperature with it, actually led to an increase in the TCO of the scheme. This was shown to be a result of a decrease in the overall system efficiency due to the use of electric immersion heaters to boost provide the hot water demand. In this scenario, we examine whether providing the hot water demand with a micro-HP, rather than with electric immersion heaters, results in improved performance for low space heating emitter temperatures.

In addition, we study the impact of a range of hot water emitter temperatures. The range of emitter temperatures included in the analysis is shown in Table 18.

Scenario results and sensitivity to key parameters

Scenario results based on Central sensitivity assumptions

Figure 35 summarises the heat supplied by the various plant and the heat delivered to meet demand over the 20 year scheme lifetime in Scenario 4. The majority of the heat is supplied by

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[32] Micro-BIHP COP data was obtained from Itho Daalderop.

the Central HP, with only 10% of the total heat supplied by the BIHPs. We note that since the BIHPs are more efficient than the immersion heaters in Scenario 3, a greater share of the heat delivered to the consumers in Scenario 4 passes through the network. As in Scenario 3, the thermal losses in the HP in DH scheme are reduced relative to the counterfactual, due to the lower network temperature.

A number of key performance metrics relating to Scenario 4 are shown in Table 19. Using the Central sensitivity assumptions, the TCO of the HP in DH scheme, at £3.7m, is approximately 64% more expensive than the TCO of the counterfactual, at £2.3m. The price of heat, at 10.5 p/kWh, is accordingly higher than the counterfactual, at 6.4 p/kWh.

Since all heat is delivered using heat pumps, the carbon intensity is much improved relative to the counterfactual. The CO_2 intensity of delivered heat is 45 gCO_2/kWh for the HP scheme as compared with 224 gCO_2/kWh for the counterfactual. This represents a reduction in CO_2 emissions of 80%, and corresponds to lifetime CO_2 savings of 6 $ktCO_2$ at a cost of £227/tCO_2.

Total efficiency on a primary energy basis is 130% for the HP in DH case as compared with 74% for the counterfactual, amounting to a 43% reduction in primary energy consumption relative to the counterfactual, using the 2015 primary energy factor for electricity. Since a decarbonising grid will mean a decreasing primary energy factor for grid electricity, the primary energy savings would be significantly higher than this when considered over the scheme lifetime.

Figure 36, which presents the breakdown of the TCO in the HP in DH and counterfactual schemes, explains the reason for the cost premium of the HP in DH scheme in this scenario. While the fuel and carbon cost of the HP in DH scheme is almost the same as for the counterfactual, the cost of the heating plant is vastly higher, at nearly £1.5m versus less than £0.1m for the gas boiler in the counterfactual scheme.

Figure 35: Summary of heat supplied and delivered over the 20 year scheme lifetime for the HP in DH scheme and the counterfactual in Scenario 4 using the Central sensitivity assumptions.

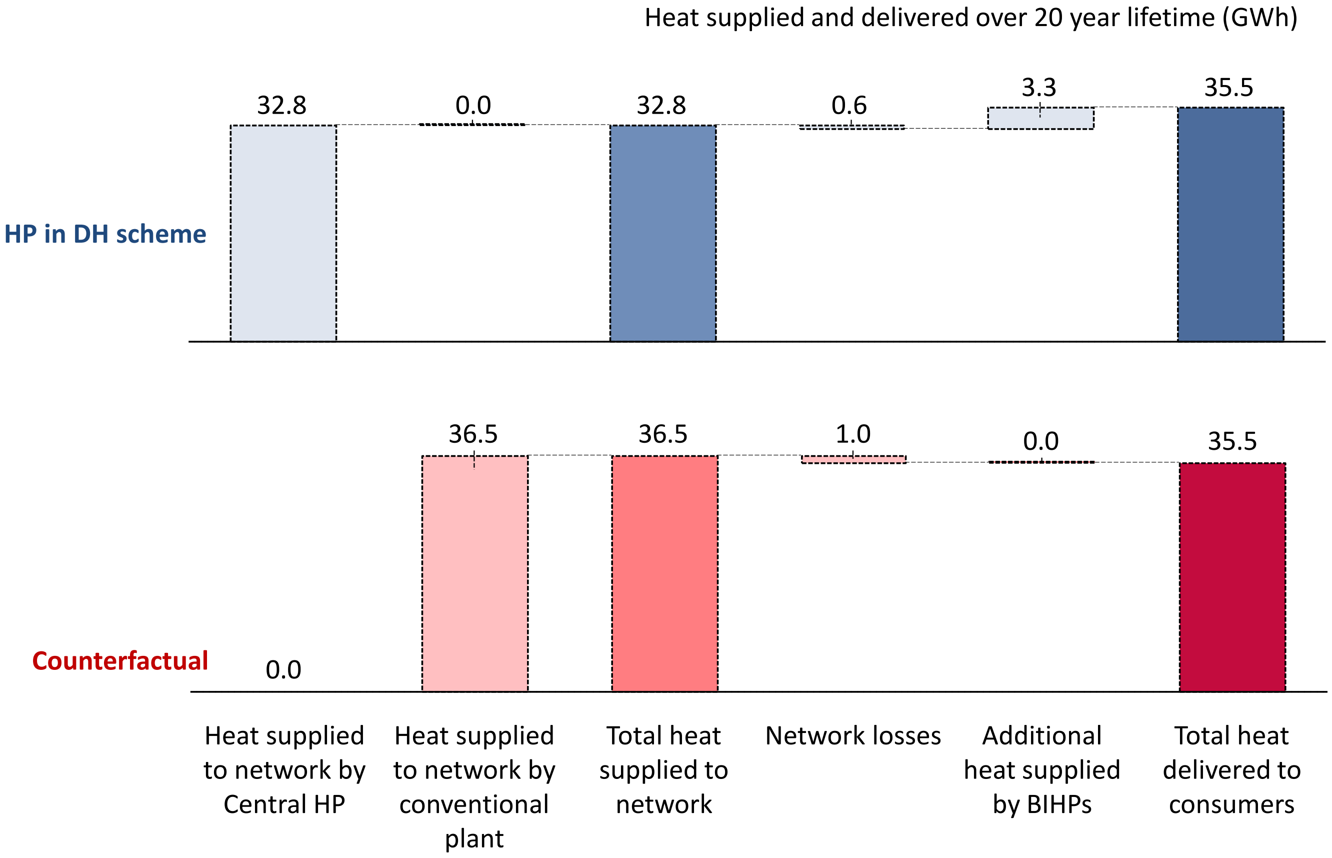

Table 19: Summary of key performance metrics for Scenario 4 using the Central sensitivity assumptions.

Parameter	***HP in DH scheme***	***Counterfactual***
TCO (£m)	3.7	2.3
Price of heat (p/kWh)	10.5	6.4
CO_2 intensity of delivered heat (gCO_2/kWh)	45	224
Efficiency of heat production on a primary energy basis (2015 value) (%)	130	74
Efficiency of heat and electricity production on a primary energy basis (2015 value)[33] (%)	No electricity production	

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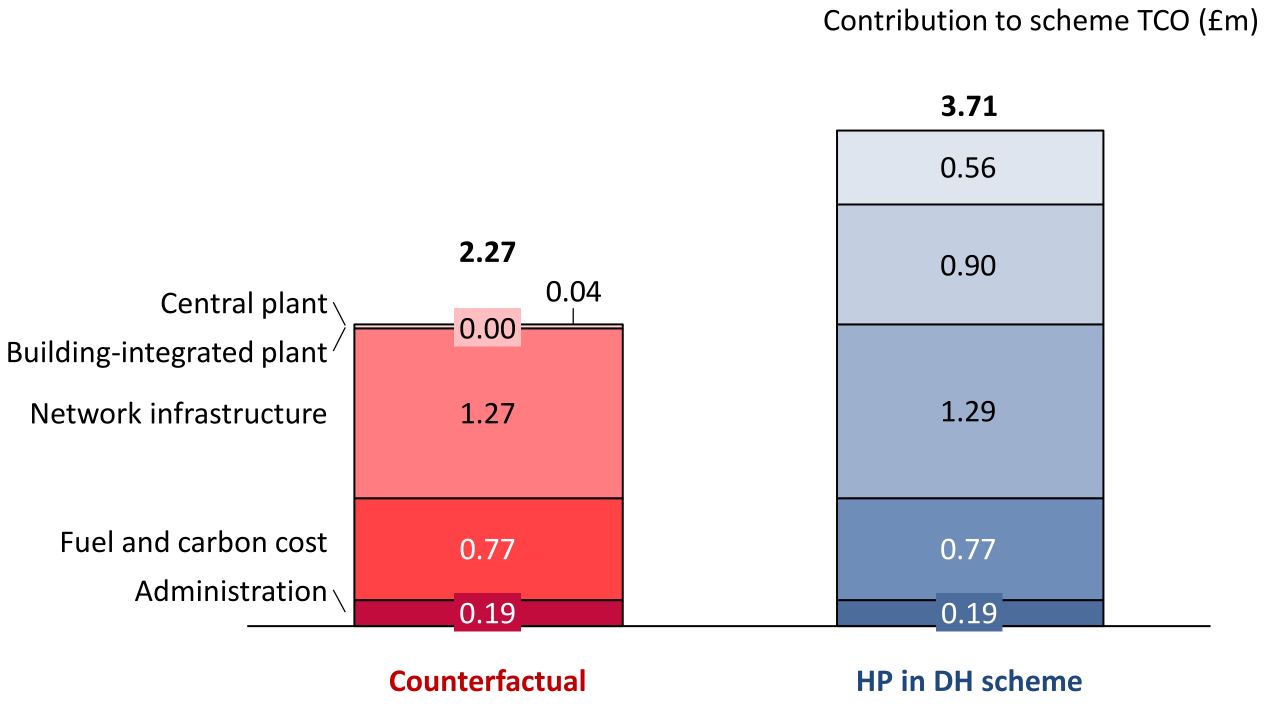
[33] See Footnote 21.

Figure 36: Breakdown of contributions to the TCO for the HP in DH scheme and the counterfactual in Scenario 4 using the Central sensitivity assumptions.



Sensitivity analysis: BIHP cost

Figure 37 shows that the price of heat is rather strongly dependent on the BIHP cost, and varies from 8.4 p/kWh to 11.6 p/kWh over the range considered. Nonetheless, over this range the price of heat of the HP in DH scheme remains higher than that of the counterfactual.

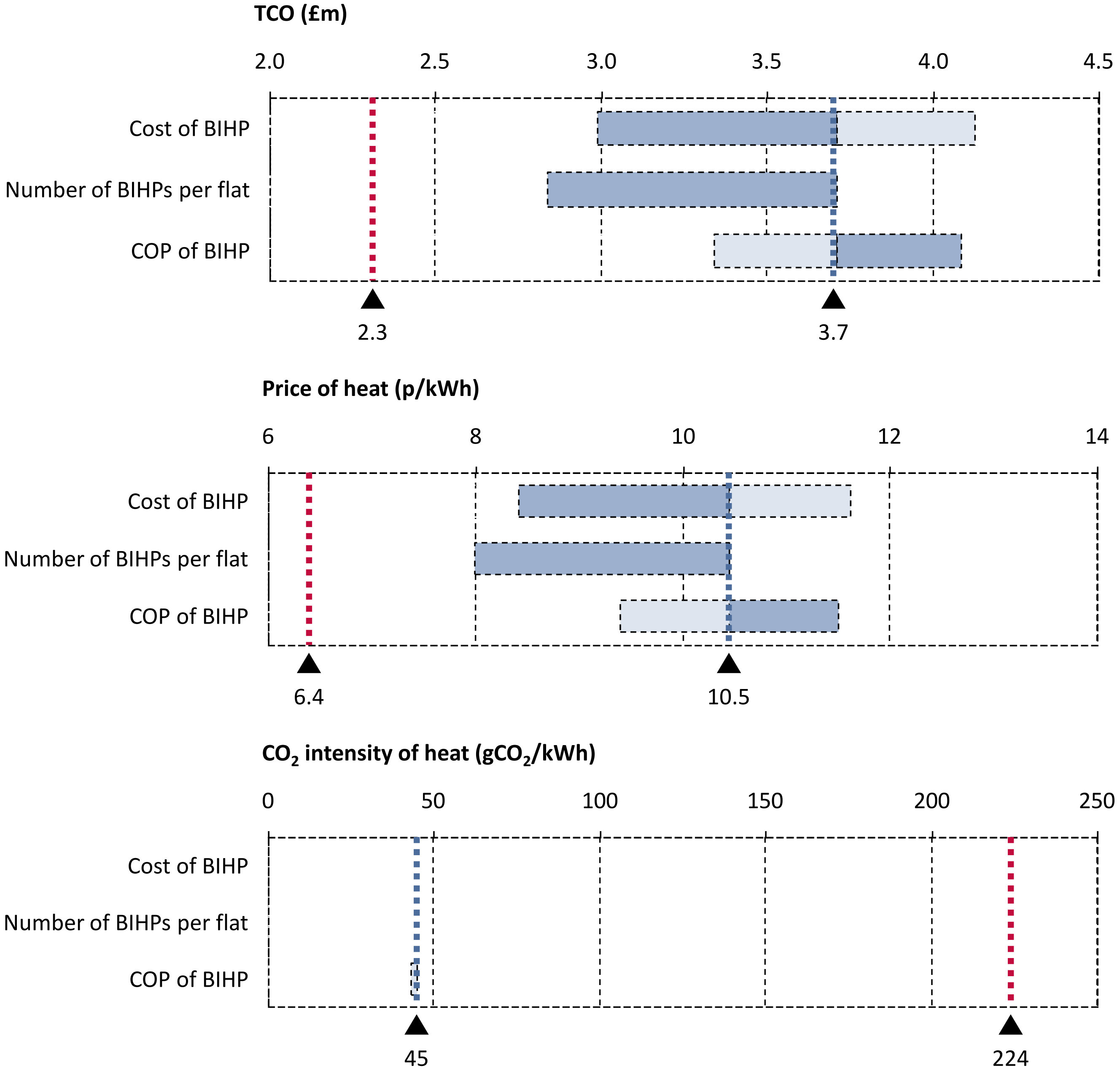
Sensitivity analysis: Number of BIHPs serving 400 flats

Figure 37 also shows that the price of heat is strongly dependent on the number of BIHPs serving the flats. As for Scenario 2, this reflects the fact that a BIHP installed in an individual flat, required to meet the peak hot water demand of that flat, is significantly over-sized outside the times of peak demand. Installing one BIHP per block of flats (that is, three BIHPs for the 400 flats) to take advantage of both the diversity of demand and the reduced cost per kW_{th} for larger BIHPs, reduces the price of heat to 8.0 p/kWh. This represents a premium of 25% versus the counterfactual.

Sensitivity analysis: BIHP COP

As seen in the same figure, the price of heat is dependent on the BIHP COP. Over the range of COP values considered, the price of heat varies from 9.4 p/kWh to 11.5 p/kWh, corresponding to a premium versus the counterfactual of between 47% and 80%.

Figure 37: Impact of the BIHP cost, number and COP assumptions on key performance metrics for Scenario 4. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 18.



Sensitivity analysis: Space heating and hot water emitter temperatures

Figure 38 shows that the trend in TCO with space heating emitter temperature observed for the HP in DH scheme in Scenario 4 is the opposite to the trend observed in Scenario 3. Consistent with this, Figure 39 shows that reducing the space heating emitter temperature from 40ºC to 30ºC results in an increase in the efficiency of heat production from 130% to 153%. This indicates that the improvement in Central HP COP (from 4.5 to 6.2) outweighs the reduction in the BIHP COP (from 4.1 to 3.6) as the network temperature decreases.

Figure 38: Impact of the emitter temperatures on key performance metrics for Scenario 4. The thick red dotted line indicates the counterfactual scheme, and the thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 18.

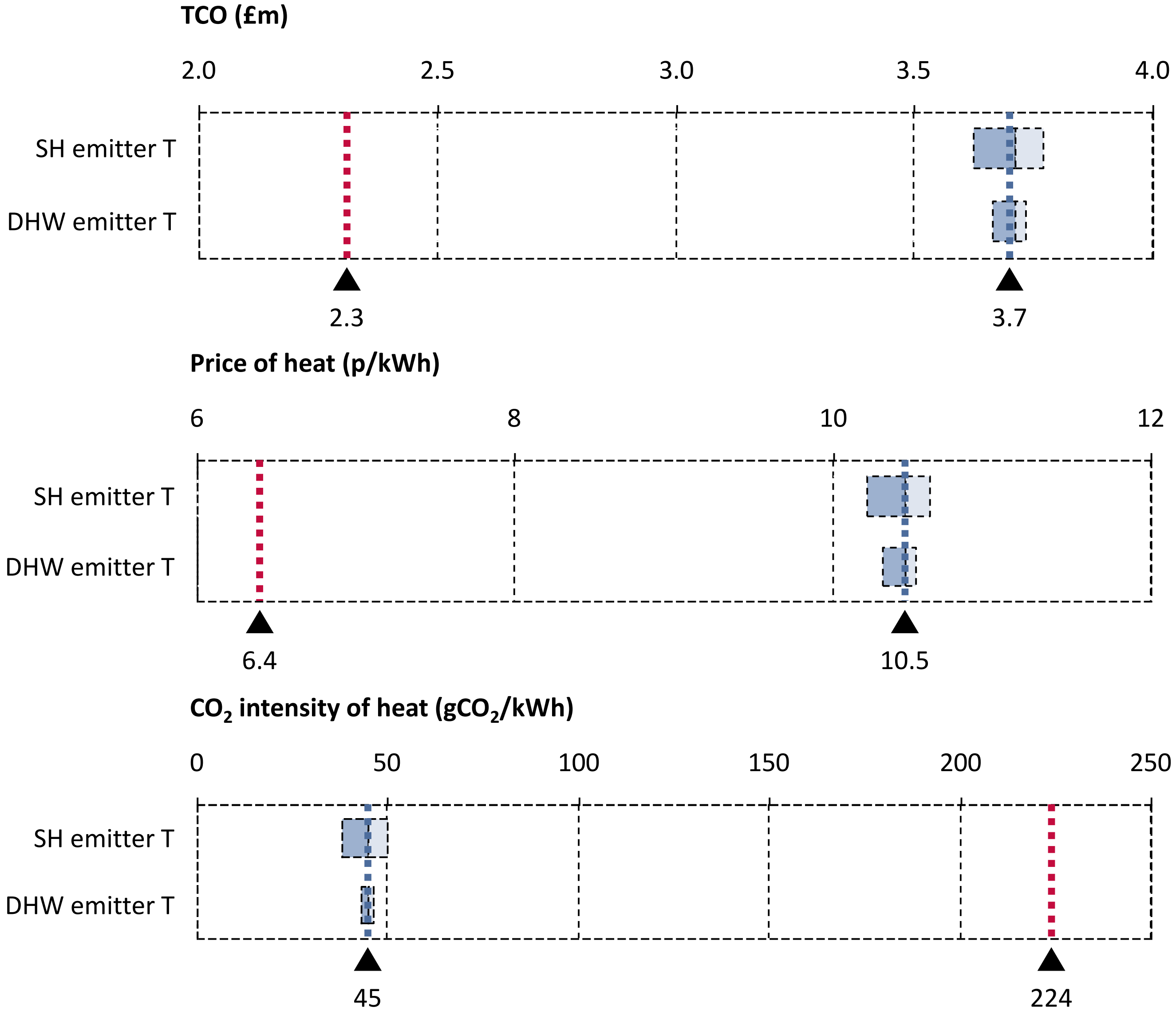
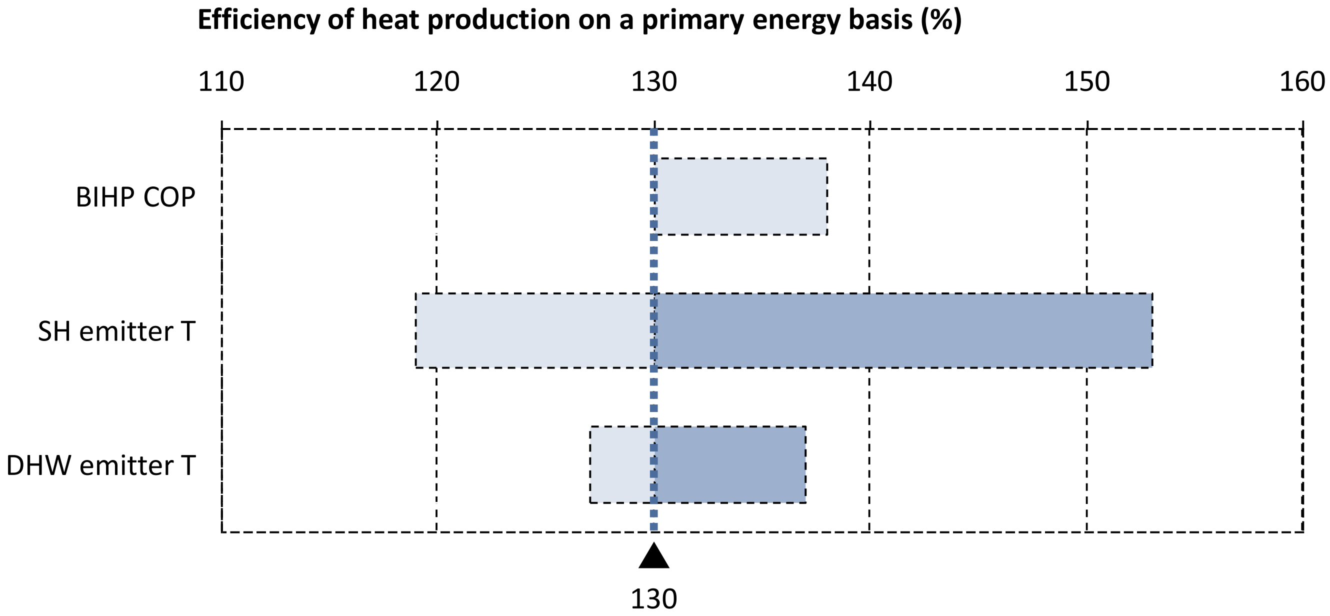


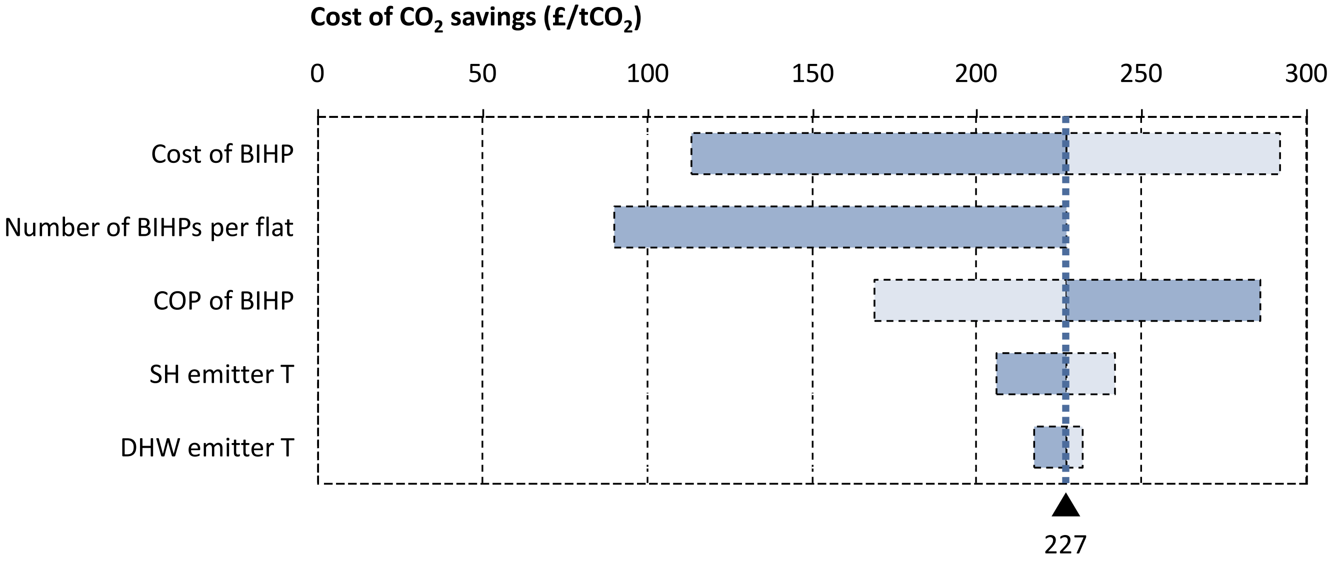
Figure 39: Impact of emitter temperatures on efficiency of heat production on a primary energy basis for Scenario 4. The thick blue line indicates the value using Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 18.



Cost of CO_2 savings

Figure 40 presents the lifetime cost of carbon savings across the sensitivities described above. The cost of CO_2 savings, at £227/tCO_2 using the Central sensitivity values, is higher than for the HP in DH scheme in Scenario 3, at £179/tCO_2. The only difference between Scenario 3 and Scenario 4 is the technology used for hot water heating, with electric immersion heaters in Scenario 3 and BIHPs in Scenario 4. This indicates that, using the Central assumptions, the increased cost of the BIHPs relative to the electric immersion heaters outweighs the benefit of the fuel savings brought through increased system efficiency. However, it can be seen that for the Low BIHP cost sensitivity the cost of CO_2 savings (at £113/tCO_2) is significantly below that in the Central case for Scenario 3. Similarly, where one BIHP is installed per block of flats, rather than per flat (as in the Low 'number of BIHPs per flat' sensitivity), the cost of CO_2 savings (at £90/tCO_2) is well below that for Scenario 3. This suggests that the evolving cost of BIHPs, and the design in terms of BIHP sizing, affect the final result in terms of the cost-optimal scheme design.

Figure 40: Cost of CO_2 savings for various sensitivities for Scenario 4. The thick blue line indicates the HP in DH scheme with Central sensitivity assumptions. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 18.



Summary of Scenario 4 results

Industry data on the COP of micro-HPs suggests that they are slightly less cost-effective than electric immersion heaters in the use case considered here

In this scenario, the HP in DH scheme investigated was almost identical to the scheme in Scenario 3. Like that scheme, it involves a Central HP supplying heat to a medium temperature network to provide the space heating demand of a new residential development directly. The one difference was that the hot water demand was provided through the use of a specialised micro-HP rather than electric immersion heaters.

Our analysis, based on industry micro-HP COP data, suggests that this configuration is likely to be less cost-effective than the configuration based on electric immersion heaters. The difference is modest. In this scenario, with hot water provision based on micro-HPs, we find the cost of CO_2 savings in the Central case to be £227/tCO_2, as compared with £179/tCO_2 for Scenario 3, with hot water provision based on electric immersion heaters.

Increasing the number of flats served by a single BIHP could make this type of scheme more competitive than the corresponding scheme using electric immersion heaters

In the Scenario studied here, using 3 large BIHPs to serve each of the blocks of flats, rather than 400 small BIHPs in each flat, leads to a reduction in the price of heat from 10.5 p/kWh to 8.0 p/kWh. This is 16% lower than the price of heat for the scheme with immersion heaters described in Scenario 3. At this price of heat, the cost of CO_2 savings falls to £90/tCO_2, as compared with £179/tCO_2 for the scheme in Scenario 3, with hot water provision based on electric immersion heaters.

Micro-HP COP data gathered appears to be surprisingly low, such that this type of scheme could be more competitive than this analysis suggests

We note that the micro-HP COP data gathered through industry consultation, at 4.1, appears to be fairly low for the operating source and sink temperatures involved. It may be expected that higher COP values could be achieved as further products enter this relatively immature market.

6. Comparison of different configurations of HP in DH

In this section, we focus on a comparison of the variety of possible DH in HP scheme configurations, rather than on a comparison of a particular HP in DH scheme with a conventional fossil fuel-based DH scheme. The objective of this section is to make an assessment of which configuration may be optimal for a given heat demand case; that is, a fixed set of consumers to be served. We study two fixed 'demand cases':

A. Small-scale scheme serving a new development consisting of 400 residential flats (in 10-storey blocks)

B. Large-scale scheme serving an existing commercial development

For each of the two demand cases, we consider all relevant scheme configurations from among the following four:

- High temperature network with a central HP serving both space heating and hot water demand ('High T network'), as illustrated in Figure 10;
- Medium temperature network with a central HP serving space heating directly, with electric immersion heaters boosting the network temperature to provide the hot water demand ('Medium T network with immersion heaters'), as illustrated in Figure 24;
- Medium temperature network with a central HP serving space heating directly, with micro-BIHPs boosting the network temperature to provide the hot water demand ('Medium T network with micro-BIHPs'), as illustrated in Figure 34;
- Low temperature network with a central HP and BIHPs providing space heating and hot water demand ('Low T network'), as illustrated in Figure 18.

In each case, we study the impact of the central and BIHP cost on the key performance metrics for the scheme.

A: Small-scale scheme serving a new development

Description of HP in DH schemes studied for Demand Case A

The key characteristics of the schemes studied are given in Table 20. For a new development, all four scheme configurations are potentially relevant, given that the high thermal efficiency of new buildings would enable a medium temperature network to provide space heating directly.

Demand Case A results

TCO comparison of different HP in DH schemes

Figure 41 presents the breakdown of the TCO for each of the four HP in DH schemes studied in Demand Case A – a small-scale scheme serving a new development of flats. The High T network and the Medium T network with immersion heaters have the lowest TCO, at £3.0m and £3.4m respectively. The two schemes including BIHPs – the Medium T network with micro-BIHPs and the Low T network – are more costly. The Medium T network with micro-BIHPs carries a premium of 24% versus the High T network, and the Low T network a premium of 25%.

The key difference in the TCO is the additional cost of the BIHPs in the two schemes where they are required. In the Medium T network with micro-BIHPs and the Low T network, the BIHPs contribute £0.90m to the TCO. The decreases in central plant cost and fuel cost for the Medium T network with BIHPs amount to only £0.08m and £0.11m respectively versus the High T network. The fuel cost is actually increased in the Low T network versus the High T network. These figures suggest that, in this case, the increased capital cost associated with the additional HPs outweighs the potential fuel savings.

Figure 41: Breakdown of contributions to the TCO for the different HP in DH schemes studied in Demand Case A.

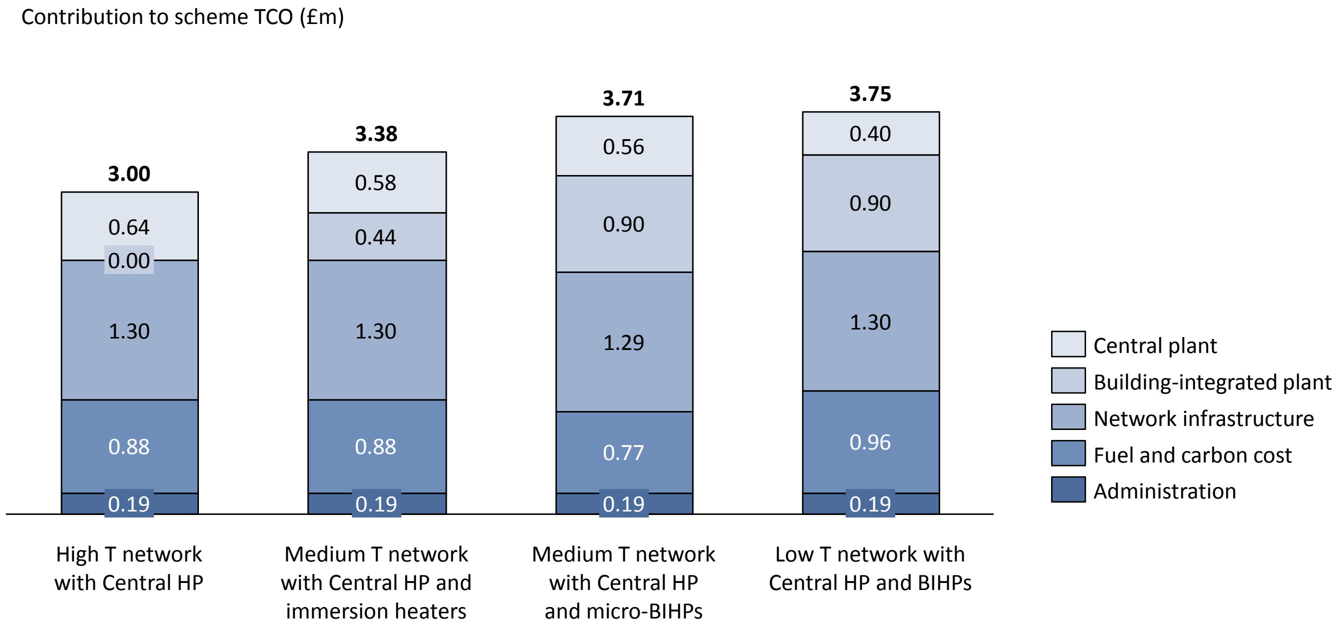


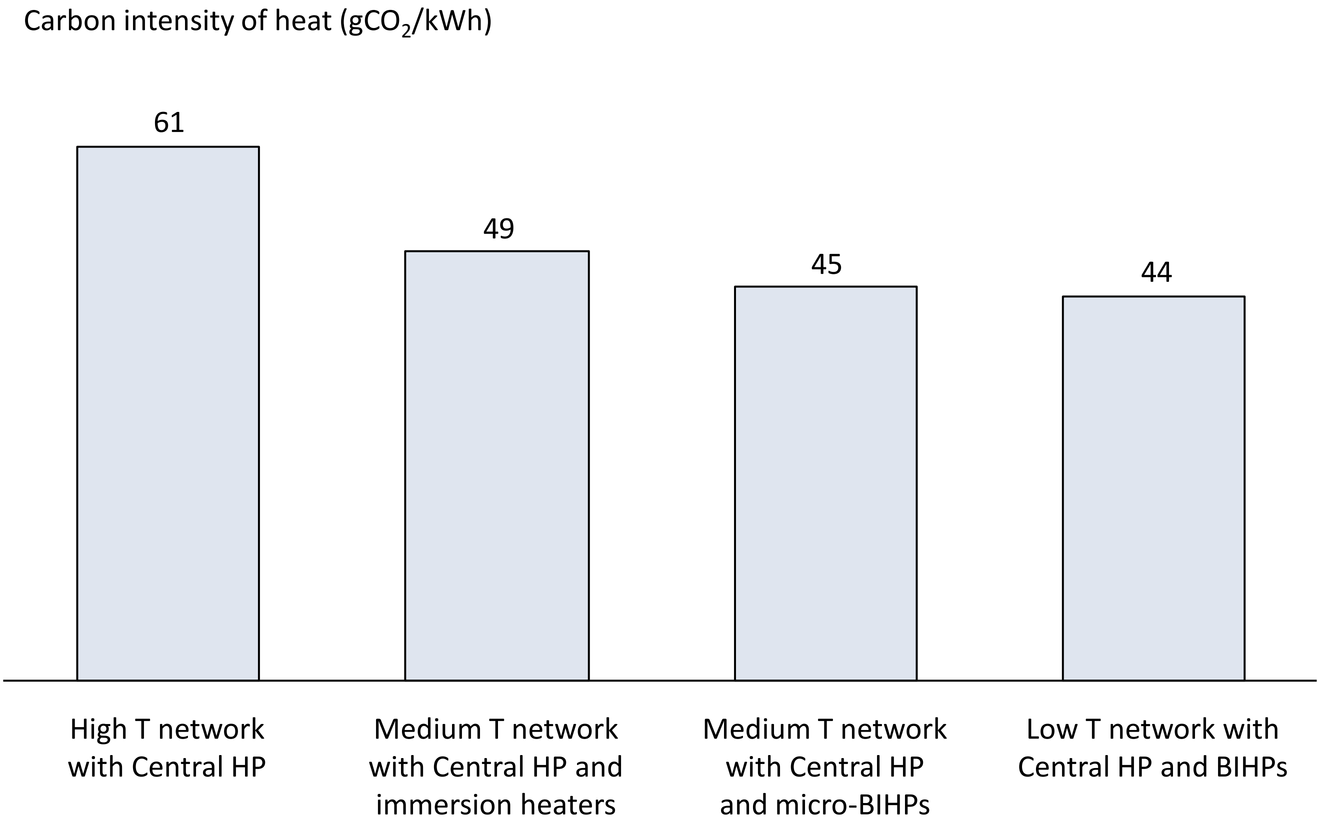
Table 20: Summary of key characteristics of HP in DH schemes studied in Demand Case A

		High T network	***Medium T network with electric immersion heaters***	***Medium T network with micro-BIHPs***	***Low T network***
Description of scheme and buildings served		Small-scale scheme serving a new development consisting of 400 residential flats (in 10-storey blocks)			
Heating	Heat source (source T)	River (10ºC)	River (10ºC)	River (10ºC)	Sea (3-18ºC)
	Central HP type (HP sink T, capacity)	WSHP (70ºC, 0.42 MW$_{\text{th}}$)	WSHP (50ºC, 0.38 MW$_{\text{th}}$)	WSHP (50ºC, 0.37 MW$_{\text{th}}$)	WSHP (11ºC, 0.27 MW$_{\text{th}}$)
	Building-integrated HP type (total capacity)	None	None	Micro-WSHP (1.20 MW$_{\text{th}}$)	WSHP (1.20 MW$_{\text{th}}$)
	Central conventional plant (capacity)	None	None	None	None
	Building-integrated conventional plant (total capacity)	None	Electric immersion heaters (2.40 MW$_{\text{th}}$)	None	None
	Network flow/return temperature (ºC)	65/55	45/35	45/35	18/11 (summer), 11/3 (winter)
	End-uses served by network	Space heating and DHW	Space heating and DHW	Space heating and DHW	Space heating and DHW
Cooling		No cooling demand treated			

CO_2 comparison of different HP in DH schemes

Figure 42 presents a comparison of the CO_2 intensity of heat across the four schemes, for Demand Case A. It can be seen that the High T network has the highest carbon intensity, at 61 gCO_2/kWh, and the Low T network the lowest, at 44 gCO_2/kWh.

Figure 42: Comparison of CO_2 emissions for the different HP in DH schemes studied in Demand Case A.



Sensitivity: Central HP cost

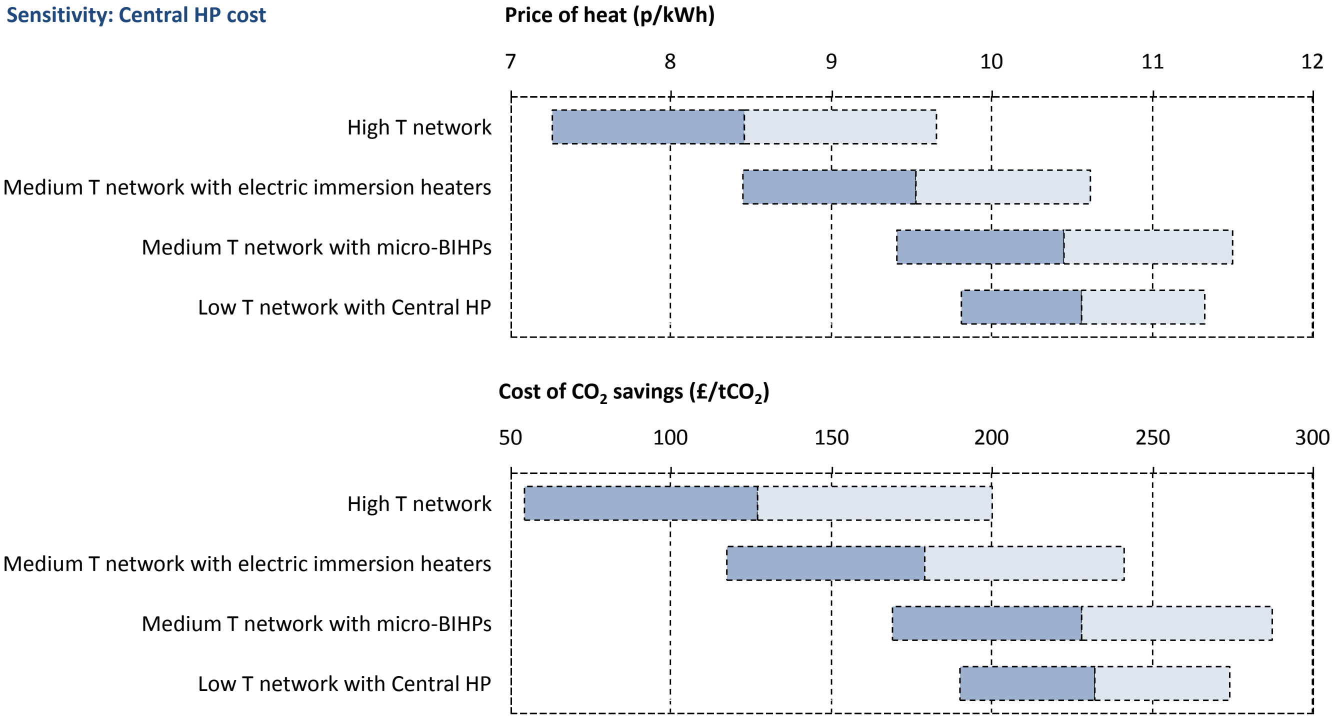
Figure 43 presents the impact of the cost of the HP on the price of heat and cost of CO_2 savings versus the counterfactual (not shown here). The sensitivity assumptions used for Demand Case A are shown in Table 21. In terms of the price of heat, the ordering of cost-effectiveness of the four schemes is largely preserved across each of the Central, Low and High HP cost assumptions. The exception is that in the High HP cost sensitivity, the price of heat for the Low T network is slightly lower than for the Medium T network with micro-BIHPs. Although there is a difference in the size of the Central HP across the four schemes, variation in the cost of the HP does not have a large effect on the order of cost-effectiveness of the scheme designs.

We find that the cost of CO_2 savings using the Central HP cost assumption is lowest for the High T network, at £127/tCO_2. The cost of CO_2 savings for the other three schemes lies in the range £179-232/tCO_2. Using the Low HP cost assumption, the cost of CO_2 savings falls to £54/tCO_2 for the High T network.

Table 21: Summary of sensitivity parameter values used for Demand Case A

Parameter	Low	Central	High
Central HP cost (£/MW$_{th}$)	500,000	1,500,000	2,500,000
BIHP cost (£/kW$_{th}$ for 3 kW$_{th}$ BIHP)[34]	343	685	1,028

Figure 43: Impact of the central HP cost on the price of heat and cost of CO_2 savings versus the counterfactual for the different HP in DH schemes studied in Demand Case A. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 8.



Sensitivity: BIHP cost

Figure 44 presents the impact of the cost of the BIHPs on the price of heat and cost of CO_2 savings versus the counterfactual (not shown here). The sensitivity assumptions used for Demand Case A are shown in Table 21. It can be seen that using the Low BIHP cost assumption of £343/kW$_{th}$ – corresponding to 50% of the current cost of BIHPs as gathered through our industry consultation exercise – results in the price of heat for the Medium T network with micro-BIHPs and the Low T network decreasing below that for the Medium T network with immersion heaters, which is unaffected. The price of heat for the High T network is also unaffected, though this remains the lowest cost scheme.

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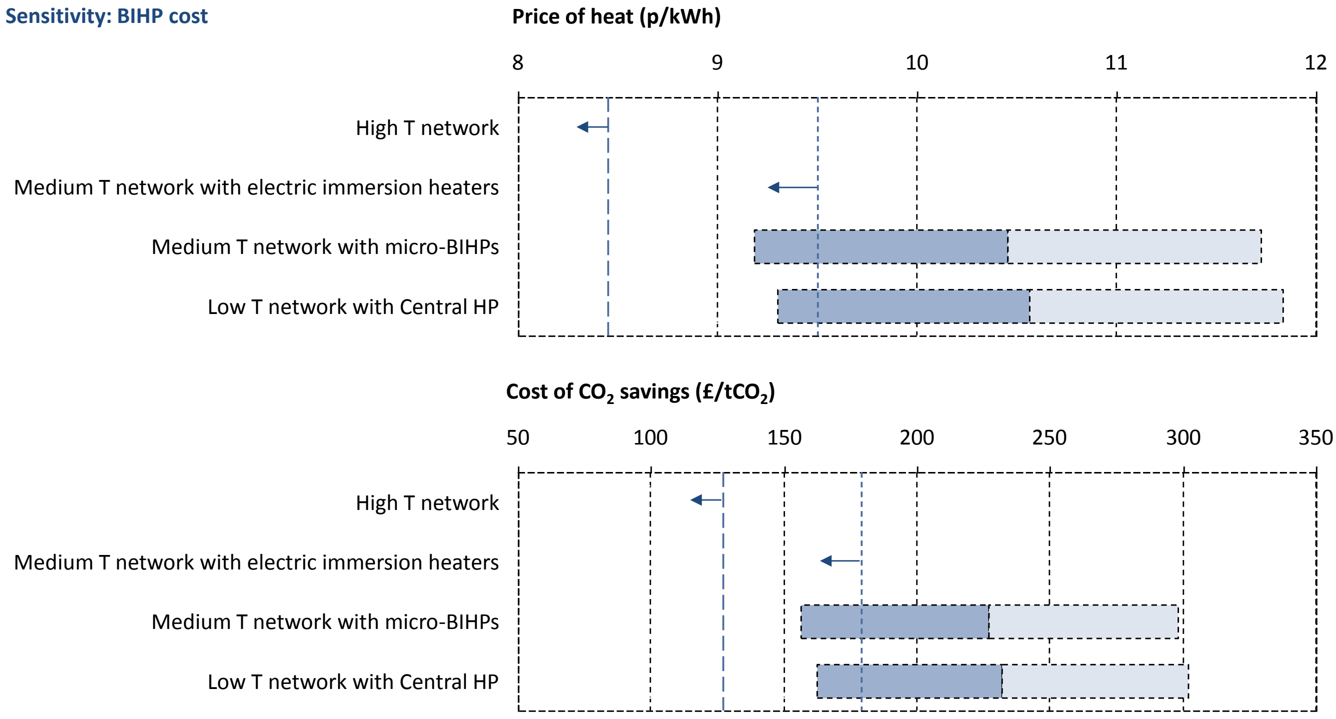
[34] For the dependence of BIHP cost on capacity, see Figure 9.

In terms of the cost of CO_2 savings, the Low BIHP cost assumption results in the four schemes becoming more clustered. The High T scheme remains the most cost-effective in terms of CO_2 savings, at £127/tCO_2, but that metric lies in the range £156-179/tCO_2 for all of the other three schemes.

Figure 44: Impact of the BIHP cost on the price of heat and cost of CO_2 savings versus the counterfactual for the different HP in DH schemes studied in Demand Case A. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions, as shown in Table 11. The dashed blue line indicates the price of heat for the 'High T network' scheme, and the solid blue line indicates the price of heat for the 'Medium T network with electric immersion heaters' scheme.



Summary of Demand Case A results

For a new residential development, all four HP in DH scheme configurations listed above are technically feasible, since the high thermal efficiency of new buildings means that the space heating demand could be served directly by a medium temperature network.

For the demand case studied here, the most cost-effective HP in DH scheme configuration is the High T network option. The Medium T network with electric immersion heaters, the Medium T network with micro-BIHPs and the Low T network option are 13%, 24% and 25% more costly in terms of the price of heat using the Central HP cost assumptions, respectively. This is driven mainly by differences in the cost of heating plant, which dominate differences in the network infrastructure cost and the fuel and carbon cost. In short, the inclusion of BIHPs does not enable a large enough reduction in the required capacity of central heating plant, or a large enough reduction in the fuel costs, to justify the additional capital cost.

A reduction in the cost of BIHPs to the Low BIHP cost assumption in Table 21, however, would result in the Medium T network with BIHPs and the Low T network becoming more competitive with the High T network, with the premium on the price of heat reducing to 9% and 10% respectively.

This indicates that, for application in a small-scale new-build residential development, a range of HP in DH scheme configurations could potentially be suitable, with the cost of BIHPs a key determinant.

B: Large-scale scheme serving an existing mixed-use development

Description of HP in DH schemes studied for Demand Case B

The key characteristics of the schemes studied are given in Table 22. For an existing development, without intensive fabric thermal efficiency retrofit, a medium temperature network is not expected to be suitable for providing space heating directly. Therefore, we focus in this case on the High T network and Low T network options.

Demand Case B results

TCO comparison of different HP in DH schemes

Figure 45 presents the breakdown of the TCO for the two HP in DH schemes studied in Demand Case B – a large-scale scheme serving an existing mixed-use development. In this case, using the Central HP cost assumptions, the Low T network option is more cost-effective than the High T network option, with a TCO of £53m as compared with £56m.

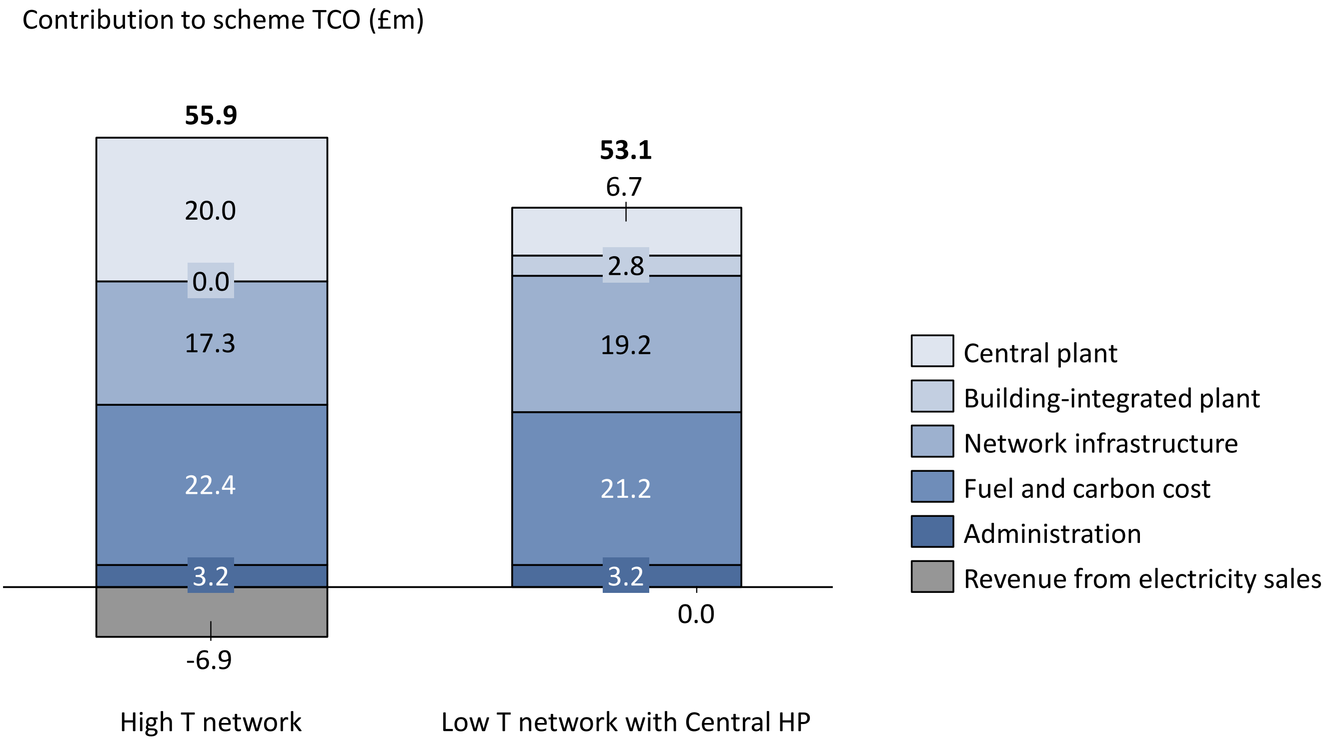
The largest difference between the two schemes is the cost of the heating plant. Both schemes include a Central HP, at 4.4 MW_{th} and 4.7 MW_{th} for the Low T network and the High T network respectively. In addition to this, the High T network includes 10.6 MW_{th} of Gas CHP plant, whereas the Low T network includes 8.0 MW_{th} of BIHPs. In this case, the capital and operating costs of the CHP are significantly higher than those of the BIHPs. The key reason for the low cost of the BIHPs in this Demand Case is that the building stock is comprised of offices, shops and restaurants, with larger heat demands than the new build flats represented in the previous Demand Case. This means that the BIHPs are large (typically tens of kW_{th}), meaning that the cost per kW_{th} is low, as shown in Figure 9. Furthermore, the large non-domestic BIHPs do not suffer from the issue of over-sizing outside times of peak demand to the same extent as the small 3-6 kW_{th} BIHPs in residential properties, since there is more diversity of demand within these larger buildings.

Much of the higher cost of heating plant for the High T network is compensated by the revenue from electricity generation from the CHP plant – this being the rationale for the capital expenditure on the CHP. In addition, the network cost is slightly higher in the Low T network, resulting from the lower network flow-return temperature difference and the associated requirement for larger diameter, more costly pipes. However, the fuel and carbon costs are slightly higher for the High T network, and overall the Low T network carries the lower cost.

Table 22: Summary of key characteristics of HP in DH schemes studied in Demand Case B

		High T network	***Low T network***
Description of scheme and buildings served		Large-scale existing commercial development	
Heating	Heat source (source T)	Sea (6-15ºC)	Sea (6-15ºC)
	Central HP type (HP sink T, capacity)	WSHP (70ºC, 4.7 MW_{th})	WSHP (11ºC, 4.4 MW_{th})
	Building-integrated HP type (total capacity)	None	WSHP (8.0 MW_{th})
	Central conventional plant (capacity)	Gas CHP (5.5 MW_{th})	None
	Building-integrated conventional plant	None	None
	Network flow/return temperature (ºC)	75/55	11/5 (winter), 15/5 (summer)
	End-uses served by network	Space heating and DHW	Space heating and DHW
Cooling		No cooling demand treated	

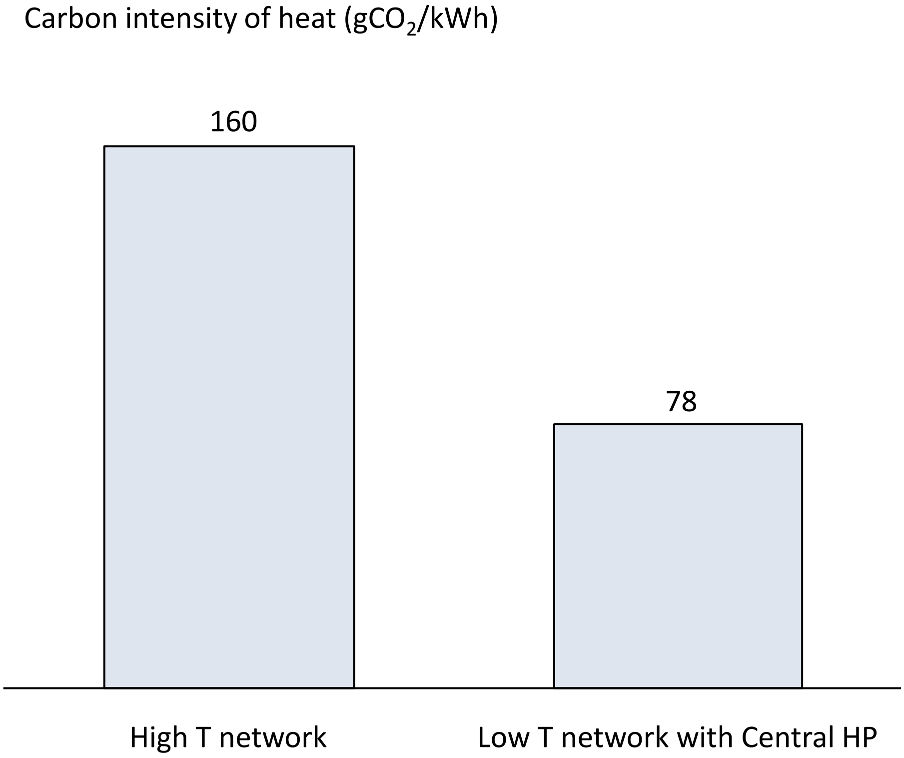
Figure 45: Breakdown of contributions to the TCO for the different HP in DH schemes studied in Demand Case B.



CO_2 comparison of different HP in DH schemes

Figure 46 presents a comparison of the CO_2 intensity of heat for the two different schemes considered in Demand Case B. It can be seen that the CO_2 intensity of heat is significantly lower for the Low T network scheme, at 78 gCO_2/kWh versus 160 gCO_2/kWh for the High T network.

Figure 46: Comparison of CO_2 emissions for the different HP in DH schemes studied in Demand Case B.



Sensitivity: Central HP cost

Figure 47 presents the impact of the cost of the central HP on the price of heat and cost of CO_2 savings (cost of CO_2 saving is calculated versus the counterfactual, which is not shown here). The sensitivity assumptions used for Demand Case B are shown in Table 23. Since the central HPs are approximately the same size for the Low T network option and the High T network option, the HP cost reduction leads to a similar reduction in the price of heat for the two schemes. The cost of CO_2 savings using the Central HP cost assumption for the Low T network is £48/tCO_2, falling to £17/tCO_2 using the Low HP cost assumption. For the High T network, the corresponding range is £51-99/tCO_2.

Table 23: Summary of sensitivity parameter values used for Demand Case B

Parameter	**Low**	**Central**	**High**
Central HP cost (£/MW_{th})	500,000	1,500,000	2,500,000
BIHP cost (£/kW_{th} for 26 kW_{th} BIHP)[35]	-	290	685

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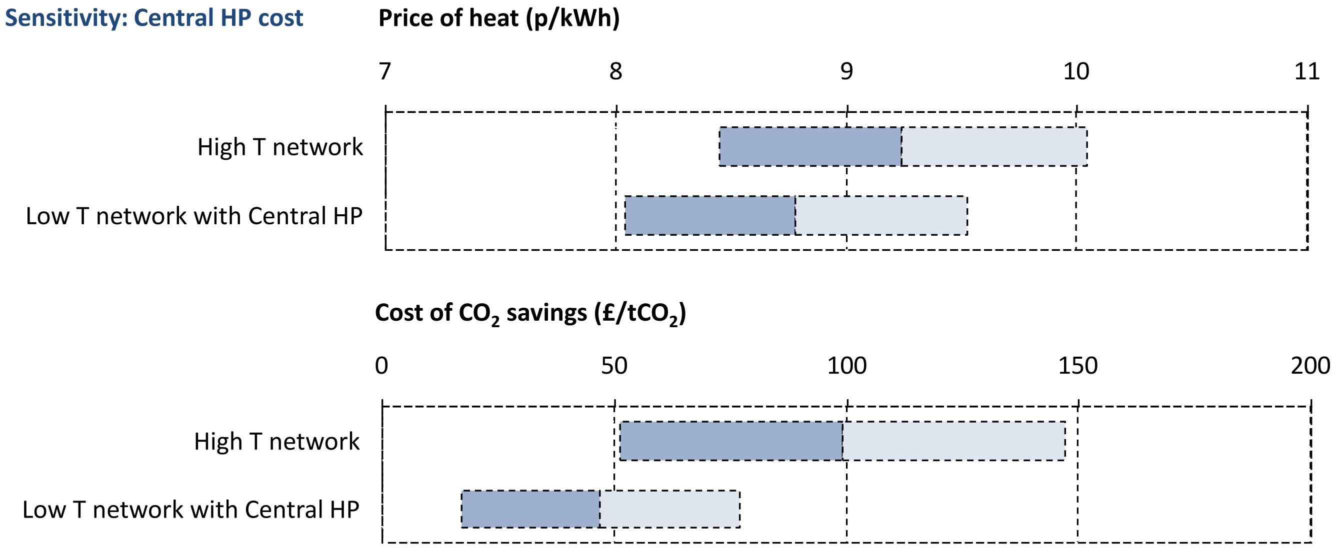
[35] For the dependence of BIHP cost on capacity, see Figure 9.

Figure 47: Impact of the central HP cost on the price of heat and cost of CO_2 savings versus the counterfactual for the different HP in DH schemes studied in Demand Case B. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions.

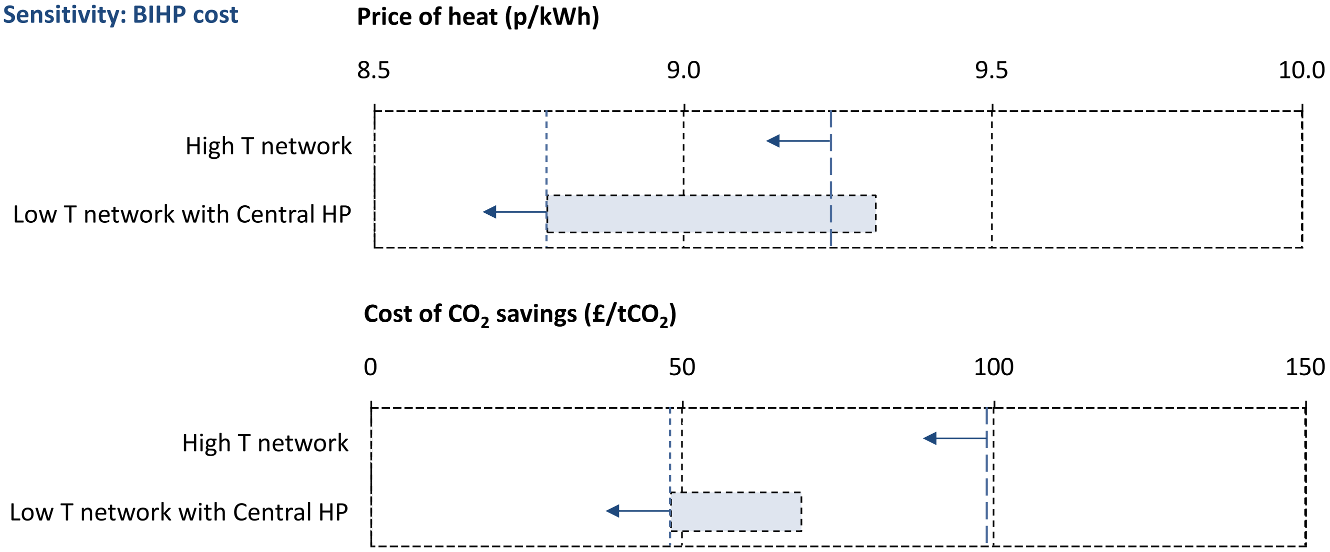


Sensitivity: BIHP cost

Figure 48 presents the impact of the cost of BIHPs on the price of heat and cost of CO_2 savings versus the counterfactual (not shown here). The sensitivity assumptions used for Demand Case B are shown in Table 23. Only a High BIHP cost sensitivity is studied here, as the Central cost value for the large BIHPs in question is towards the minimum considered appropriate.

Since no BIHPs are included in the High T network scheme, only the Low T network is affected by a change in BIHP cost. Using the High BIHP cost assumption, the price of heat for the Low T network increases to 9.3 p/kWh, slightly higher than the price of heat for the High T network, at 9.2 p/kWh. However, due to the lower carbon intensity of heat, the cost of CO_2 savings relative to the counterfactual remains lower in the Low T network, at £69/tCO_2 as compared with £99/tCO_2 for the High T network.

Figure 48: Impact of the BIHP cost on the price of heat and cost of CO_2 savings versus the counterfactual for the different HP in DH schemes studied in Demand Case B. The darker bars represent the Low sensitivity assumptions, and the lighter bars the High sensitivity assumptions. The dashed blue line indicates the price of heat for the 'High T network' scheme, and the solid blue line indicates the price of heat for the 'Low T network' scheme.



Summary of Demand Case B results

For an existing mixed-use development, the low thermal efficiency of the buildings means that it is not viable to serve the space heating demand directly from a Medium T network. Therefore, of the four HP in DH scheme configurations listed above, only the High T network option and the Low T network option are feasible.

For the demand case studied here, the most cost-effective HP in DH scheme configuration is the Low T network option, the High T network option being approximately 5% more costly using the Central HP cost assumptions. The higher cost of the High T network is despite lower network infrastructure costs, and the additional revenue from the electricity generated by the CHP plant. The Low T network, however, benefits from a significantly lower cost of heating plant. Since the BIHPs in this case serve large non-domestic buildings, the cost per kW_{th} is low, and can be sized to a more diversified demand than a BIHP serving a single residential flat.

Furthermore, a reduction in the cost of HPs is likely to favour the Low T network option. Since a similar capacity of Central HP is required in both cases, a reduction in the cost of the central HP affects both schemes similarly. In contrast, since only the Low T network option includes a BIHP, a reduction in the cost of BIHPs results in a decrease in the cost premium of the Low T network versus the High T network.

The carbon intensity of the Low T network, at 78 gCO_2/kWh, is substantially lower than that of the High T network, at 160 gCO_2/kWh. Using the Central assumptions, the cost of CO_2 savings versus the counterfactual is £48/tCO_2 for the Low T network and £99/$tCO_2$for the High T network. For the Low Central HP cost assumption in Table 23, the cost of CO_2 savings for the Low T network falls to £17/tCO_2.

7. Exploration of cost-effective heat pump in district heating scheme types

Introduction

The previous two chapters showed that although some of the schemes modelled thus far perform very well in terms of CO_2 savings, they are all more costly over their lifetime than conventional heat networks without heat pumps. In this chapter, scheme types are explored which could be cost effective compared to a counterfactual district heating scheme heated by gas CHP or boilers. These terms are defined as follows:

- *'Counterfactual district heating scheme'*: as in the rest of this report, this is taken to be a conventional heat network of 80°C flow, 60°C return temperature. In reality these temperatures would vary over a year but they are fixed here for simplicity.
- *'Cost-effective'*: not necessarily cheaper than the counterfactual scheme, but as close to it as possible. Cost-effectiveness is assessed on the basis of scheme Total Cost of Ownership (TCO). Other indicators of scheme success which are not purely based on cost, such as CO_2 savings or CO_2 abatement cost, are treated in the previous report.

Since it has been shown in previous chapters that direct substitution of gas-fired heating plant with heat pumps would normally entail an increase in capital expenditure, much of the content of this analysis concerns how to make up for this increase by using heat pumps to lower the running cost in various ways. The analysis was carried out using a combination of the model and some off-model calculations.

The analysis first sets out the context of the difficulty for heat pumps of operating at lower cost than gas-fired plant, given projected UK electricity and gas prices. Three ways of modifying heat networks or system operation are then explored to try to overcome this barrier.

Context: electricity and gas prices

It was stated above that if heat pumps are to replace conventional plant in heat networks without a significant cost premium, they must have lower running costs than their conventional counterparts. However, in the UK, electricity is and is expected to remain several times more expensive per unit than gas. To work out the impact of this for heat pumps some off-model analysis is carried out below. Figure 49 shows DECC's projected trajectories for retail industrial electricity and gas prices over the lifetime (taken to be 20 years) of a scheme planned now and installed in 2018[36]. Note that CO_2 price is already included in electricity price and has been added onto gas price in the Figure.

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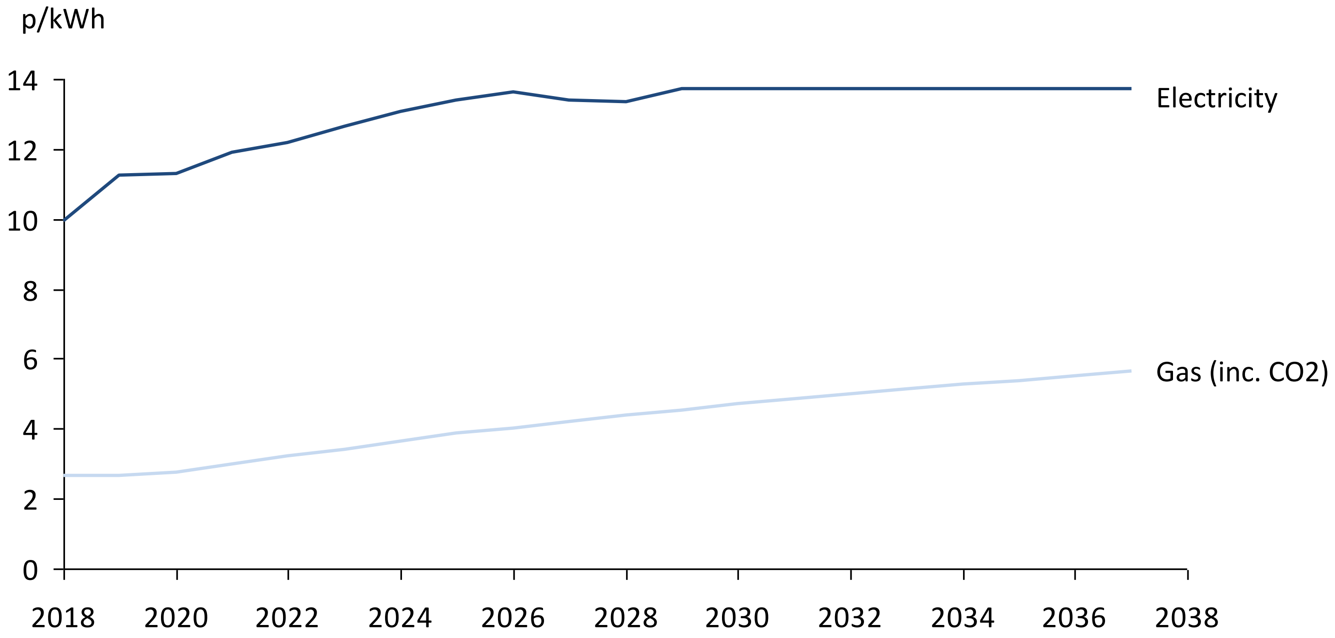
[36] Source: DECC (2014): Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal, Tables 3, 4, 5.

Figure 49: Electricity and gas price projections, 2018-2037



Given the average electricity/gas price ratio over the 20-year period in consideration, and the efficiency of gas-based counterfactual heating plant, it is possible to calculate the minimum COP of a heat pump which beats a boiler or CHP counterfactual on fuel cost:

Boiler counterfactual:

The undiscounted average electricity/gas price ratio is calculated as follows:

$$\frac{\sum_{year=1}^{year=20} elec\ price}{\sum_{year=1}^{year=20} gas\ price}$$

This yields a ratio of 3.18.[37] For a boiler of thermal efficiency 85% and an electricity/gas price ratio of 3.18, the minimum COP of heat pump which beats a boiler on fuel cost is **2.70**. This seems an achievable COP to attain over a year.

CHP counterfactual:

CHP, however, is a more challenging counterfactual for a heat pump to beat. For each unit of gas burned the operator receives revenue from electricity exported to the grid[38]; in this calculation this revenue is subtracted from the gas price, to create an effective gas price.

Using a thermal efficiency of 52% and an electrical efficiency of 28%, this gives an average electricity/effective gas price ratio of 8.52, and thus the COP of a heat pump which beats CHP on fuel cost must exceed **4.43**. This is a very high COP to achieve over a year.

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[37] If a discount rate is applied, this number increases, therefore the COP of a heat pump beating a boiler on fuel cost also increases.

[38] Please see Appendix 1 for electricity purchase and export prices used in this analysis.

Heat pumps in conventional temperature district heating networks

The above calculations will now be applied to a conventional district heating context. After this, more novel networks with lower temperatures will be explored.

Conventional heat networks in the UK are generally heated using gas CHP as baseload, with a flow temperature of around 80°C (higher in winter, sometimes lower in summer) and return temperature of around 60°C. Substituting some or all of this gas CHP for a heat pump therefore requires a heat pump to output at over 60°C to be able to perform a useful function. It also requires a locally available heat source; the most commonly available heat sources are a body of water (river, canal, lake) or air. It is very unlikely that the COP of a heat pump whose source is around 5-15 degrees and whose sink temperature is around 70 degrees can exceed 4.4 as required in the previous section.

This point will now be demonstrated by setting up a scheme in which a heat pump replaces a proportion of the CHP in the counterfactual scheme, all in the context of an 80°C/60°C network, supplying heat to existing non-domestic buildings as may be found in a UK city centre.

A best case[39] and a medium case were modelled using a water source (such as a river) at 10°C and the results are shown in Figure 50. Please note that, similar to Figure 49, the EU ETS carbon price is already included in the electricity price, whereas it is added separately on to the gas cost in the simulations below.

Inputs to conventional temperature network modelling

Parameter	CHP counterfactual	Heat pump scheme: high COP	Heat pump scheme: medium COP
Space heating emitter/DHW temperatures, °C	75/60		
Network flow/return temperature, °C	80/60		
% peak demand met by gas-fired plant	100	50	50
Heat pump sink temperature, °C	N/A	75	75
Heat pump SCOP	N/A	3.68	2.21

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[39] Using manufacturer COP data for 10°C source and 70°C sink temperature from Star Refrigeration referring to the Drammen installation, Norway

Figure 50: conventional temperature network

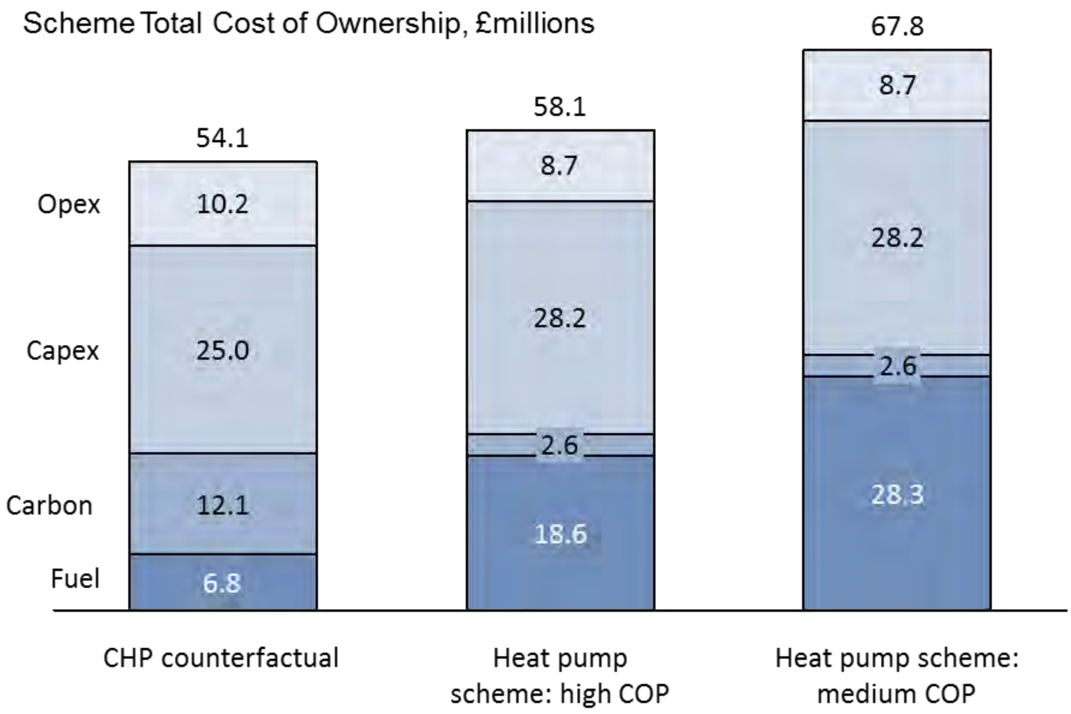


Figure 50 shows the TCO breakdown of the counterfactual and two heat pump schemes. Please note that the 'fuel' component of the chart is the resultant of positive cost of gas and electricity and the revenue (negative cost) from electricity generated by the CHP.

As expected, both capital expenditure and fuel/carbon cost have increased from the counterfactual to the heat pump schemes. Under the best case COP (of 3.86), the fuel/carbon cost comes close to the counterfactual fuel cost, but in the medium COP case the fuel/carbon cost is 63% higher.

Figure 50 illustrates that with today's best available heat pump technology, conventional temperature networks with low/ambient temperature heat sources such as rivers are not likely to achieve a high enough COP to beat a CHP counterfactual on fuel cost. In order to do this, either the COP needs to be increased beyond 4.4 by decreasing the source-sink temperature gap, or a means must be found beside efficiency to run the heat pump more cheaply.

There are a number of ways that each of the above objectives can be achieved. Three will explored in this chapter: using CHP to power a heat pump, incorporating sources of relatively high temperature waste heat, and lowering the network temperature.

Lowering running costs 1: using CHP to run heat pumps

The two previous sections explained the challenge for heat pumps of trying to beat CHP on running cost. Using the same network setup as in the previous section – that is, conventional temperature and with some of the heat supplied by CHP – this section explores whether it is possible to bring down the running cost by using electricity generated by the CHP to run the heat pump.

The main effect of this strategy is that the heat pump is powered by lower cost electricity than would have been the case if electricity had been purchased from the grid, so it is expected that where heat pumps and CHP exist in the same network, it should be cheaper to run the heat pump from CHP electricity than to run both types of plant separately. The strategy is contingent on running the heat pump and CHP at the same time; this is realistic at least in winter months since the daily time of high heat demand tends to coincide with the time of high electricity price (the CHP electricity which is not required to run the heat pump is sold to the grid).

Once again, the counterfactual used in the modelling is a CHP-only scheme. The trade-off encountered by incorporating heat pumps into the scheme is the loss of CHP revenue (since some of the CHP electricity is now being used to run the heat pump) versus the decreased gas expenditure (since some of the heat is now provided by the heat pump instead of the CHP).

A short piece of off-model analysis was carried out to explore the effect of heat pump COP on this setup, and to find the minimum COP at which schemes incorporating heat pumps can beat the CHP-only counterfactual on the metric of 'fuel & carbon cost' – the sum of fuel cost and carbon cost.

Figure 51: different combinations of CHP and heat pump, using COP = 3

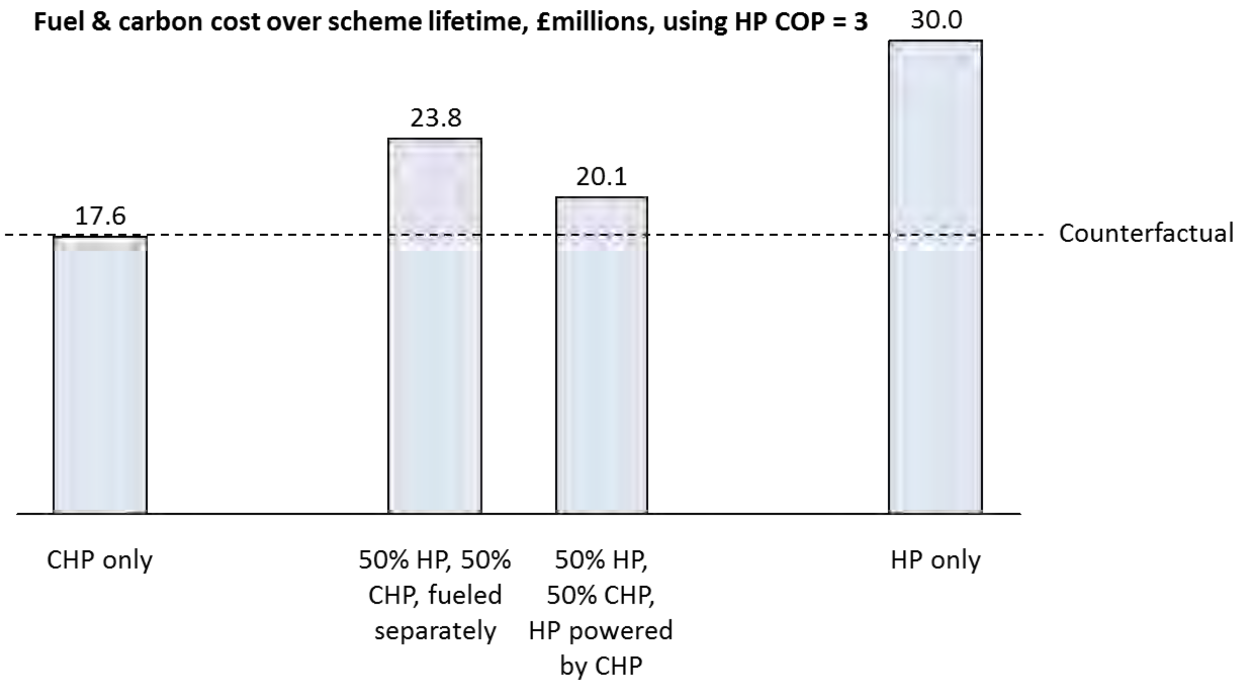


Figure 51 illustrates the effect of this strategy on total fuel & carbon cost. It can be seen that using CHP electricity to power the heat pump does indeed lower the fuel cost, but at a heat pump COP of 3, the lowest fuel & carbon cost is still achieved by the CHP only system.

Figure 52: different combinations of CHP and heat pump, using COP = 4

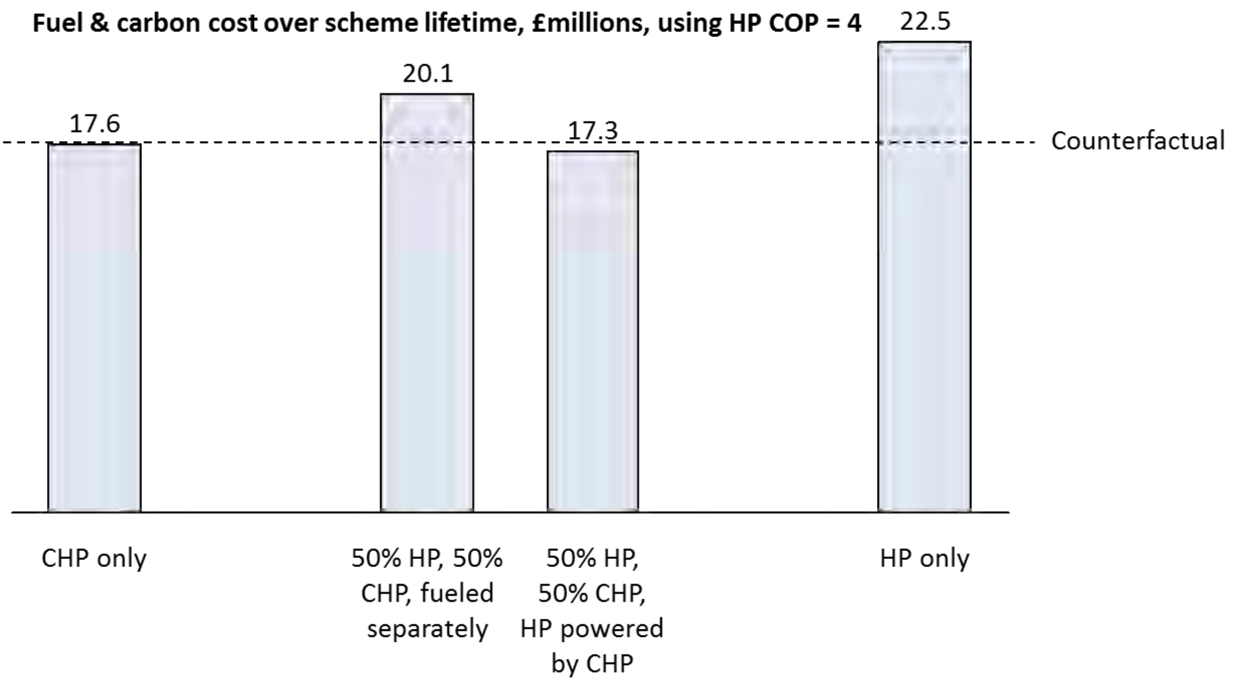


Figure 52 shows the same four configurations, but using a higher COP. This time, using CHP electricity to power the heat pump has led to lower running costs overall.

In fact, whereas earlier it was calculated that a COP of 4.4 was required to allow heat pumps to beat a CHP counterfactual, if CHP electricity is used to power the heat pump then the threshold COP is 3.9. The strategy has helped to lower this threshold COP, however 3.9 is still a very high COP to require. Furthermore, in this section the focus was purely running cost – to make up for the increased capital expenditure from incorporating heat pumps the COP would need to be even higher.

To achieve such high COPs, the gap between the source and sink temperature must be reduced; one way to do this is to increase the source temperature by heat sources at higher temperatures than ambient. This is treated next.

Lowering running costs 2: incorporating CHP waste heat

Incorporation of waste heat into a network can be carried out in several ways. One promising application is the use of a heat pump which can operate at high temperatures (e.g. using a source temperature of 50°C) to recover otherwise waste heat from a CHP. This particular strategy also carries on the previous theme of incorporating heat pumps into networks alongside gas CHP.

One successful example of district-scale CHP heat recovery using heat pumps is in Stockholm, where a 7.2 MW heat pump was fitted onto the flue of an energy-from-waste CHP. The heat pump captures heat at 50°C to use as its source and heats the district heating return flow from 60°C to 65°C, resulting in a COP of 6.5.

This setup is modelled below in a UK context, under the following configurations:

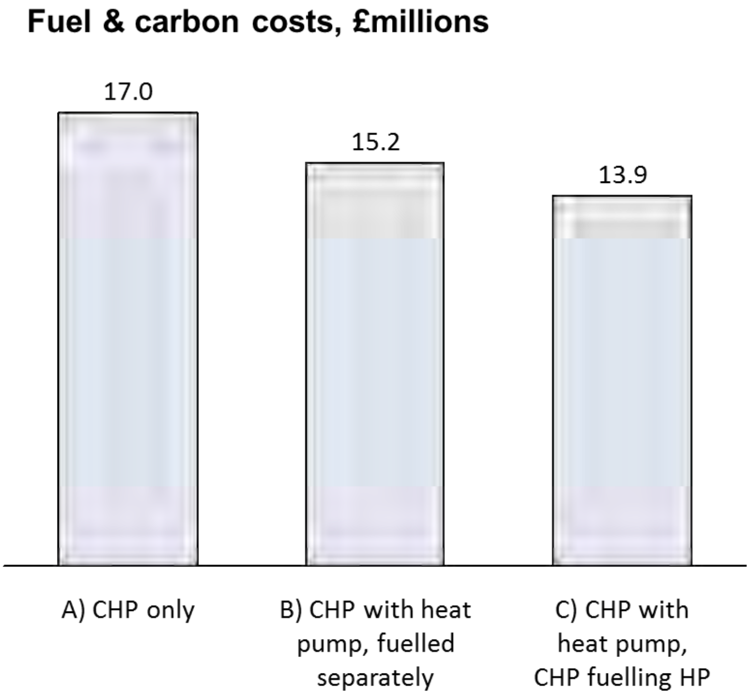
- A) Counterfactual: gas CHP
- B) Heat pump in series with gas CHP: heat pump heats 50°C to 65°C, CHP heats 65°C to 80°C.
- C) Heat pump incorporated as above but with the heat pump powered by electricity generated by the CHP.

Inputs to conventional temperature network with CHP and heat pumps in series

Parameter	A) CHP only	CHP and heat pump - both B) and C)
Space heating emitter/DHW temperatures, °C	75/60	
Network flow/return temperature, °C	80/60	
% peak demand met by CHP	100	50% (heat pump in series with CHP)
Heat pump source temperature, °C, and nature of source	N/A	50, waste heat from CHP
Heat pump sink temperature, °C	N/A	65
Heat pump SCOP	N/A	6.5

Firstly, the fuel & carbon costs are shown, followed by the scheme TCO.

Figure 53: fuel & carbon costs, heat pumps recovering heat from CHP



The fuel/carbon cost saving achieved by carrying out half of the heating using heat pumps, although noticeable in Figure 53, is not dramatic as might be expected from use of a heat pump with a COP of 6.5; this is because of the lost CHP revenue. The export price for CHP generation, although lower than the purchase price for electricity, is still high enough for lost CHP revenue to be important.

Figure 54: scheme TCO, heat pumps recovering heat from CHP

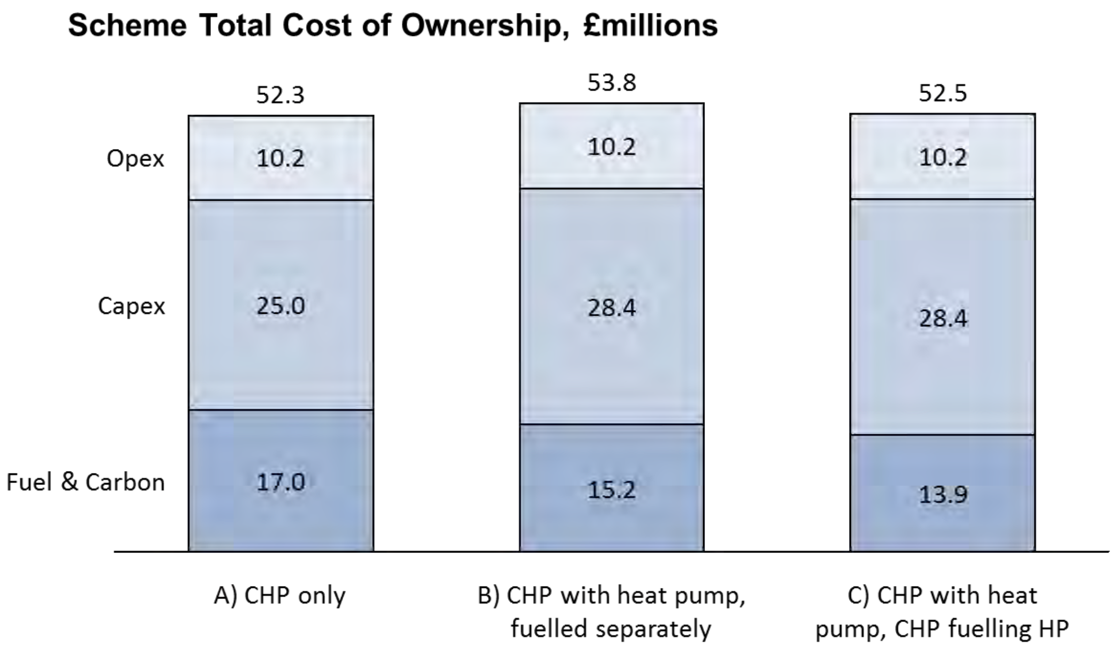


Figure 54 shows the scheme total cost of ownership for the three configurations. Please note that 'opex', or operating cost, has been set to constant; in general heat pumps are less costly to maintain than CHP[40] but in this case the complexity of the heating plant has been increased by fitting a heat pump onto a CHP, so it was judged that there should be no reduction in operating costs.

Moving from bar A to B in Figure 54, the extra capital expenditure associated with the incorporation of the heat pumps outweighs the fuel and carbon financial saving. Moving to bar C, most of this can be recuperated by using the CHP electricity to fuel the heat pump; and on balance the cost is now about the same as the CHP-only counterfactual.

So far, the analysis has considered the efficiency increases available from increasing the heat pump COP through increasing its source temperature. We now move to the other way of increasing the COP: by lowering the heat pump's sink temperature. Since the heat pump can only provide useful heating if its sink temperature is above the flow temperature of the district heating network, this next section explores the effect of decreasing the network flow temperature.

Lowering running costs 3: reducing the network temperature

The conventional temperature networks used in the analysis up to this point would be more or less suitable to provide heat to any types of building, whether new or existing. Moving to lower temperature networks normally excludes thermally inefficient buildings from a district heating scheme, so this section will use new-build housing estates as the building type in the schemes

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[40] Reference for operating costs: industry consultation carried out by Element Energy for DECC, 2014.

to be modelled. It will also use gas boilers as the counterfactual heating plant, on the assumption that these are smaller schemes.

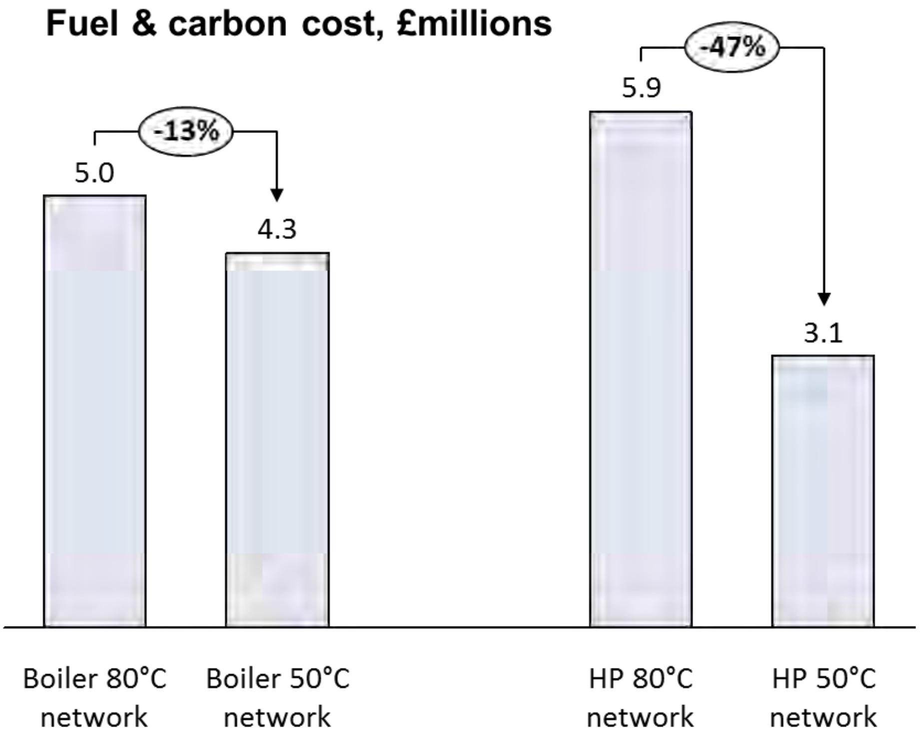
Building type for all model runs in low network temperature analysis

Parameter	Boiler counterfactual	Heat pump scheme
Demand type	800 new-build terraced houses	
Demand served annually, MWh, and end-use breakdown	4,500 (33% DHW, 67% space heating)	

Two benefits are obtained if the network flow temperature is reduced: increased heat pump COP and lower thermal losses. Since the latter would occur anyway without the presence of a heat pump (i.e. if the temperature of the network in the counterfactual scheme reduced, then thermal losses would reduce), it is useful to examine the relative size of both effects, firstly on the fuel & carbon cost alone, and secondly as part of the overall scheme cost (TCO).

Figure 55 demonstrates the effect of reducing the network temperature from 80°C to 50°C. Please note that the extent to which networks really can operate at 50°C is explored later.

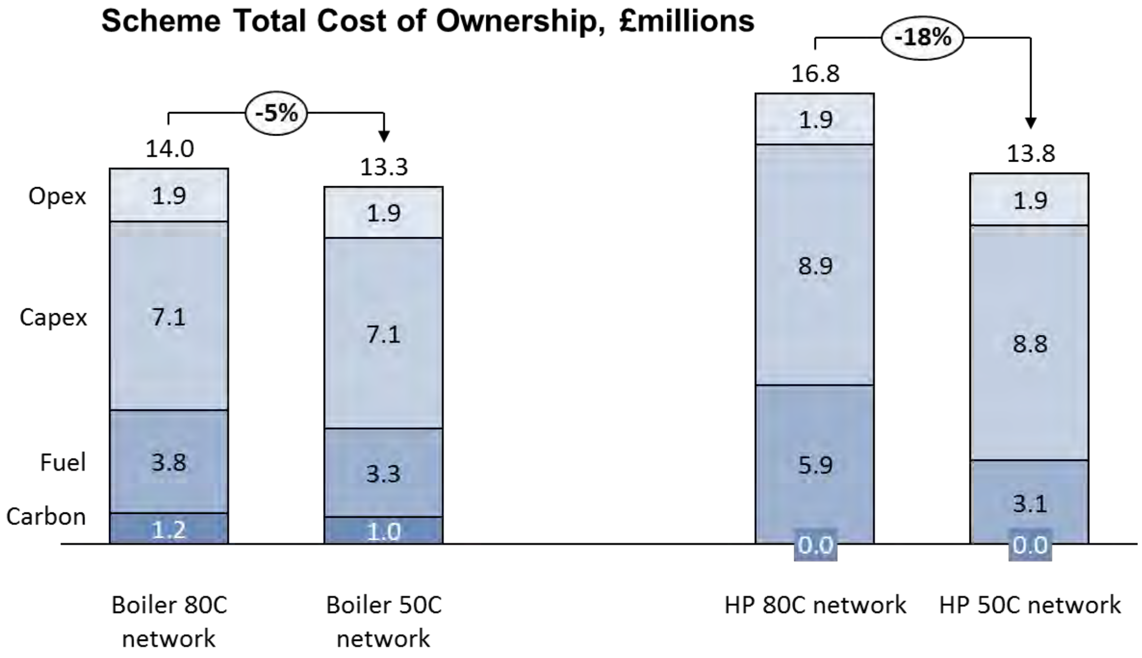
Figure 55: effect of reducing network temperature on fuel & carbon expenditure



The effect of reducing network losses by operating at lower temperatures is a 13% reduction of fuel & carbon cost, as shown in Figure 55. The same percentage reduction of fuel & carbon costs can also be attributed to reduction of network losses in the heat pump scheme, such that the remaining 34% reduction can be attribute to improvements in heat pump performance, giving the overall fuel and carbon cost reduction of 47%. It can thus be seen that the effect of increased heat pump performance has a larger effect than reducing network losses.

The same reduction in network temperature has a smaller effect on scheme TCO, as shown in Figure 56 since in this scheme the largest expense is not fuel but capital expenditure. This is more likely to be the case in schemes serving new buildings. In fact, the counterfactual scheme only yields a saving of 5% of the TCO if network temperature is lowered. The heat pump scheme shows a greater saving, due to the effect of the heat pump COP increasing.

Figure 56: effect of reducing network temperature on scheme TCO



It is clear that in heat pump schemes, delivering heat at as low a temperature as possible is desirable for cost reduction, mostly to improve the heat pump performance. The next two sections will explore different ways of achieving the required space heating and DHW temperatures in the context of lower temperature networks.

Medium versus low temperature networks

There are two main ways of using lower-than-conventional temperature networks with heat pumps to provide heat to buildings at the desired temperatures. These have been previously introduced in Scenarios 2 and 3-4 within the modelling in Chapters 5 and 6; they are summarised again here:

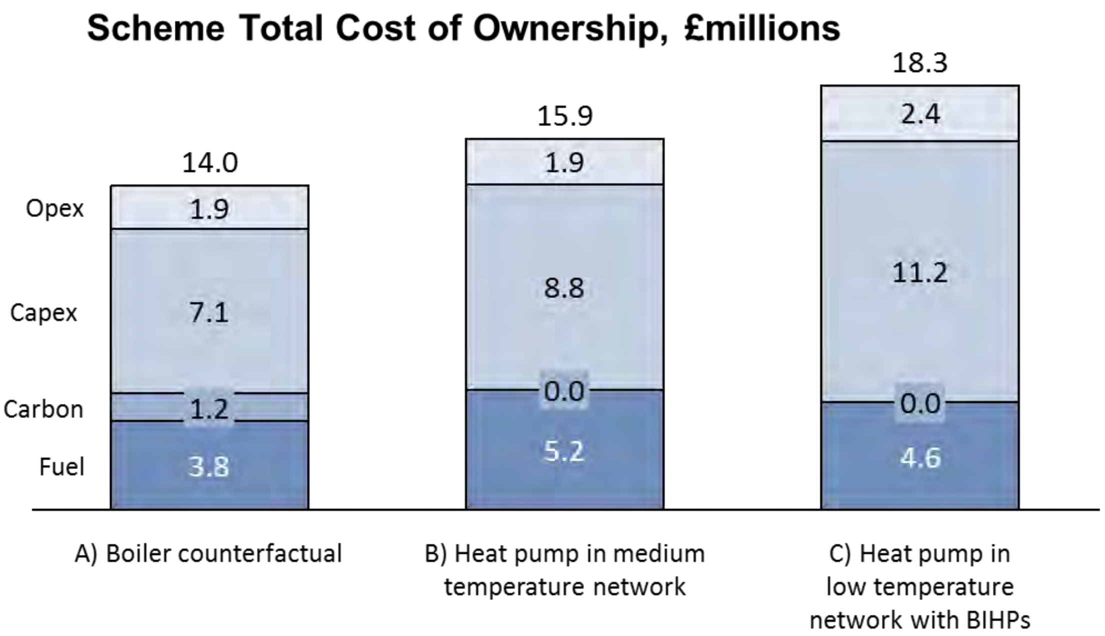
- Medium temperature networks: using the heat pump to heat the network, which then delivers straight to the building's distribution circuits. If the temperature required for space heating and DHW differ then this method must deliver heat at the higher of the two temperatures.
- Low temperature networks: carrying out minimal heating at the central plant end of the network, so that the network is at or just above ambient temperatures, and then uses distributed heat pumps in each building to raise the temperature to that required for space heating and DHW. This method takes advantage of the fact that space heating emitter temperatures are often lower than DHW temperatures in new buildings, by providing heat at each required temperature instead of the upper of the two, and thus achieving a higher COP for some of the heating.

These two types of scheme are compared against each other and against a boiler counterfactual below.

Inputs for medium versus low temperature network modelling

Parameter	A) Boiler counterfactual	B) Heat pump scheme: all heating by central HP ('medium' temperature network)	C) Heat pump scheme: central HP and BIHPs ('low' temperature network)
Emitter temperatures, degrees C	45 (space heating) 60 (DHW)	45 (space heating) 60 (DHW)	45 (space heating) 60 (DHW)
Network flow/return temperature, degrees C	80/60	65/45	11 in winter, 15 in summer
% peak demand met by gas-fired plant	100	0	0
Heat pump sink temperature, degrees C	N/A	65	Central HP: 10 in winter, not used in summer. BIHPs: 60 for space heating, 45 for DHW
Heat pump SCOP	N/A	2.38	Central HP: 11 BIHPs: 3.9

Figure 57: medium and low temperature networks



Bars B and C in Figure 57 show that, moving from the medium to the low temperature network, the small decrease in fuel expenditure is outweighed by the relatively larger increase in capital expenditure. The reasons behind this are as follows:

- In bar C, despite electricity consumption reducing due to lower network losses and some of the heat being delivered at a lower temperature, fuel expenditure is not reduced in proportion to this. This is because electricity is now consumed by individual households, at the domestic retail price, which is higher per unit than it would be if purchased by a central heat pump operator.

- The high capital cost in bar C is made up of both a central heat pump carrying out the first part of the heating to stop water freezing in the network and heat pumps in each building. The latter must be sized to meet the peak demand of each house; the diversity benefit of district heating for plant sizing is thus lost.
- An increase in operating costs is observed in bar C: the scheme operator is responsible for the maintenance of a large number of distributed heat pumps.

The conclusion from comparing ‘medium’ versus ‘low’ temperature networks is that the latter, although energy efficient in terms of reducing network losses and only heating to the required temperatures, entail a significant cost increase[41], from the purchase, running and maintenance of a large amount of distributed heating plant.

We therefore move away from ‘low’ temperature networks and instead focus in on ‘medium’ temperature networks which do not require any or as much distributed plant.

Bringing the network temperature down without requiring large amounts of distributed heating plant

In the UK the lowest acceptable distribution network temperature for district heating serving new developments is likely to be around 65°C. This is so that, after a temperature drop caused by a heat exchanger, DHW can be supplied at 60°C. This scheme configuration was already modelled in the previous section (the ‘medium’ temperature network) and its cost was higher than the boiler counterfactual (since the fuel cost was similar and the capex was greater); this is shown again in Figure 58.

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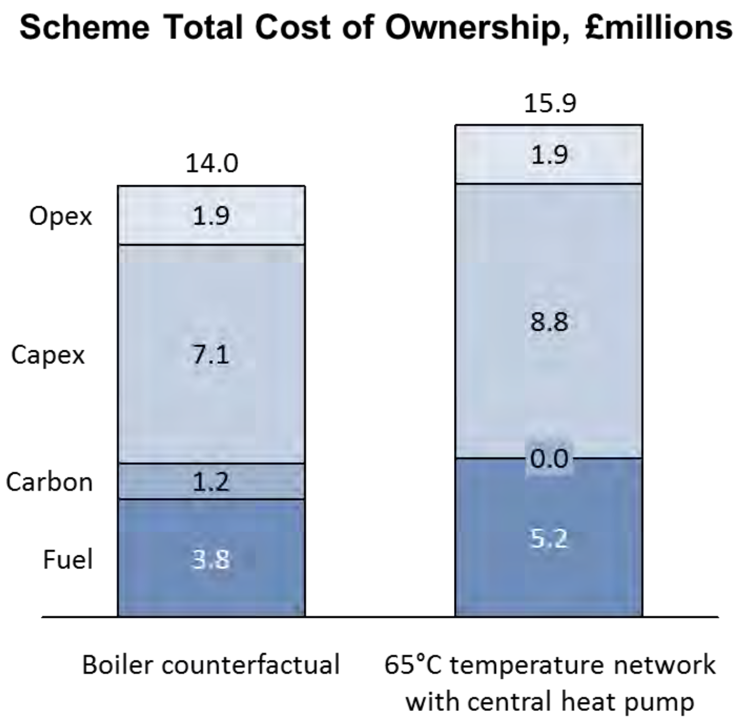
[41] However, cooling demand improves their economics although this is not modelled here – see the main report.

Figure 58: 65°C temperature network versus boiler counterfactual in 80°C network



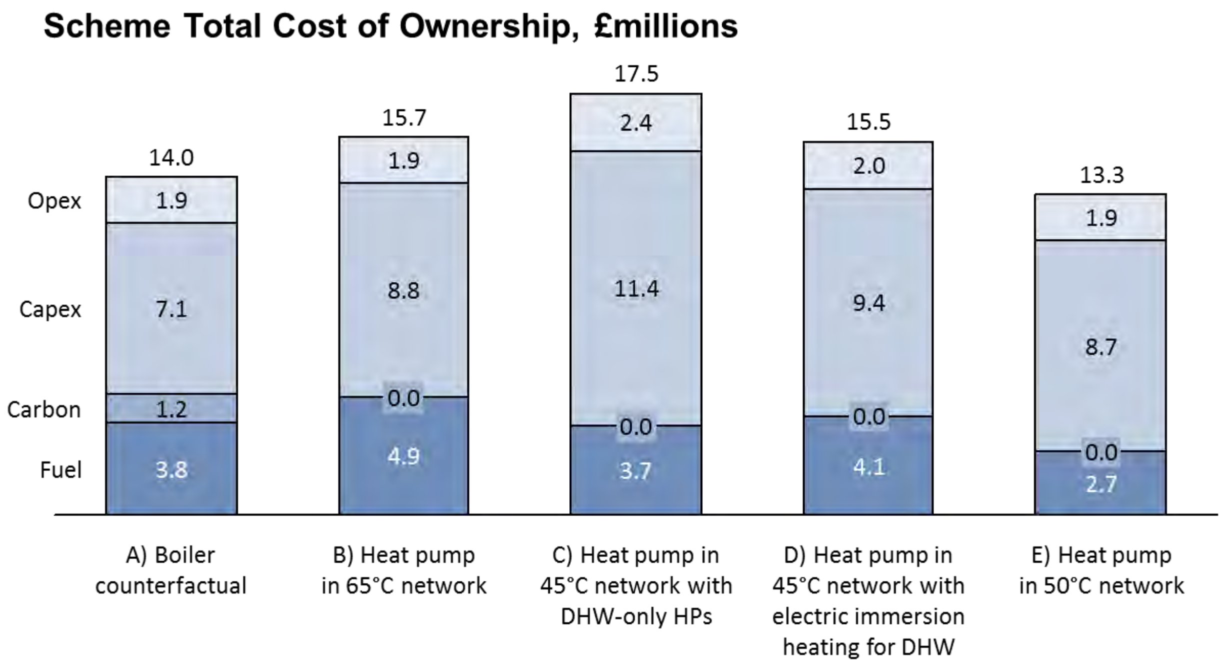
To decrease the running cost of the heat pump scheme, we wish to further reduce the network temperature. Rather than lowering this to ambient temperature and upgrading its heat using building-scale heat pumps to provide the space heating and hot water, an alternative strategy is to use the network to provide space heating and minimal building-scale plant to upgrade this heat to that required for DHW.

Figure 59 shows several means of implementing this. Bars A and B are the counterfactual and low temperature network from Figure 58. Bars C and D use a network temperature of 45°C, suitable for underfloor space heating, and use small heat pumps and electric immersion heaters respectively to provide DHW using the network as a starting point. Bar E shows a situation which does not meet UK regulations but is accepted in Denmark: providing both space heating and DHW at 45°C, using a network temperature of 50°C.

An interesting feature of Figure 59 is that, while the scheme with small heat pumps for DHW (bar C) is noticeably more expensive than the scheme using the 65°C network (bar B), the scheme with immersion heating for DHW (bar D) is not, as its fuel cost is lower than that in the 65°C network scheme. This occurs even though the second stage of DHW heating has an effective COP of only 1.

Using the assumptions in this modelling, the boiler counterfactual is beaten by the scheme shown in bar E: that using the 50°C network for both space heating and DHW. Although these results should be interpreted as insights rather than definitive conclusions, as the relative TCO performance of these schemes is subject to many sensitivities as demonstrated in the main report, it is nevertheless interesting to observe that the increase in capital expenditure has been more than compensated for by the reduction in fuel cost in only this scheme.

Figure 59: different ways of providing space heating and DHW from low temperature networks



This section has explored ways of providing DHW in the most cost-effective way and shown that extra expense is incurred if additional building-scale plant is used. However, at conventional UK heating temperatures for low energy buildings (60°C for DHW, 45°C for underfloor space heating), as the ratio of DHW demand to space heating demand decreases, the extra capex for DHW heating plant decreases and more of the total heat is provided at 45°C, the lower of the two temperatures. It could therefore be the case that buildings with relatively low DHW demand compared space heating demand (e.g. offices) could benefit from the schemes in bars C and D.

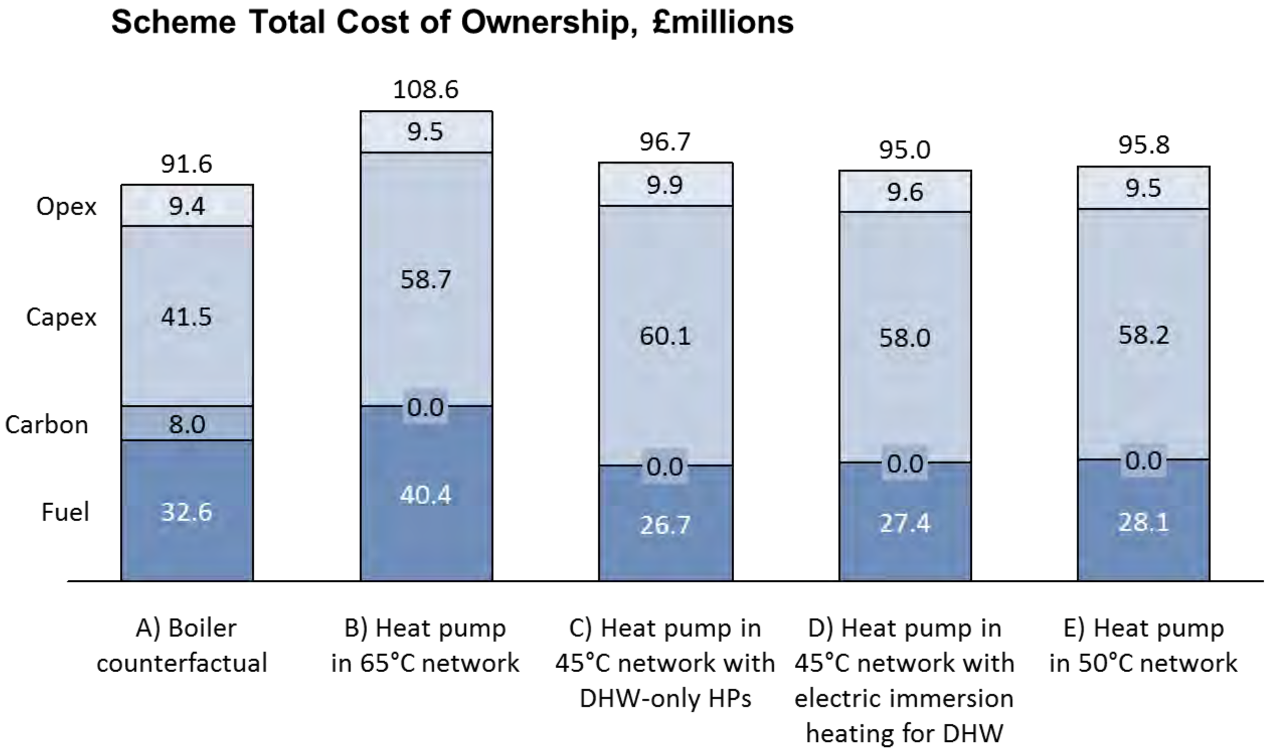
Figure 60 illustrates this point by showing the same schemes as Figure 59 but with 800 new-build offices instead of 800 new dwellings. Whereas in Figure 59 the most expensive scheme was that using DHW-only heat pumps to upgrade heat from the network to provide DHW, this is not the case in Figure 60. Here, lowering the network temperature from 65°C to 45°C brings about cost savings which are not offset by the extra plant needed to provide DHW.

Again, these results are indicative only, but demonstrate the point that the ratio of DHW to space heating demand alters the suitability of different heat pump in district heating configurations and a low ratio improves the viability of schemes providing only space heating from the network.

Building type for schemes modelled in Figure 60

Parameter	Boiler counterfactual	Heat pump scheme
Demand type	800 new-build offices	
Demand served annually, MWh, and end-use breakdown	32,700 (14% DHW, 86% space heating)	

Figure 60: different ways of providing space heating and DHW from low temperature networks – offices example



Conclusion

This chapter started from the previous finding that the use of heat pumps in heat networks usually leads to a capital cost increase over conventional heating plant. Therefore, if heat pumps are to be cost-competitive overall, ways to reduce running cost must be found. However, heat pumps are hindered from outperforming gas-fired plant on running cost due to electricity prices: the relatively high price of electricity compared to gas in the UK and the high electricity export price lead to CHP normally being cheaper to run than heat pumps.

This analysis explored ways in which this barrier could be overcome. Although the use of heat pumps in heat networks does entail a cost increase in most configurations, it was shown that there exist certain scheme types whose cost is comparable to conventional networks without heat pumps. These scheme types fall into two categories:

1. In schemes in which there is CHP installed as part of the heating strategy, cost-competitive uses of heat pumps are:

   - The use of high-COP heat pumps powered by CHP electricity
   - The use of heat pumps to recover waste heat from CHP operation

2. In schemes in which there is scope to lower the network temperature (i.e. when supplying thermally efficient buildings), doing this is beneficial, with the majority of the benefit being attributed to enhanced heat pump performance as opposed to reduced network losses. Cost-competitive uses of heat pumps here are:

   - For schemes in which DHW demand is relatively low compared to space heating demand (e.g. offices) providing space heating from the network and using additional plant (which could be heat pumps) for DHW is cost-efficient.

- For schemes in which DHW demand is a larger part of overall heat demand, the additional plant can drive up the cost. In these schemes, it was shown that either reducing the network temperature as much as possible while still providing DHW, or using inexpensive additional plant to provide the DHW, are the most cost-effective solutions.

All of the above results are sensitive to a number of factors including electricity and gas prices and heat pump COP. However, the principles of what drives the cost competitiveness of heat pump in district heating schemes have been set out in the above analysis, and the likely successful scheme types have been derived.

The next chapter brings together findings from the three analysis chapters.

8. Discussion

We have studied a wide variety of heat pump in district heating scheme configurations

We have defined a set of four distinct HP in DH scheme configurations covering the key approaches to integrating HPs in DH networks. These are:

- High temperature network with a central HP serving both space heating and hot water demand ('High T network');
- Medium temperature network with a central HP serving space heating directly, with electric immersion heaters boosting the network temperature to provide the hot water demand ('Medium T network with immersion heaters');
- Medium temperature network with a central HP serving space heating directly, with micro-BIHPs boosting the network temperature to provide the hot water demand ('Medium T network with micro-BIHPs');
- Low temperature network with a central HP and BIHPs providing space heating and hot water demand ('Low T network').

We have studied a large number of variations on these four basic configurations through sensitivity analyses relating to different aspects of the scheme design, including:

- Variation in the characteristics of the heat demand served by the network, including the heat density and the space heating and hot water emitter temperatures;
- Variation in the contribution of the central HP to the overall network demand, through the use of additional gas-based heating plant, and through the variation of the HP sink temperature.

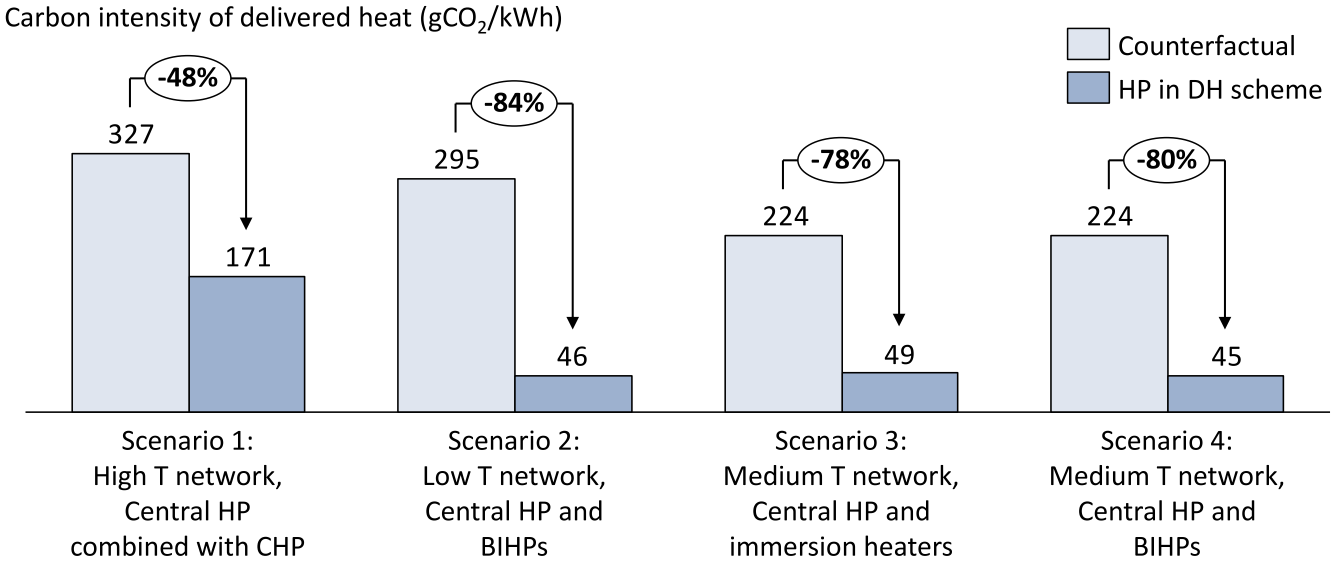
We have examined in detail the carbon and cost impacts of incorporating heat pumps into district heating

HP in DH schemes could allow CO_2 savings of up to 84% versus the counterfactual

We have found that CO_2 savings versus the counterfactual scheme, assuming the current trajectory towards low carbon electricity generation, are in the range 48-84% for the four core Scenarios studied. This is presented in Figure 61. HP in DH schemes are therefore potentially very significant as a low carbon, renewable heating option.

The very low carbon intensity of the Low T network reflects the large efficiency gain of using two HPs operating over smaller temperature ranges, and the fact that the scheme is based entirely on rapidly-decarbonising grid electricity. The carbon intensity of the High T network is typically the highest due to the use of single HP operating over a larger temperature range, and the use of additional gas-based heating plant to raise the temperature of the water to the network temperature and/or provide peaking, as typically observed for this type of scheme.

Figure 61: Comparison of the carbon intensity of delivered heat for the counterfactual and the HP in DH scheme for each of the four Scenarios studied (using the Central sensitivity assumptions).



The price of heat delivered is typically higher for heat pump in district heating schemes than for the counterfactual, leading to a relatively high cost of carbon savings

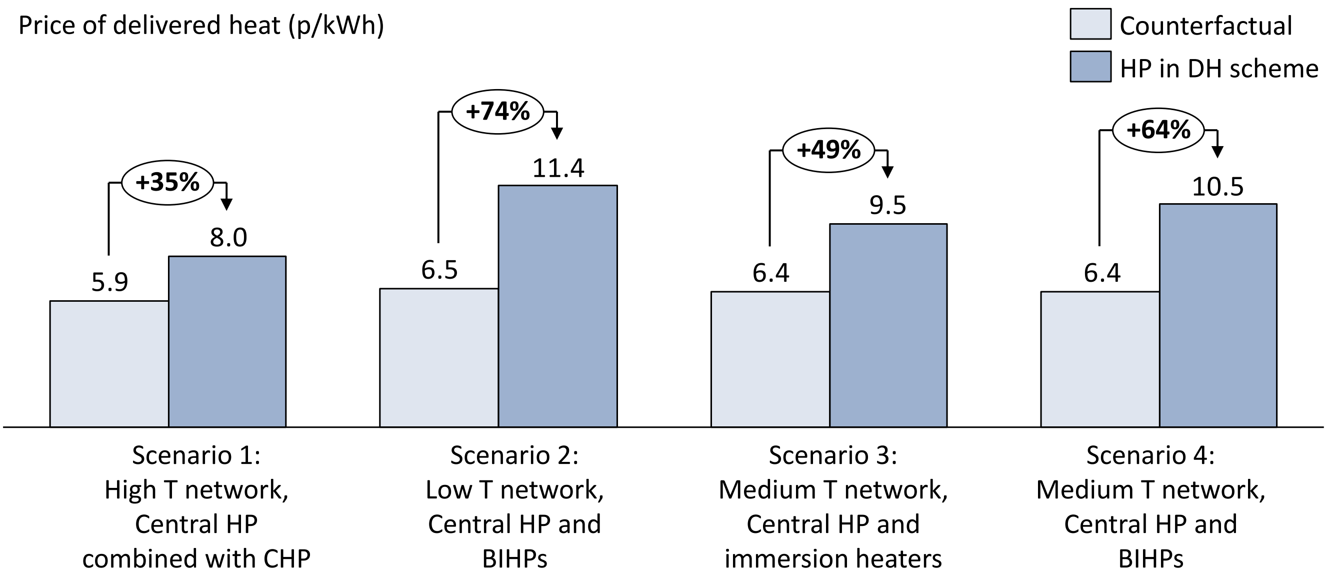
However, we have found that at current costs, heat pump in district heating schemes are likely to provide heat at a significantly higher cost than the counterfactual gas-based district heating schemes. As shown in Figure 62, the premium for the price of heat for district heating schemes incorporating heat pumps is in the range 35-74% using the Central sensitivity assumptions. The main reasons for this include:

- High capital cost of heat pumps (particularly MW-scale heat pumps)
- Lost revenue from electricity sales when compared with schemes involving gas-CHP
- Higher capacity of heating plant required where building-integrated heat pumps serve the peak demand in individual dwellings (versus gas-based district heating)
- Higher network costs (versus gas-based district heating) where low temperature networks require larger diameter pipes (assuming use of conventional heat pipe materials)

It is important to note that the costs presented are dependent on a wide range of other factors, including scheme design choices as well as variation in cost and performance input data. The impact of these factors has been explored in this study, and the findings are discussed below.

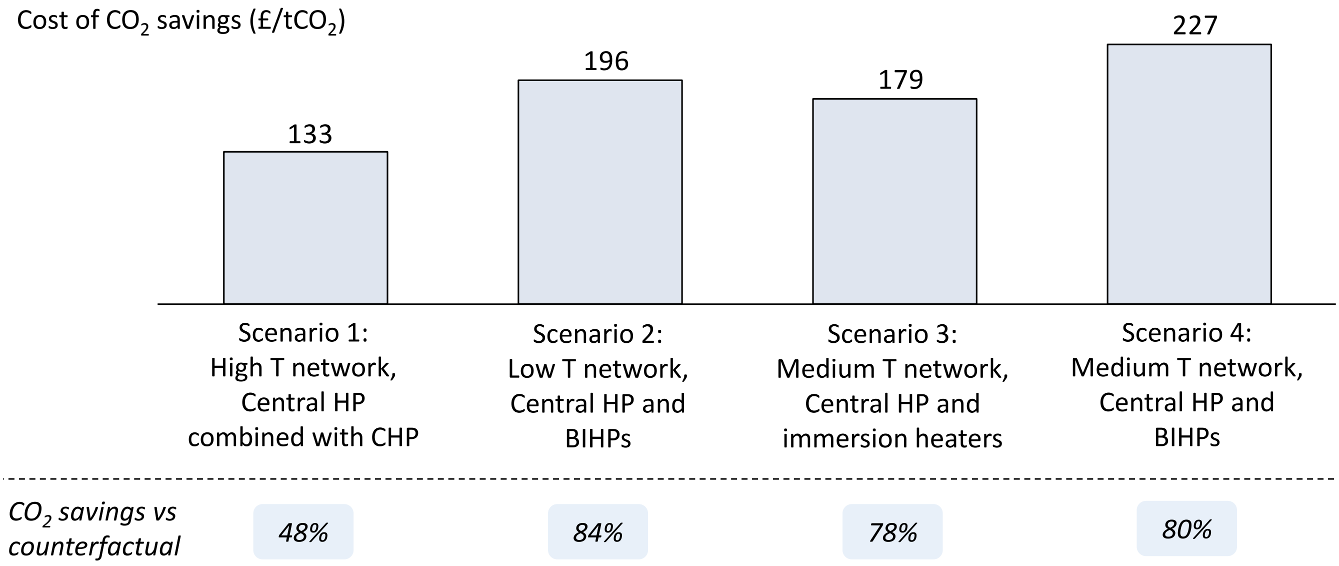
We also highlight the fact that the analysis presented includes no subsidy for the heat pump schemes (including the UK's existing Renewable Heat Incentive) in order that a 'baseline' comparison can be made. The results suggest that if the large CO_2 savings on offer are to be achieved, there will need to be a continuation of financial support for renewable heat and/or interventions to ensure a high effective price of carbon emissions.

Figure 62: Comparison of the price of heat for the counterfactual and the HP in DH scheme for each of the four Scenarios studied (using the Central sensitivity assumptions).



In the four core Scenarios studied, we have found the cost of CO_2 savings for heat pump schemes versus the counterfactual to lie in the range £133-227/tCO_2, as shown in Figure 63.

Figure 63: Cost of CO_2 savings of the HP in DH scheme versus the counterfactual for each of the four Scenarios studied (using the Central sensitivity assumptions).



The lowest cost heat pump in district heating scheme configuration will vary between different sites

In Section 6 we presented a direct comparison of the different HP in DH scheme configurations for two ‘demand cases’. We have found that for Demand case A, a small-scale scheme serving a new residential development, the most cost-effective configuration is the High T network with

Central HP. In Demand case B, however, the Low T network with Central HP and BIHPs is slightly less costly. The most cost-effective scheme design – aside from a consideration of the associated CO_2 emissions – will vary from site to site. The key factors contributing to this variation in relative cost between the various HP in DH schemes and the counterfactual between different sites are described below.

We have studied the impact on scheme viability of a range of scheme design choices and of variation in cost and performance input data

While all scheme configurations are potentially suitable for serving new buildings, the choice is more limited for existing buildings

A key factor determining which HP in DH scheme configurations may be suitable for a given situation is the thermal efficiency level of the buildings to be served by the network. The level of thermal efficiency determines the possible space heating emitter temperature. All four HP in DH scheme configurations listed above are potentially suitable for new build, due to their relatively high thermal efficiency. However, Medium T network options are not generally suitable for existing buildings, since their relatively low thermal efficiency requires higher space heating emitter temperatures.[42]

Heat density of the area served is critical for the viability of all DH schemes – involving HPs or not – but Low T networks are particularly dependent on a high heat density

All DH schemes require a high heat density in order to limit the length of pipework required and the associated infrastructure cost, which makes up a large fraction of the total scheme cost. We find that for an average heat density of 125 kWh/m^2/yr, the infrastructure cost for a High T network HP in DH scheme serving an existing mixed-use development (in Scenario 1) is around 31% of the total scheme cost. Increasing the average heat density to 200 kWh/m^2/yr reduces the price of heat by 10%, from 8.0 p/kWh to 7.2 p/kWh.

Variation in heat density impacts the cost of certain HP in DH scheme configurations more severely than others. In particular, a low T network typically requires larger diameter and therefore more costly pipes than a high T network, so an increase in the length of pipework required will penalise the low T network more than the high T network. We find for the case of an existing mixed-use development (in Demand case B) that the network infrastructure cost for a Low T network scheme is 11% higher than the network infrastructure cost of a High T network scheme (assuming the same pipe material is used in each case, but accounting for the reduced requirement for pipe insulation in the Low T network case).

A range of scheme design parameters can be varied to find the desired balance between cost and CO_2 savings

Contribution of the HP to the overall heat demand in fractional terms

We have studied the effect of varying the contribution of a central HP in series with a gas boiler and in parallel with a gas-CHP plant, together serving a High T network for an existing mixed-

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[42] Here, we refer to the typical UK existing building, rather than recently-built existing buildings, which may have a higher level of thermal efficiency.

use development (in Scenario 1). We find that, although the HP in DH scheme is more expensive than the counterfactual, increasing the contribution of the HP and series gas boiler from 10% to 90% leads to a 52% decrease in CO_2 savings, with an increase in the cost of those savings of only 11% from £104/tCO_2 to £87/tCO_2. This reflects the fact that the CO_2 savings increase faster than the scheme TCO over this range. Recognising that the price of heat increases over this range from 6.4 p/kWh to 8.6 p/kWh, the optimal choice will depend on the balance between the cost and environmental objectives for the scheme.

HP sink temperature

A lower HP sink temperature results in a higher HP COP but, for a fixed network temperature, also increases the required contribution of the gas-based plant to ensure the network temperature is achieved. We have studied the effect of varying the HP sink temperature, again in the case of a High T network serving an existing mixed-use development (in Scenario 1). With a network flow temperature of 80ºC, we find that as the HP sink temperature is reduced from 70ºC to 50ºC, the absolute CO_2 emissions increase, but the cost of CO_2 savings is reduced from £133/tCO_2 to £68/tCO_2. This reflects the fact that the reduced electricity costs resulting from an improvement in the HP COP from 2.2 to 3.9 outweigh the increase in gas costs resulting from an increased contribution of the gas-based plant, whereas the net change in carbon emissions is positive. As for the other design choices described above, therefore, the optimal choice of HP sink temperature will be strongly dependent on the balance of cost and environmental objectives, as well as on the details of the particular scheme.

Method for hot water provision where medium temperature networks are used

For new-build schemes, the overall scheme efficiency can also be improved by tuning the space heating emitter temperature. A low space heating emitter temperature – where this implies using a lower network temperature – will lead to a higher COP for the central HP. However, where the hot water is required to be delivered at a higher temperature (typically at 60ºC or higher), this leads to an increase in the additional heating required for hot water provision.

In Medium T networks with electric immersion heaters boosting the network temperature to provide the hot water demand, a lower space heating emitter temperature increases the contribution of the immersion heaters, which will tend to lead to an increase in carbon emissions. In the case of a small-scale new residential development (as in Scenario 3), we find that reducing the space heating emitter temperature from 40ºC to 30ºC results in both a slight increase in the price of heat (from 9.5 p/kWh to 9.8 p/kWh) and an increase in the cost of CO_2 savings from £179/tCO_2 to £201/tCO_2.

For the corresponding case of a Medium T network with BIHPs providing the hot water demand (in Scenario 4), we find that reducing the space heating emitter temperature from 40ºC and 30ºC leads to a reduction in the price of heat (from 10.5 p/kWh to 10.2 p/kWh) and a reduction in the cost of CO_2 savings from £227/tCO_2 to £217/tCO_2. This reflects the fact that the increase in efficiency of the central HP outweighs the decrease in efficiency of the BIHPs.

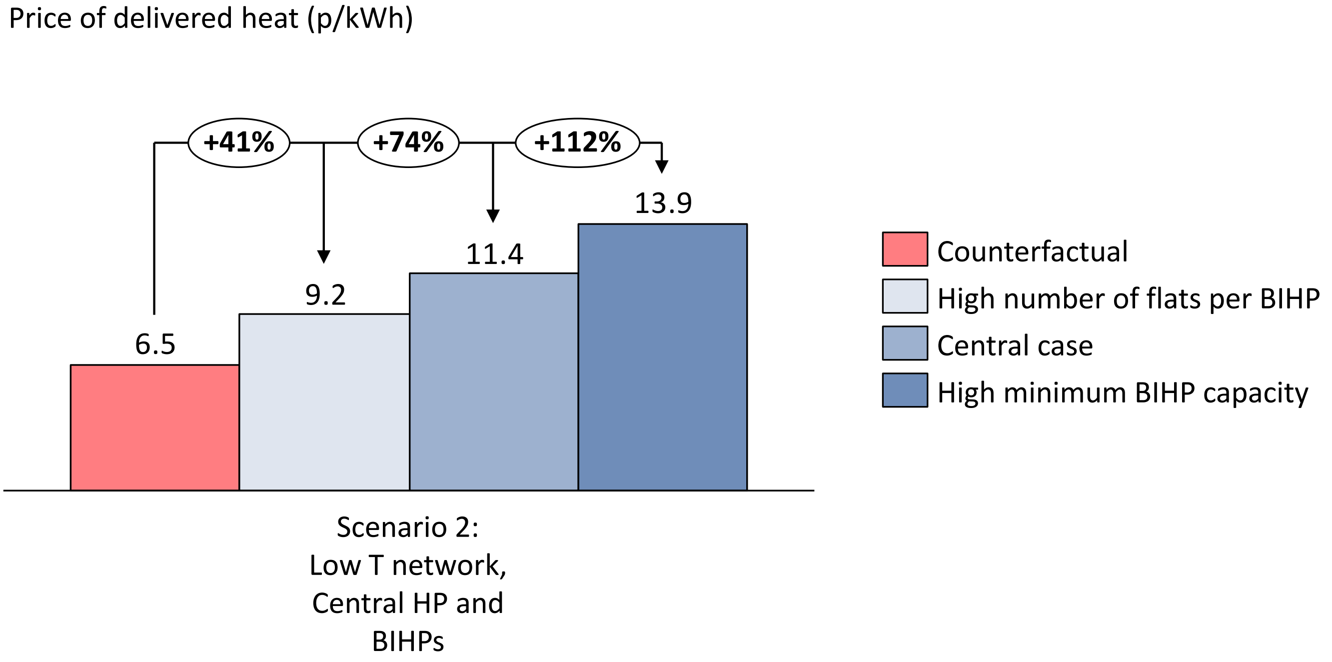
Building-integrated heat pump design and sizing choices

Due to the relatively high cost of BIHPs, equipment sizing is a key consideration. Using a separate heat pump to meet the heating and hot water demand in each dwelling – in the case of a residential development – is likely to entail significant oversizing outside times of peak demand unless substantial thermal storage is also installed. In the case of a development of new flats, in Scenario 2, we have studied the impact of installing either a 3 kW_{th} heat pump (the

Central case) or a 6 kW$_{th}$ heat pump (the High minimum BIHP capacity case). The result is shown in Figure 64.

If, alternatively, one BIHP is used to serve a larger number of flats, diversity in the demand will lead to a reduced capacity requirement on a per flat basis. Furthermore, as the BIHP capacity increases, the cost per kW$_{th}$ decreases. Therefore, there is a strong cost advantage to serving multiple flats with a single BIHP, providing that the required capacity is not so large that there is no longer an 'off-the-shelf' option. Figure 64 shows the impact on the price of heat, in Scenario 2, of serving a whole block of 40 flats with a single heat pump (the High number of flats per BIHP case).

Figure 64: Impact on the price of heat of varying the assumptions on the number of flats served by each BIHP, and on the minimum BIHP capacity per flat in Scenario 2.



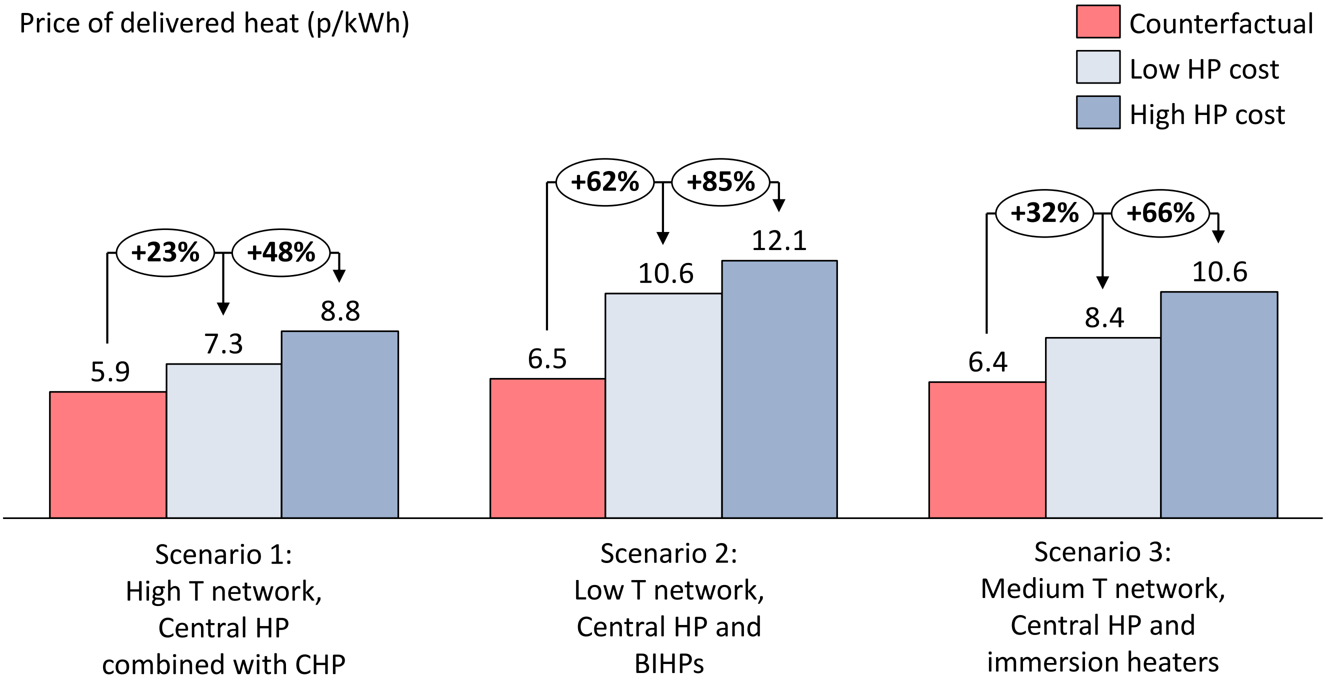
The cost of large heat pumps and the COP achieved are key assumptions carrying significant uncertainty

Central heat pump cost

As well as variations in scheme design, we have considered the impact of uncertainty in the input data for HP cost and COP. The small number of operational HP in DH schemes mean that there is considerable uncertainty around the values that could be achieved in a reproducible way in the UK. The range of uncertainty in input data for the HP cost is discussed in Section 3.

The impact of varying the Central HP cost for each of Scenarios 1, 2 and 3 is shown in Figure 65. Since all three of these HP in DH schemes include central HPs, the variation in central HP cost affects all configurations in a significant way.

Figure 65: Impact on the price of heat of varying the assumptions on the cost of the Central HP in Scenarios 1, 2 and 3.



Heat pump COP

In general, improving heat pump COP will have a beneficial impact on the price of heat and CO_2 saving. An exception to this, as discussed above, might be when the higher CO_2 is achieved by reducing the HP sink temperature, if this results in a greater reliance on gas-based plant to achieve the network temperature. The practical challenges of achieving high COP values are described in Section 3.

We have shown that a High T network with a Central HP serving a large-scale, existing mixed-use development (in Scenario 1), leads to a price of heat of 8.0 p/kWh using the central sensitivity assumptions, representing a premium of 35% versus the counterfactual. This is based on achieving the Central HP COP assumption of 2.2 for a HP sink temperature of 70°C. In Section 5, we presented the impact of achieving a lower or a higher COP than this. We find that a reduction in the COP, for a sink temperature of 70°C, to 1.5 leads to an increase in the price of heat from 8.0 p/kWh to 8.8 p/kWh, representing a 48% premium versus the counterfactual. An increase in the COP to 3.6 leads to a decrease in the price of heat to 7.3 p/kWh, representing a 23% premium. Over this range, the variation in the cost of CO_2 savings versus the counterfactual is very large, from £227/tCO_2 in the Low COP case to £75/tCO_2 in the High COP case. This demonstrates the critical importance of achieving a sufficiently high HP COP.

We have illustrated a number of ways of lowering the running cost of heat pump schemes to bring their overall cost down towards that of conventional DH schemes

High electricity prices are a barrier to HP schemes with low running cost

There are a number of ways of overcoming this barrier in certain scenarios. In schemes which have CHP and heat pumps together, heat pumps have been shown to provide efficient heat recovery from CHP, and also to provide running cost savings if powered by CHP electricity (although there is a CO_2 penalty arising from this option).

In schemes in which there is scope to deliver heat at lower temperatures, the analysis showed that of the two benefits (reduced network losses, high heat pump COP) it is the latter which provides the greatest effect.

The level to which the network temperature can be reduced depends on the cost penalty incurred if extra building-scale heating plant has to be used to provide DHW at the required temperature. This in turn depends on the relative size of the DHW demand. In a domestic context it was shown to be more cost effective to lower the network temperature to the minimum which can still provide DHW , whereas in some non-domestic contexts with less DHW demand it could be advantageous to further reduce the network temperature and install the relevant additional plant for DHW.

9. Conclusions

Heat pumps can be incorporated into heat networks in a wide variety of ways, as evidenced by existing schemes

The range of operational schemes spans high, medium and low temperature district heating networks. Large, centralised heat pumps can be used to provide heat to a network, and smaller, building-integrated heat pumps can use a network as a heat source.

Alongside a decarbonising grid, integrating heat pumps into district heating offers large CO_2 emissions reduction potential

Four core Scenarios modelled here yielded CO_2 savings in the range 48-84% compared to the counterfactual scheme, assuming grid decarbonisation consistent with current DECC projections.

The highest CO_2 savings were obtained from schemes in which more of the heating carried out in the counterfactual by conventional plant is displaced by heat pumps. CO_2 savings are further increased for lower network temperatures, when heat pumps work over smaller temperature ranges and network thermal losses are minimised. Therefore, medium and low temperature networks were found to offer the greatest CO_2 savings.

For each of the scenarios modelled here, the price of heat is likely to be significantly higher for district heating schemes incorporating heat pumps

The cost increase for heat pump in district heating schemes is due largely to the high capital cost of the heat pumps. The uncertainty associated with the cost of large-capacity heat pumps is high, but current data shows that they are likely to be more expensive than other heat supply options. On the other hand, installing building integrated heat pumps in individual dwellings, and thus losing the benefit of diversified demand, will tend to increase total installed heat pump capacity and total cost of heating plant.

The extent to which heat pumps replace conventional heating plant will therefore depend on the balance between environmental and economic objectives

In the four core Scenarios modelled, we have found the cost of CO_2 savings for heat pump schemes versus their counterfactuals to lie in the range £133-227/tCO_2. This suggests that if the large CO_2 savings on offer are to be achieved, there will need to be a continuation of financial support for renewable heat and/or interventions to ensure a high effective price of carbon emissions.

However, further cost savings could be achieved by using heat pumps in schemes where both heating and cooling are required

Cooling demand is often a driver for the installation of heat pumps over other technologies in heat network applications. Using heat pumps for both heating and cooling can help increase the thermodynamic efficiency of a system if heating and cooling loads are balanced either instantaneously or seasonally.

Schemes using a large number of building-integrated heat pumps present additional challenges in terms of operation and control

Ensuring good performance of a large number of building integrated heat pumps can present a challenge for scheme operators, whereas centralised heat pumps whose control lies with the scheme operator are easier to maintain. Furthermore, the operation of centralised heat pumps can be optimised with respect to the rest of the system (for example other plant, or dynamic electricity prices).

We do not identify a single optimum scheme type for the UK, with each type presenting advantages and disadvantages for particular sites and heat demand cases

The most suitable scheme for a given area depends on a variety of site-specific factors. It is therefore likely that, at least in the early stages of deployment, a variety of scheme configurations will be trialled: a ‘standard’ system design is not easily transferred between applications, nor is current standard district heating practice directly transferrable to HP in DH applications. On the other hand, this presents the opportunity to design highly efficient, bespoke systems by, for example, using different local heat sources at different times of the year or making use of natural local thermal storage.

A number of promising scheme types are identified for specific situations

In schemes in which there is CHP installed as part of the heating plant, the use of heat pumps powered by CHP electricity and also to recover waste heat from CHP operation leads to running cost potentially being reduced sufficiently to offset the increased capital cost associated with the heat pumps. In schemes in which there is scope to lower the network temperature (i.e. when supplying thermally efficient buildings), doing this is beneficial, with the majority of the benefit being attributed to enhanced heat pump performance and the rest to reduced network losses. However, reducing the network temperature to lower than that required for DHW provision can often result in scheme costs rising again as additional plant for DHW heating must be installed.

10. Further work

Two main areas in which this study could be extended are model functionality and incorporation of additional sources of data.

Extension of model functionality

In order to more realistically replicate existing schemes and in particular illustrate more of the benefits of heat pumps, the following improvements are suggested as next steps:

- Allowing the sink temperature of the heat pump to vary seasonally, as is commonly the case in larger schemes in which heat pump operation is dynamically optimised with respect to the rest of the system. For example, the Scandinavian schemes reduce the sink temperature of the heat pump during the coldest weeks of the year.
- Incorporating the relationship between heat (or coolth) extracted from a finite source such as the ground or an aquifer and the resulting temperature of the source. This would illustrate the benefits of ATES and GSHP systems with balanced heating and cooling loads, in terms of preheating the source for winter and precooling for summer, allowing for more efficient heat pump operation. Conversely, if only heating load were present, the decrease in temperature of the heat source through the winter and thus the decrease in efficiency of the heat pump could be captured.
- Building in more sophisticated algorithms to allow the heat pump to participate in demand side response. The industry consultation indicated that there is interest in using large capacity heat pumps with networks to provide system-level benefits. The model currently contains functionality to force the heat pump not to run at certain electricity prices; further work could couple this to time-of-use tariffs or other incentives to control heat pump operation.

Incorporation of additional data

Gathering more data where this was limited would serve several useful purposes, especially in the areas of costs and cooling networks:

- Reduction of uncertainty in important sensitivities such as large-capacity heat pump costs
- Representation of the potential for schemes which are expensive now to become less so in the future, through reduction in capital costs or improvement in heat pump technology. On this latter point, COP data for very efficient high temperature heat pumps, heat pumps used in space cooling and micro-heat pumps used for provision of DHW were especially limited in this study.

- Investigation of optimum scheme design options where heating and cooling loads are present. For example, if heat pumps and a heat network are already envisaged for a site, then the marginal benefits of adding a cooling network using the same heat pumps could be explored versus the use of conventional cooling solutions.

Appendix 1: Price and CO_2 intensity projections used in the scenario analysis

CO_2 emission factor of grid electricity, tonne/MWh			
Year	Domestic	Commercial/ Public sector	Industrial
2015	0.473	0.465	0.456
2016	0.370	0.363	0.356
2017	0.356	0.350	0.343
2018	0.336	0.330	0.324
2019	0.291	0.286	0.280
2020	0.260	0.255	0.251
2021	0.234	0.229	0.225
2022	0.216	0.212	0.208
2023	0.205	0.201	0.197
2024	0.182	0.179	0.175
2025	0.165	0.162	0.159
2026	0.138	0.135	0.133
2027	0.127	0.125	0.122
2028	0.112	0.110	0.108
2029	0.115	0.113	0.111
2030	0.112	0.109	0.107
2031	0.103	0.101	0.099
2032	0.087	0.086	0.084
2033	0.073	0.072	0.070
2034	0.062	0.061	0.060
2035	0.056	0.055	0.054
2036	0.060	0.059	0.058
2037	0.054	0.053	0.052
2038	0.054	0.053	0.052
2039	0.057	0.056	0.055
2040	0.052	0.051	0.050
2041	0.046	0.045	0.045
2042	0.045	0.044	0.044
2043	0.040	0.039	0.039
2044	0.036	0.035	0.034
2045	0.037	0.036	0.035
2046	0.034	0.033	0.033
2047	0.031	0.031	0.030
2048	0.037	0.036	0.035
2049	0.032	0.032	0.031
2050	0.032	0.032	0.031

Industrial gas price, p/kWh		
low	central	high
2.1	2.7	3.4
2.1	2.8	3.5
2.1	2.7	3.6
2.0	2.6	3.6
2.0	2.6	3.7
2.0	2.7	3.8
2.0	2.8	3.9
2.0	2.8	4.0
2.0	2.9	4.0
2.0	3.0	4.1
2.0	3.1	4.2
2.0	3.1	4.3
2.0	3.2	4.4
2.0	3.2	4.5
2.0	3.2	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5
2.0	3.3	4.5

CO2 price, £/tCO_2e (traded)
4.6
4.7
4.8
5.0
5.2
5.3
12.6
19.8
27.0
34.3
41.5
48.7
56.0
63.2
70.4
77.7
84.9
92.1
99.3
106.5
113.7
120.9
128.1
135.4
142.6
149.8
157.0
164.2
171.4
178.6
185.8
193.0
200.3
207.5
214.7
221.9

	Electricity price, p/kWh								
	Low			Central			High		
Year	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial
2015	15.4	9.4	8.1	15.9	10.5	9.2	16.6	11.9	10.5
2016	15.6	9.9	8.6	16.9	11.3	9.9	18.5	12.7	11.3
2017	16.4	10.1	8.7	18.0	11.3	9.9	19.6	13.0	11.6
2018	16.6	10.4	8.9	18.1	11.4	9.9	20.1	13.5	11.9
2019	18.1	12.0	10.5	19.3	12.8	11.3	21.4	14.8	13.3
2020	18.4	11.8	10.2	19.3	12.9	11.3	21.8	15.0	13.3
2021	18.8	12.4	10.8	20.0	13.5	11.9	22.1	15.5	13.9
2022	19.1	12.6	10.9	20.3	13.8	12.2	22.7	15.7	14.0
2023	18.9	13.0	11.3	20.3	14.4	12.7	22.3	16.0	14.2
2024	19.4	13.5	11.7	20.7	14.8	13.1	22.6	16.4	14.6
2025	20.1	14.1	12.1	21.3	15.3	13.4	22.9	16.4	14.6
2026	20.5	14.4	12.3	21.7	15.5	13.6	23.1	16.7	14.9
2027	20.4	14.4	12.3	21.6	15.3	13.4	22.9	16.6	14.7
2028	20.5	14.5	12.3	21.6	15.3	13.3	22.8	16.5	14.6
2029	20.4	14.7	12.6	21.4	15.7	13.7	22.7	16.8	15.0
2030	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2031	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2032	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2033	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2034	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2035	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2036	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2037	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2038	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2039	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2040	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2041	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2042	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2043	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2044	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2045	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2046	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2047	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2048	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2049	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5
2050	20.6	14.7	12.5	21.7	15.7	13.7	23.4	17.3	15.5

Year	Electricity export price, p/kWh
2015	6.4
2016	7.1
2017	7.0
2018	7.1
2019	8.4
2020	8.2
2021	8.7
2022	8.9
2023	9.3
2024	9.7
2025	10.1
2026	10.4
2027	10.1
2028	10.1
2029	10.5
2030	10.4
2031	10.4
2032	10.4
2033	10.4
2034	10.4
2035	10.4
2036	10.4
2037	10.4
2038	10.4
2039	10.4
2040	10.4
2041	10.4
2042	10.4
2043	10.4
2044	10.4
2045	10.4
2046	10.4
2047	10.4
2048	10.4
2049	10.4
2050	10.4

Appendix 2: Validation of key modelling steps

To ensure confidence in the capability of the model to recreate HP in DH schemes to a satisfactory level, it is necessary to carry out validation of the model as far as possible against existing HP in DH schemes. This could be undertaken in two ways: checking the final outputs of the entire model, or intermediate outputs arising from individual processes within the model.

The former approach was deemed less useful, since obtaining the main output metrics (in particular, price of heat) for real HP in DH schemes not only relies on very few data points, those points are not always meaningful to compare to model outputs. This point can be illustrated using examples from the Case Studies section: if a heat pump is retrofitted into an existing network (as in the Helsinki scheme), the price of heat from the scheme will likely not take the network capital cost into account. Alternatively, if heat pumps are installed in new-build flats (as in the Duindorp scheme), a quoted price of heat may not take into account the purchase of the building integrated plant, as the BIHPs might be priced into the cost of building dwellings as opposed to the HP in DH scheme.

Therefore, instead of validating the final outputs of the model, a focus was put on intermediate outputs of individual processes. Of particular importance was the manner in which the heating network is constructed in the model, and especially the algorithms determining the:

i) Relationship between building internal floor area and pipe length; and the
ii) Relationship between building internal floor area and heat demand.

Data on five existing district heating schemes collected by AECOM[43] were used to investigate these relationships. The data contained the number of domestic and non-domestic buildings and the total floor area of each building type respectively, the buried pipe length, and the heat demand. The building data were then input in the model to observe whether a similar length of pipe were predicted to that actually installed, and whether a similar heat demand was generated by the model to that in reality. These comparisons are illustrated below.

Relationship between building internal floor area and pipe length

It was necessary to make one further assumption to set up this relationship in the model. The aforementioned dataset did not state the number of storeys per building. That is, total internal floor area was present, but how this translated into building footprint – important for calculating pipe lengths - was not. Therefore, the validation exercise used an upper and lower bound for footprint, using ‘low rise’ and ‘high rise’ assumptions respectively. Most of the actual schemes’ buried pipe length then fell within the range predicted by the model; this is shown in Figure 66.

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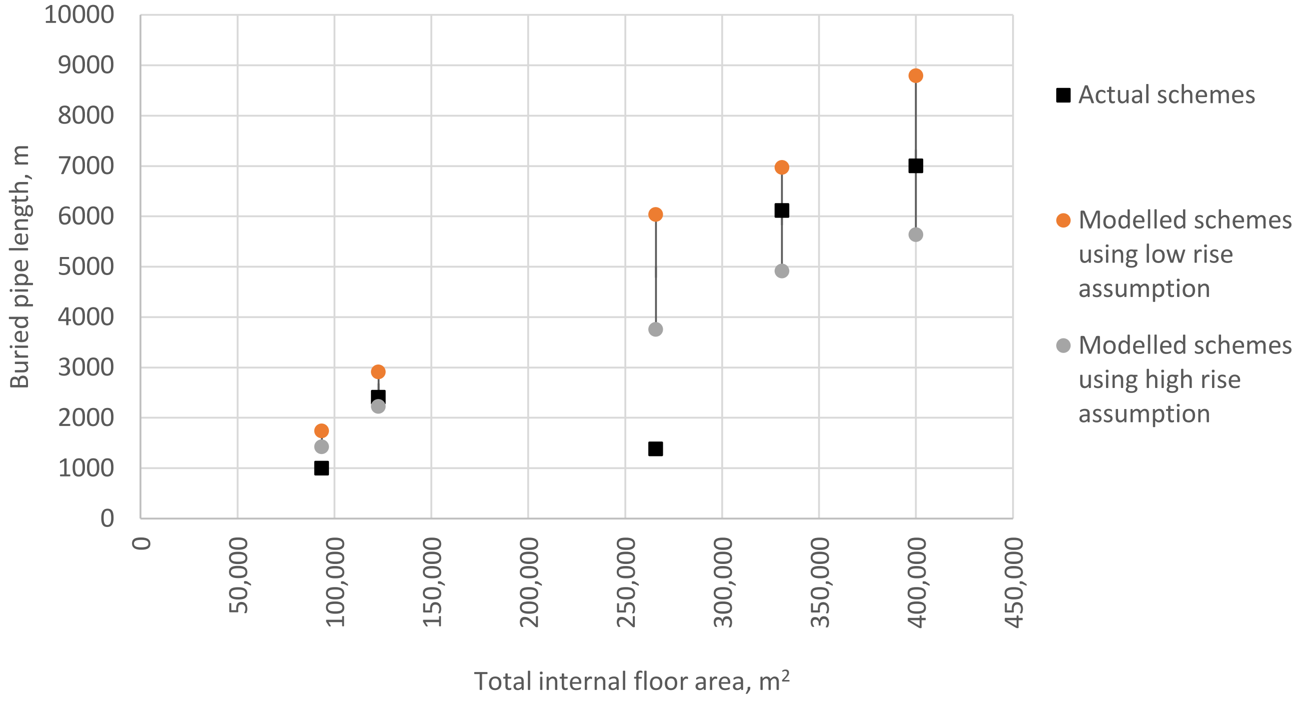
[43] AECOM, 2015. *Assessment of the Costs, Performance, and Characteristics of UK Heat Networks*, Report for DECC

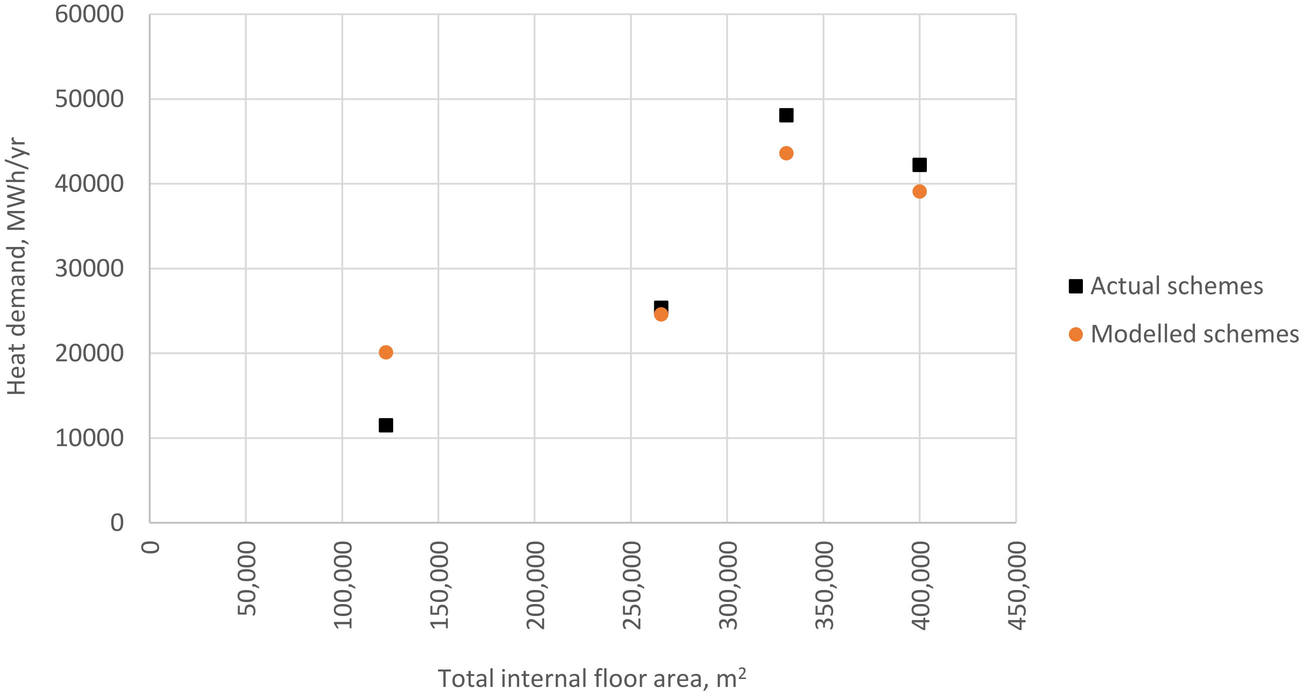
Figure 66: Buried pipe length versus building total internal floor area for real and modelled schemes



Relationship between building internal floor area and heat demand

Although the exact nature of the non-domestic buildings in the data was not known, the heat demand generated by the model by inputting the domestic and non-domestic floor areas as recorded in the data resembled that of actual schemes; see Figure 67.

Figure 67: Heat demand versus building total internal floor area for real and modelled schemes



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