Department for Energy Security & Net Zero

Heat Network Optimisation Guide

Heat Network Optimisation Guide

Authors

This document was prepared by FairHeat under contract to the Department for Energy Security and Net Zero.

The primary authors include Tom Burton, Tom Naughton, Gareth Jones, and Freddie Harcourt.

Quality assurance was provided by Huw Blackwell (Anthesis).

Disclaimer

Contents

1. Introduction

The UK's 2050 decarbonisation objectives face unique complexities given that 80% of the buildings they will serve already exist, with many of these relying on heat networks to deliver hot water and space heating to customers. Sometimes referred to as district heating (multiple buildings) or communal heating systems (single buildings), these networks are key for reducing carbon emissions by facilitating the centralised production and distribution of heat. However, the current state of these networks shows variable performance, a critical issue that needs to be addressed.

The variability in the performance of these networks is due to a myriad of factors, including system design, installation methods, and maintenance practices. The fact that a significant majority of the buildings they will serve are already constructed poses an additional challenge. Ensuring these networks effectively integrate with the existing infrastructure and perform efficiently is an essential task.

In light of these challenges, there is an increasing demand to optimise and reduce the operating temperatures of existing heat networks. Elevating their performance to a consistent, high level will enhance the experience of the customers, their reliability, and overall contribution to the country's decarbonisation target. This standardisation will also enable the seamless integration of these networks into future city scale district heating systems, ensuring their vital role in achieving the UK's environmental targets.

The UK government has shown its commitment to the standardisation of heat network performance through the Heat Networks Technical Assurance Scheme (HNTAS). This guidance, in conjunction with the CIBSE Heat Networks Code of Practice (CP1) is being developed and is expected to come into force in 2025. The scheme will legally obligate heat network operators to adhere to minimum technical standards.

Guidance Purpose

FairHeat, in collaboration with Anthesis were commissioned by the Department for Energy Security and Net Zero (DESNZ) to produce heat network optimisation guidance for the industry. This was to support the work being undertaken through the Heat Network Efficiency Scheme (HNES) and to improve the consumer experience of existing heat networks. This is fundamentally delivered through providing reliable, low cost and efficient heat.

This document is primarily aimed at technical engineers that are working on optimising existing heat networks. However, it will also be useful for heat network operators that have technical skills in-house or are looking to procure optimisation studies from third party consultants. Individuals or organisations that do not have a technical background, but are responsible for the operation of heat networks, can use this document to ensure their consultants are following the correct methodologies, that they have the necessary skills and expertise, and that they are producing the required level of output.

It should be highlighted that this document is primarily focused on optimising the performance of existing residential and mixed-use heat networks, however, in general, the guidance outlined will also be relevant to non-residential heat networks. Similarly, the document does not consideration cooling or ultra-low temperature heat networks (sometimes referred to as ambient heat networks).

Guidance Material

This document is structured in a methodical way in order to guide the technical engineer through the heat network optimisation process.

This starts with defining the principles for improving operating heat networks. It emphasizes a phased approach to optimising heat network performance, ensuring that urgent issues are addressed before considering long-term optimisation.

The guidance outlines the three main phases of the optimisation assessment process for heat networks. These phases are an initial investigation, a techno-economic options appraisal, and an implementation plan. The decision to proceed to each phase depends on factors such as the heat network's size and complexity, the available budget, and project timescales. The document also provides a detailed breakdown of the tasks, outcomes, and key outputs for each stage of the process. It emphasizes the importance of understanding system performance and issues, determining potential interventions, and finalizing the business case.

To understand the performance of an existing heat network and to evaluate the impact of improvement measures, the guidance recommends using Key Performance Indicators (KPIs) for quantitative analysis of heat network performance, with data sourced from various systems like BMS, heat meters, and utility metering. A selection of recommended KPIs is provided.

Site Audit

A site audit is essential in understanding how a heat network is currently operating and what potential root causes of any performance issues are present. It also provides a good opportunity to gather key system information and to discuss the operation with the customer, who can often provide key insights. This document emphasizes the need for consultation with system owners and operators and outlines the inspection process for the network and dwellings. It also provides a checklist of key activities to be performed within energy centres and substations during the audit.

Technical Analysis

Once the site audit has been completed and the behaviour of the network is fully understood, baseline technical analysis is undertaken. This document sets out the key data analysis and modelling techniques that should be employed, emphasizing the use of live heat meter data to diagnose causes of poor network performance. Common examples are provided such as repairing or replacing faulty components within the Heat Interface Unit (HIU).

Determining and Modelling Interventions

Improving heat network performance is the primary focus of the guide, employing Root Cause Analysis (RCA) to identify and address underlying issues rather than just treating symptoms. Interdependencies of potential interventions are emphasized, underscoring the need for a holistic approach and modelling the impact of potential interventions on various factors, including heat losses, energy consumption, and maintenance, is discussed in detail. Looking towards the future, the guide suggests options for decarbonisation and recommends Optimisation Studies for a smooth transition towards a decarbonised heating network. Practical examples are provided, along with the introduction of the '5 whys' technique, a powerful tool for effective problem-solving.

Business Case

Understanding the financial implications of potential interventions is crucial for any business case, as it allows decision-makers to evaluate the cost-effectiveness and potential return on investment. The guidance suggests employing methodologies such as simple payback and net present value (NPV) for this purpose. When undertaking the analysis, it is important to consider various inputs such as capital, operational and replacement expenditure, as well as indirect social costs. The document also emphasizes the importance of identifying and mitigating operational risks and provides guidance on how to interpret the outputs from any techno-economic models.

Typical Failure States

Based on an in-depth review of over 40 operational heat networks, the document outlines 16 typical failures seen on heat networks. Each category of failure is detailed with its frequency, impact, ability to optimise on an operating system, and cost to optimise.

1.1. Commonly used terminology

The definitions below are used throughout this document. It is noted that whilst these definitions will may not be suitable to all systems, they do represent the majority of heat networks and mirror the terminology used in the CIBSE Heat networks: Code of Practice for the UK CP1 2020 (CIBSE CP1).

Heat Network

Heat networks are systems in which there is a centralised generation of heat, which is then distributed via a set of pipes either within a building in the case of a communal distribution system or to multiple different buildings in the case of a district distribution system.

Energy Centre

A plant room (or plant rooms) which contains heat generation plant (boilers, CHP, ASHPs) and associated ancillary equipment (pumps, thermal stores etc). Note the energy centre can feature external space (such as rooftops) for Air Source Heat Pumps (ASHPs).

District Distribution Network

The distribution pipes that connect the energy centre to buildings connected to the system. Typically, this is mostly buried pre-insulated pipework or pipework routed though basements to connect separate buildings.

In many communal systems there is no district distribution network all pipework is within a single building. I.e., heat flows directly from the energy centre into the communal distribution system.

Communal Distribution Network

The distribution pipework within the building but not within the final consumer system. Typically, the communal distribution system connects a substation (defined below) within the basement, to the consumer Heat Interface Units (HIUs). The communal distribution system consists of risers, lateral pipework and terminal runs.

Consumer Heating System

The consumer heating system represents the part of the network located within the consumer element. A common piece of consumer connection equipment is a heat interface unit (HIU), which transfers heat from the communal distribution pipework throughout a building to the specific space heating and hot water circuits within the consumer element. Alternatively certain networks might utilise hot water cylinders. Other consumer heating system equipment includes items such as radiators or underfloor heating systems.

For the purposes of this report, the consumer heating systems referred to are primarily dwellings.

Substation

The separation of the district and communal networks is typically (but not always) demarcated by a substation. A substation can either be:

- Direct: Water from the network distribution pipework flows directly into the downstream systems, whether this is district distribution, communal distribution or both (i.e., district distribution flowing into communal distribution). The substation will have a limited number of components, such as isolation valves and heat meters.
- Indirect: Network distribution systems, whether this is district distribution, communal distribution or both (i.e., district distribution flowing into communal distribution), are hydraulically separated via a plate heat exchanger (or horizontal calorifier in older systems). An indirect substation will feature a plate heat exchangers, pumps, and additional pressurisation equipment.

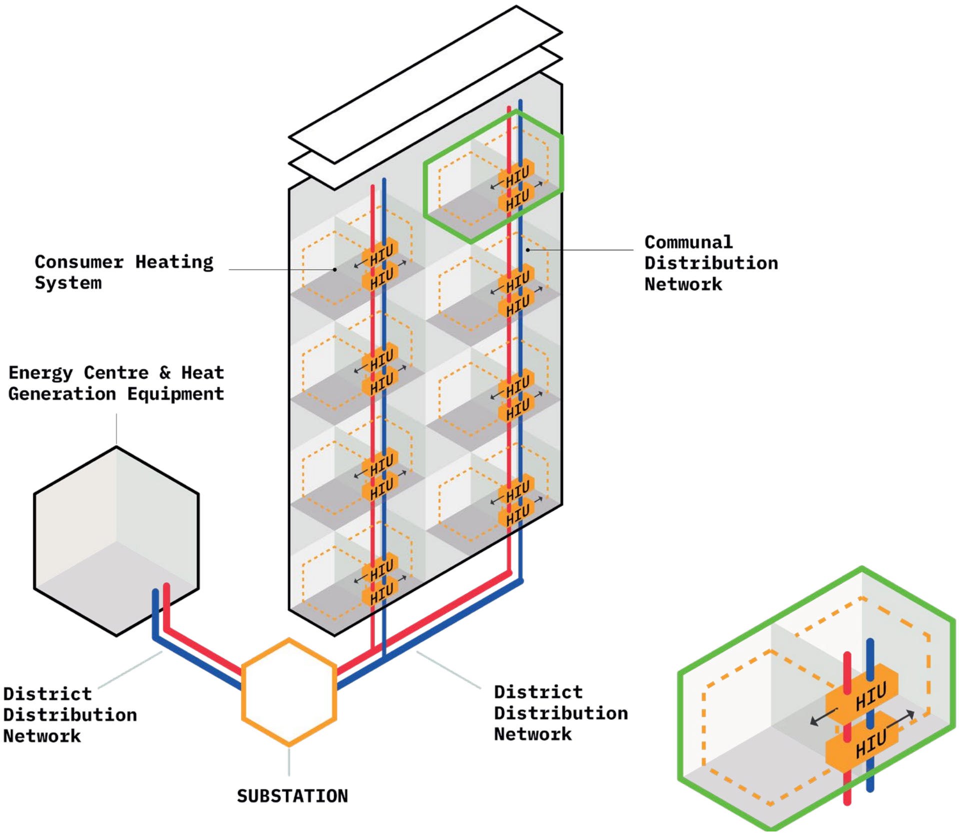


Figure 1: Typical breakdown of different sections of a heat network

1.2. Understanding network typologies

Heat networks can be designed in different ways and have varying configuration types. It is important to note that the types of heat network discussed within section 1.2 are not exhaustive of all possible networks, but it does cover the vast majority of systems.

1.2.1. Distribution system

A distribution system refers to how heat is transported around a building in a heat network i.e., the communal distribution system referred to in section 1.1.

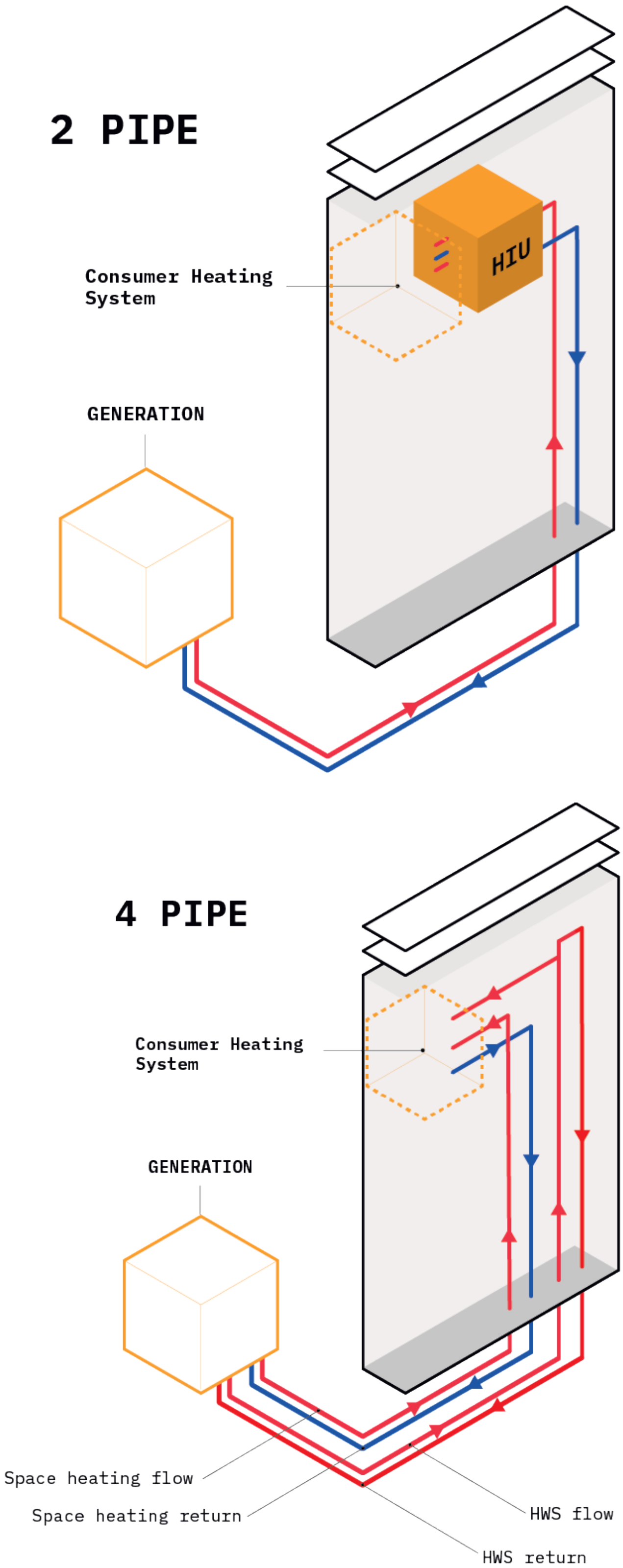


Figure 2: Illustration of two pipe and four pipe heat networks

1.2.1.1. Two-pipe

A two-pipe configuration means that the space heating and domestic hot water are carried within the same pipework resulting in one flow pipe and one return pipe from where heat is generated.

1.2.1.2. Four-pipe

A four-pipe configuration has separate pipes for heating and hot water, resulting in two flow and two return pipes.

It is possible to utilise weather compensation of the space heating circuits within four pipe systems as there is hydraulic separation between the space heating and domestic hot water circuits. Therefore, the temperature of the space heating circuit can be reduced when the external temperature is sufficiently high and the demand for heating is lower. The space heating flow temperature will not be limited by requirements to mitigate Legionella formation as they would in two pipe systems as they do not also supply domestic hot water.

These are typically found within older systems and usually will incorporate a hot water cylinder within each dwelling. Alternatively, if a centralised hot water system, otherwise known as a recirculation system is present, this would also result in a four-pipe system where there would be no domestic hot water equipment present within the dwelling.

1.2.2. Consumer space heating system

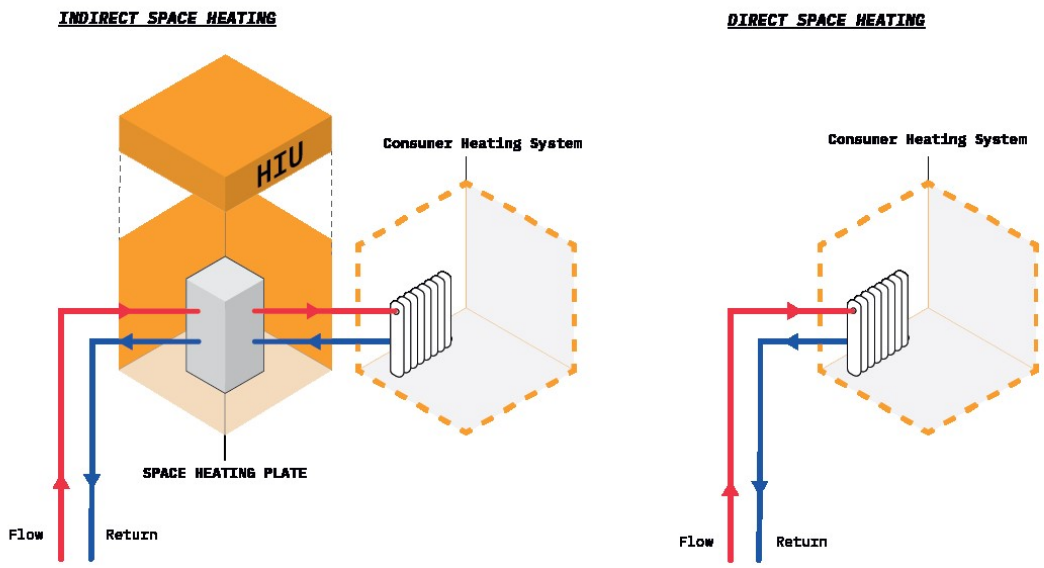


Figure 3: Indirect vs direct space heating systems

1.2.2.1. Indirect

Indirect systems have hydraulic separation, in the form of a heat exchanger, in place between the communal distribution system within the building, and the consumer heating system within the dwelling.

This means leaks that occur across the building or within the dwelling will not have a direct impact on the overall heat network and will not impact other dwellings.

The dwelling space heating systems are also not subject to the pressure ratings of the network. Therefore, radiators and valves for example do not require high pressure ratings and the network pressure rating does not need to be as strictly constrained to protect equipment located outside of the dwelling.

1.2.2.2. Direct

A direct system is one where the water within the communal distribution network flows directly through the dwelling heating systems of the building without hydraulic separation.

Direct systems can still utilise a mixing control valve in order to achieve network flow temperatures that are lower than the upstream network flow temperatures.

Direct HIU systems generally have a lower CAPEX and OPEX as there is less equipment within the HIUs (such as plate heat exchangers, pumps, control valves and expansion vessels). These systems allow for centralised water treatment and pumping, reducing the complexity and maintenance requirements of dwelling space heating systems.

Direct systems enable higher emitter temperatures for a given network flow temperature, as the temperature drop across the PHE which is present in an indirect system is avoided. It is also possible to utilise weather compensation on direct space heating system, as long as the minimum temperature is sufficient for DHW delivery. Therefore, the temperature of the space heating circuit can be reduced when the external temperature is sufficiently high and the demand for heating is lower.

The communal distribution network and dwelling heating systems are not separated hydraulically on direct systems, meaning that dwelling space heating circuits are exposed to network pressures. This requires consideration with equipment selection and also when reviewing the risk of elevated pressures in the dwellings and to operatives. As highlighted in the CIBSE Heat Networks Design Guide (2021), specific consideration should be made with pressures above 7 bar within a dwelling.

1.2.3. Domestic hot water system

1.2.3.1. Instantaneous

Instantaneous hot water systems refer to the instant production of domestic hot water on demand when required by the user with there being no limit to the duration of the hot water supply.

In general, they enable lower flow and return temperatures in comparison to hot water cylinders reducing heat losses, as well as occupying less space within the dwelling.

Instantaneous systems require a suitable keep-warm strategy to ensure that DHW delivery times meet resident comfort expectations.

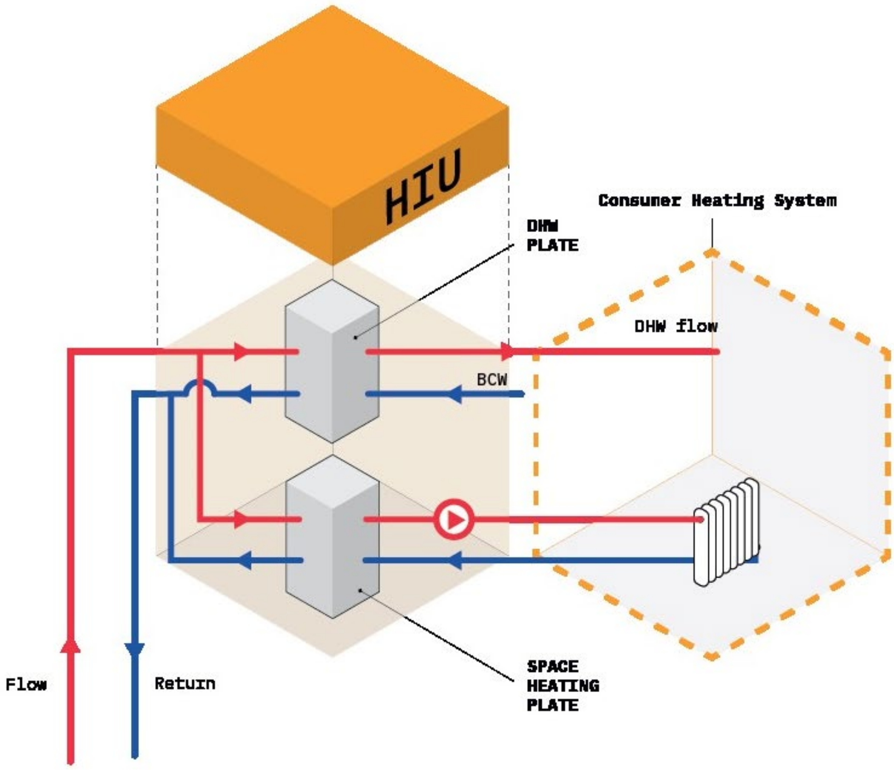


Figure 4: Illustration of instantaneous hot water provision

1.2.3.2. Stored hot water (cylinders)

Hot water can be produced and then stored within a cylinder for later use.

Storage solutions provide a degree of back up storage enabling short term interruptions to the network supply to be tolerated. This is particularly useful where electric immersion heaters are installed which can provide additional heat.

Stored hot water systems can be installed in both two-pipe and four-pipe distribution networks; however, they are more commonly seen in four-pipe systems.

Stored hot water needs to be maintained at a higher temperature to mitigate the risk of Legionella formation. Therefore, hot water flow temperatures are higher in storage applications. It should be noted that there may be other health and safety considerations, such as pressure, with respect to hot water cylinders.

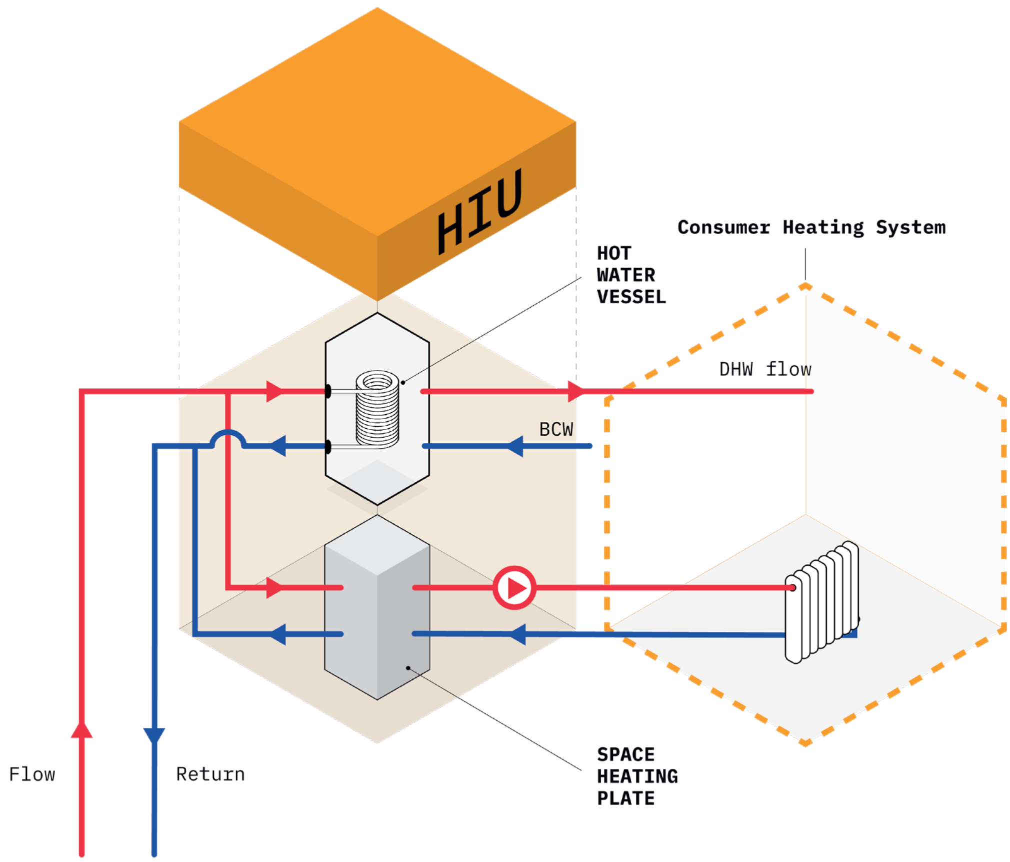


Figure 5: Illustration of stored hot water provision

1.2.3.3. Recirculation

In a hot water recirculation system, water is constantly flowing around a 'recirculation loop'.

These systems are four-pipe and enable hot water to be constantly available for the user. Although space is saved within dwellings as no additional equipment hot water equipment is required, additional space is needed within risers to fit the four-pipe system.

Recirculated systems also need to be operated at higher temperatures to mitigate the risk of Legionella formation.

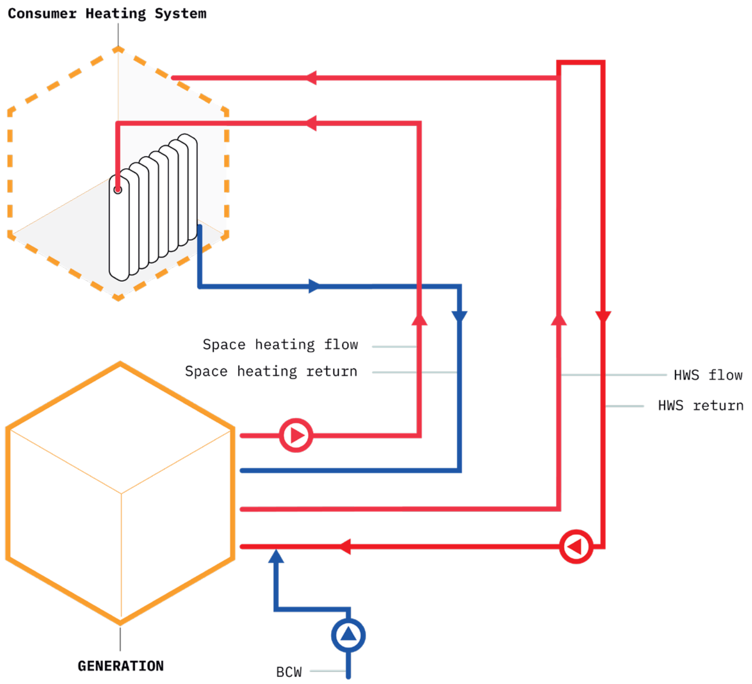


Figure 6: Illustration of a recirculation loop

1.2.4. Space heating configuration

1.2.4.1. Independent

Independent space heating configurations refer to individual dwelling space heating circuits per dwelling. For example, an individual HIU located within each dwelling is an independent system. This means that so long as all communal distribution pipework is external to the dwellings, end users can dictate when heating is used within their individual heating system (e.g. pipework within a dwelling).

1.2.4.2. Shared connection

A shared connection means that multiple dwellings will be supplied by the same consumer heating system. A typical shared connection radiator set up consists of one riser feeding radiators within different floors/dwellings is shown in Figure 7.

This typically causes issues associated with space heating control as distribution pipework within dwellings will be hot regardless of if the end user has turned on their heating or not. This also causes issues associated with effectively metering the space heating usage of individual end users compared.

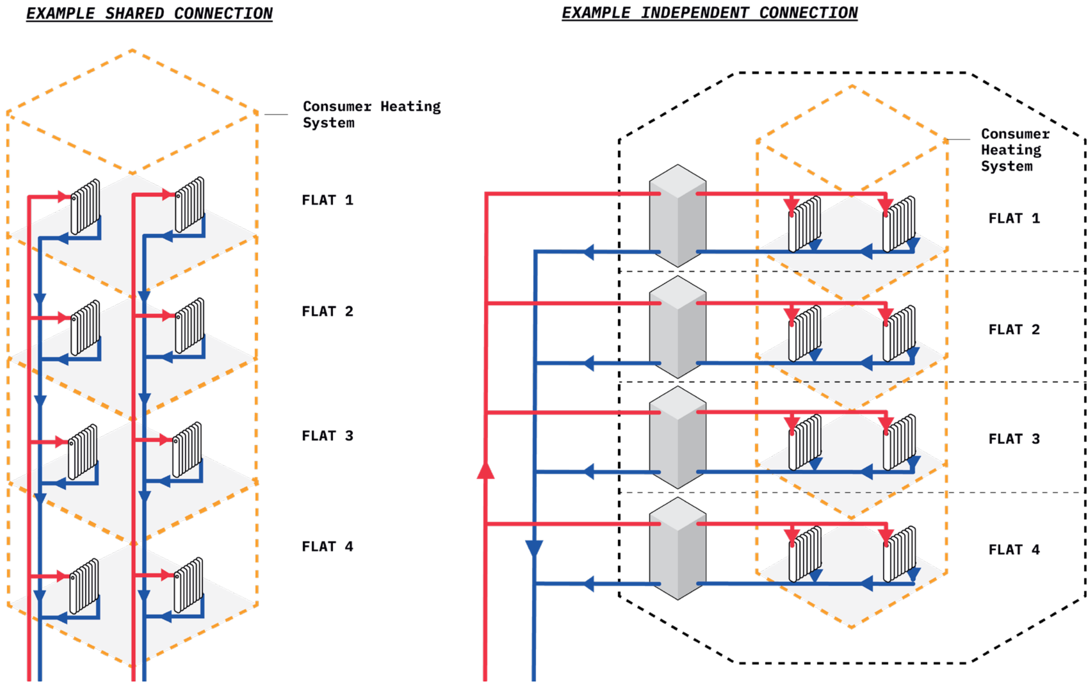


Figure 7: Illustration of shared and individual heating systems

1.3. Heat network optimisation principles

The main objective of an optimisation study is to analyse existing heat networks, identify where sub-optimal outcomes are being experienced, and to deliver business cases for performance improvements to the heat network operator for cost-effective interventions which have been quantified against an agreed set of performance criteria.

While the specific performance criteria may vary depending on the technical nature of the site or operator there are consistent principles which will lead to improved network performance.

1.3.1. Key principles of good network performance

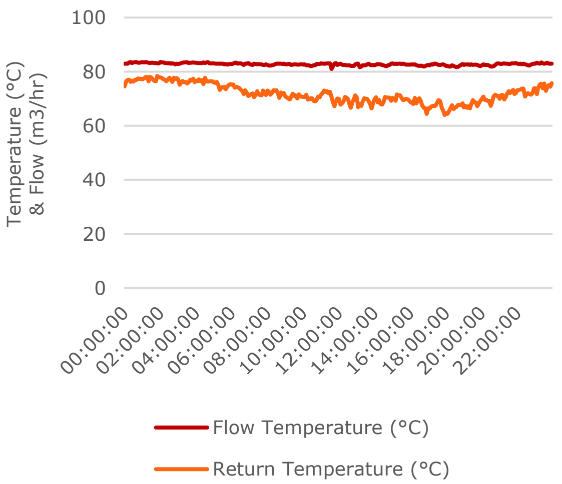
Typically, the greatest source of inefficiency in a heat network are heat losses within the heat distribution network and energy centre. System losses lead to high kWh unit costs to the end user and can have a negative economic impact on the operator of the heat network. Elevated losses can also lead to significant secondary issues such as overheating of corridors.

In high performing residential heat networks heat losses of less than 70 W/dwelling should be achieved, although this level of performance may not be economically viable in legacy systems. CIBSE CP1 Heat networks: Code of Practice for the UK, 2020 states 100 W/dwelling is the maximum acceptable Communal Distribution system heat loss.

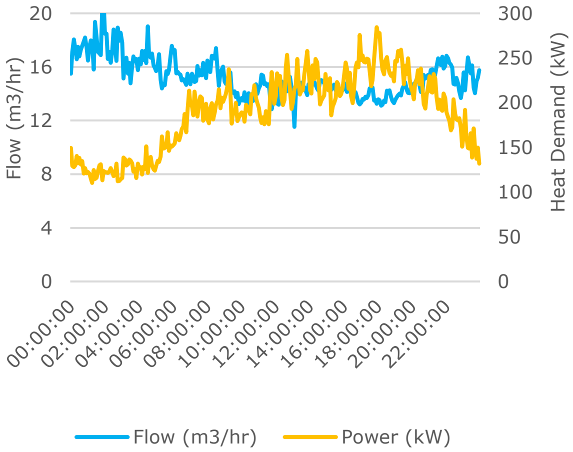
The following factors contribute to a high performing heat network with low network heat losses:

- Low system flow temperature: System flow temperatures are dictated by the required temperature to supply space heating and hot water to dwellings. The higher the flow temperature the greater heat losses. Flow temperatures should be minimized, while ensuring system users maintain an adequate hot water and heating system performance.
- Low system return temperature & variable flow rate: To minimize heat losses from system return pipework, system return temperatures should be consistently at least 20 °C lower than the flow temperature and can be greater than 50 °C lower. Flow through the system should all be controlled and vary to meet demand.
    - High system return temperatures are a symptom of uncontrolled system flow rate resulting in a low system "Delta T"[1]. In a poorly performing network, system flow rates are consistently high. A comparison of system temperature and flow rates is presented in Figure 8 below.
- Maximised Insulation: Ensuring that heat networks are well insulated is fundamental to reducing network heat losses. While insulating pipework is important, a high performing network should ensure all valves, flanges and ancillaries are insulated with insulation jackets. Where possible, networks should seek to insulate to thicknesses selected via a whole lifecycle cost assessment or following industry best practice as set out in CIBSE CP1 Heat networks: Code of Practice for the UK, 2020. Insulating to thicknesses outlined in Building Regulation (Part L) is typically not sufficient to mitigate system heat losses.
- Minimized network length and pipe diameters: Heat losses are proportional to network length and pipe diameter and therefore will have a significant effect on the overall heat network losses.
    - Pipework length can be reduced by moving to a multiple riser approach with no lateral pipework in corridors.
    - Pipework diameters can be optimised by complying with design methodologies outlined within CIBSE CP1 Heat networks: Code of Practice for the UK (2020).
- Network length and pipework diameters are challenging to modify in operational sites, due to associated cost of replacing network pipework and/or changing network routing. However, in some circumstances (for example where existing pipework is life expired) there will be opportunities to optimise these parameters.

- [1] "Delta T" is the difference between the flow temperature and the return temperature in the network

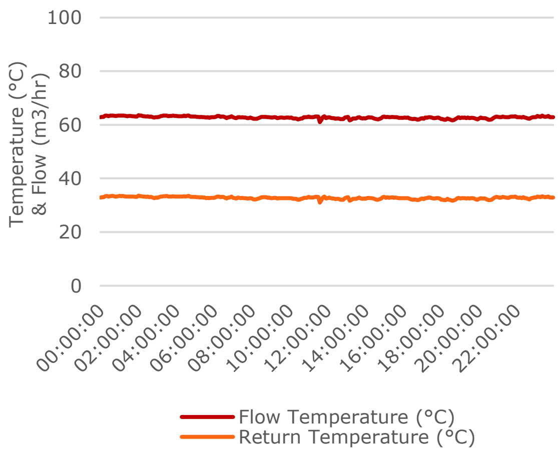


- High flow temperature (80°C)
- High return temperature (>60°C)
- Variable "delta T" typically less than 20°C

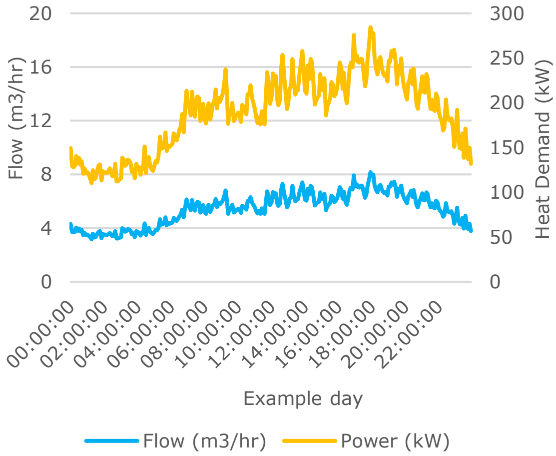


- High average flow rate
- No or limited variation of flow rate with heat demand.

Poorly performing network



- Low flow temperature
- Low return temperature
- Consistent "delta T" of 30°C+.



- Low average flow rate
- Flow rate varies with heat demand.

High performing network

Figure 8: Examples of system flow temperature, return temperatures, flow rate and power for a poorly performing heat network and a high performing heat network.

The above principles will contribute to a distribution network with low heat losses. A high performing network will also have a plantroom/energy centre design to maximise heat generation efficiency and distribution efficiency. A well-designed Energy Centre will have the following characteristics:

- Efficient heat generation equipment hydraulic arrangement: An efficient Energy Centre will have a hydraulic arrangement which facilitates heat generation plant to operate at its optimal efficiency and minimise carbon emissions. For example, a system should:
- Ensure that condensing boilers are able to condense during normal operation.
- Prioritise the lowest cost and/or carbon plant in a network with multiple heat sources.

- Efficient pump arrangement: A high performing network will have suitably sized pumps operating in parallel (unless required for remote locations in larger networks) and typically is optimal to have a single set of network distribution pumps (rather than per block distribution pumps). Having incorrectly sized pumps or multiple pump sets results inefficient operation and increased power consumption.
- Effective control strategy: A good controls strategy will ensure heat sources are able operate efficiently, provide a robust approach to maintaining stable network flow temperature and sufficient differential pressure throughout the network and provide reliable operation of equipment.

A high performing network should be set up to minimise operational risk and ensure the system is maintainable. A large number of networks are overly complex or lack suitable water treatment plant resulting a negative impact on system efficiency, reliability, maintainability and operability. A high performing network will:

- Eliminate unnecessary hydraulic separations: The use of plate heat exchangers should be avoided wherever possible, unless there are compelling legal and technical reasons for utilising them. For example, hydraulic separation might be justified where new heat generation plant is connected to a legacy heating system as the hydraulic separation would protect the new plant from poor water quality in the existing system.
- Including a hydraulic separation in a network requires several supporting items of capital and ancillary equipment, which increases operating and maintenance costs. This extra equipment also introduces several new points of failure, leading to an increased reactive maintenance burden as well. Substations also require an increase in heat generation temperature to facilitate heat transfer, which impacts heat losses generation efficiency and therefore the overall cost of heat. This is illustrated in Figure 9.
- Avoid cylinders, recirculation or trace heating for DHW generation: Domestic systems that incorporate cylinders, DHW recirculation or trace heating typically operate with higher return temperatures (increasing heat losses) than instantaneous hot water generation plate heat exchangers, and effective design can negate the requirement for trace heating
- Have effective water quality equipment and monitoring: While good system water quality is not always related to a direct reduction in operating costs in the short term, the long-term benefits of good water quality are improved operational efficiency and reduced risk of high cost equipment failures.

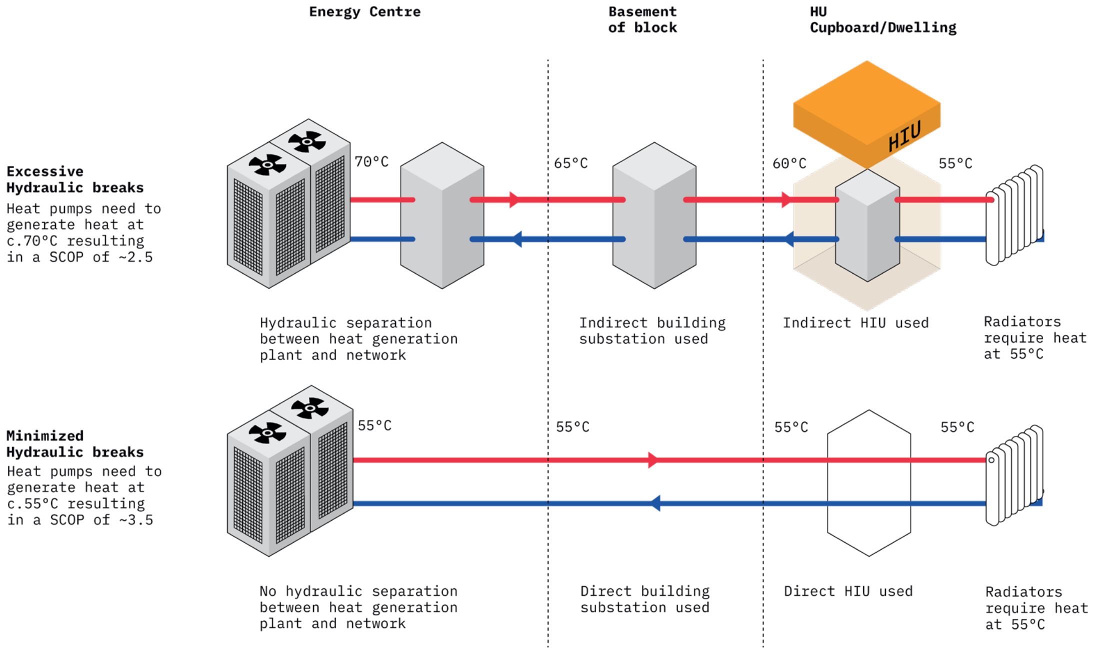


Figure 9: Figure illustrating the impact of hydraulic breaks on heat generation temperature and heat pump COP.

1.3.2. Principles for improving performance

When approaching the challenge of improving the performance of a heat network, it is important to develop and follow a clear process. Without a clear methodical approach to the project, it can be challenging to determine the progress of the project and what outputs are expected at each stage.

The outputs of any heat network optimisation project should be determined by the consultant and heat network operator at the beginning of the project. Determining the required outputs allows the heat network operator to assess whether the optimisation measures proposed were effective and whether they should be applied on other heat networks.

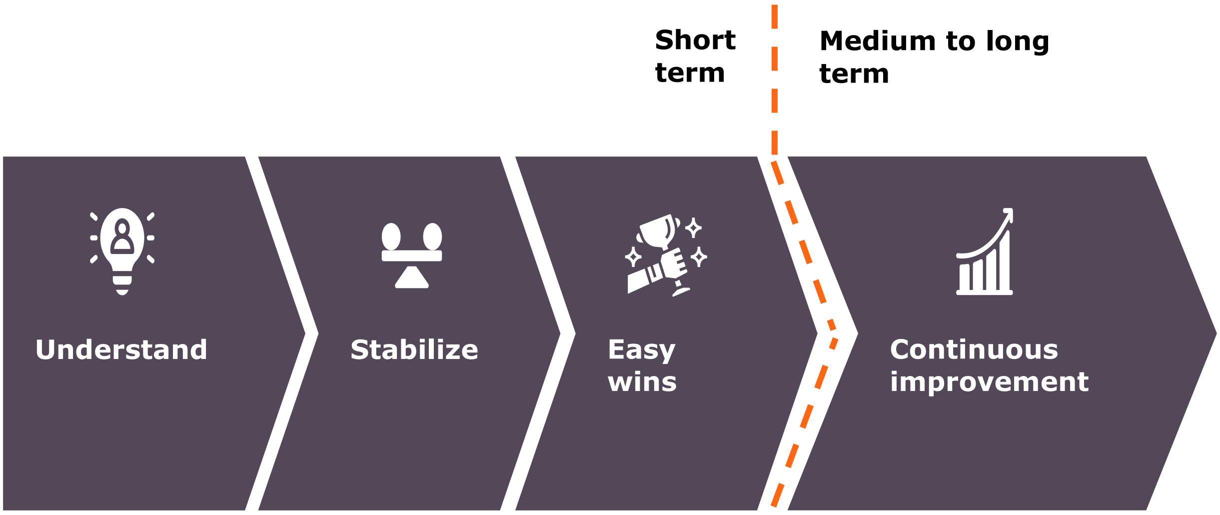


Figure 10: Phased approach to optimising heat network performance.

When assessing a poorly performing heat network, a phased approach is required to ensure that urgent issues are addressed prior to considering the long term optimisation of the network.

The first stage of improving performance is to understand the underlying issues with a network (potentially part of the optimisation study). Further information on the common failure states of heat networks is detailed in Section 8.

Once the root cause of the issues have been identified then it may be necessary to stabilize the heat network. In this context, stabilizing refers to measures that can be undertaken very quickly and that will have immediate and large impacts on heat network performance and reliability. In circumstances where the network is in complete failure, the stabilization measures may be ensuring all customers have a heat supply.

Once the heat network has been stabilized then a series of quick, easy win measures should be carried out. These are typically interventions that have very short payback times but require more planning and design input but can still be performed relatively quickly.

Once the system has now been stabilized and the easy wins implemented then the performance should be improved further and the system made more reliable. In the medium to long-term plan for the heat network, a continuous improvement approach is required.

The aim of continuous improvement the aim is to ensure that there is an ongoing effort to incrementally improve the performance over the longer term. As shown in Figure 11, the steps in the continuous improvement cycle are as follows:

1. **Measure:** Without being able to measure network performance, it is challenging to evaluate and validate the impact of potential interventions. For the continuous improvement process to be effective, there needs to be a method of extracting operational data either on site or securely via the internet.

2. **Analyze:** Once collated, data can be used to assess potential optimisations.

3. **Test:** Potential measures can be tested (piloted) on a smaller sample to assess their effectiveness. For example, HIU replacement could be tested on a small number of flats to confirm the improvements in performance, or in larger networks, measures can be tested at a whole block level.

4. **Implement:** If testing shows that the intervention measures have the desired effect then then they can be implemented throughout the heat network

1. **Measure** (the continuous improvement cycle repeats): The network data can be monitored post-implementation to confirm desired outcomes have been achieved and identify other areas where network performance can be improved.

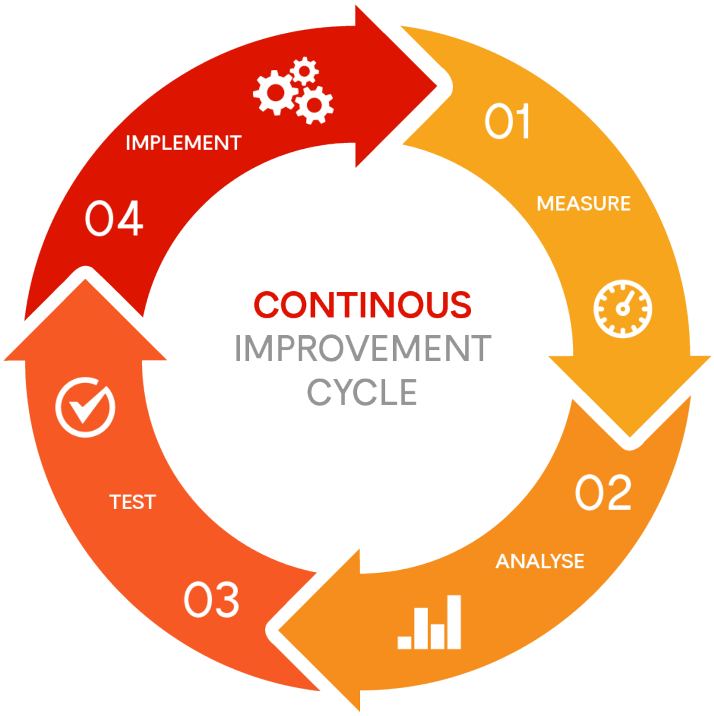


Figure 11: Continuous improvement cycle

Through adopting the continuous improvement cycle, network performance can be gradually optimised. Therefore, while optimisation studies may recommend a large number of measures, they will typically be delivered over a number of years and may adapt subject to the impact of initial interventions and the resources of the network operator.

1.3.3. Optimisation Hierarchy

The Optimisation Hierarchy (Figure 12) provides a guide for engineers when approaching heat network optimisation. It states, in order of importance to heat network performance, consumer heating systems are the most critical, followed by the district/communal distribution system with the energy centre being of least importance. This is not to say that the network and energy centre performance have no impact on overall heat network performance but just recommends a hierarchy of importance.

When approaching heat network optimisation, it has been common to consider the energy centre (plant room) as the main driver of the system efficiency. However, while the energy centre contains the largest and most complex equipment in the system, it can only have a limited impact on the network heat losses.

Contrary to this approach, the requirements and performance of consumer heating systems (e.g. dwellings) are the most important aspect affecting the overall performance of the heat network. End user requirements dictate the minimum flow temperature that the entire network can operate at, and the end user equipment performance defines the minimum return temperature throughout the system.

The minimum flow temperature that the network can operate at is typically constrained by higher of the:

- Temperature required to generate domestic hot water for dwellings; or
- Temperature required to generate sufficient space heating output for dwellings (typically the constraining temperature).

Other constraints can include equipment and pipe sizes that cannot provide the required peak heat demand at lower flow temperatures. However, it should be noted that a combination of historic system oversizing and potential incremental improvements in fabric performance of the end user buildings means that there are usually opportunities to reduce flow temperatures.

Consumer connections and heating systems (such as HIUs and space heating emitters) also have a direct impact on the district/communal distribution return temperatures.

Minimising both flow and return system temperatures (while maintaining required performance) results in the lowest possible heat losses across the entire heat network. As the minimum flow and return temperatures are largely set by dwelling equipment, they are most the important element optimise to in order to achieve an efficient heat network.

Once the consumer (e.g. dwelling) performance has been optimised, the network (district and communal) should be addressed.

Finally, the energy centre should be optimised to ensure that the entire system is operating efficiently.

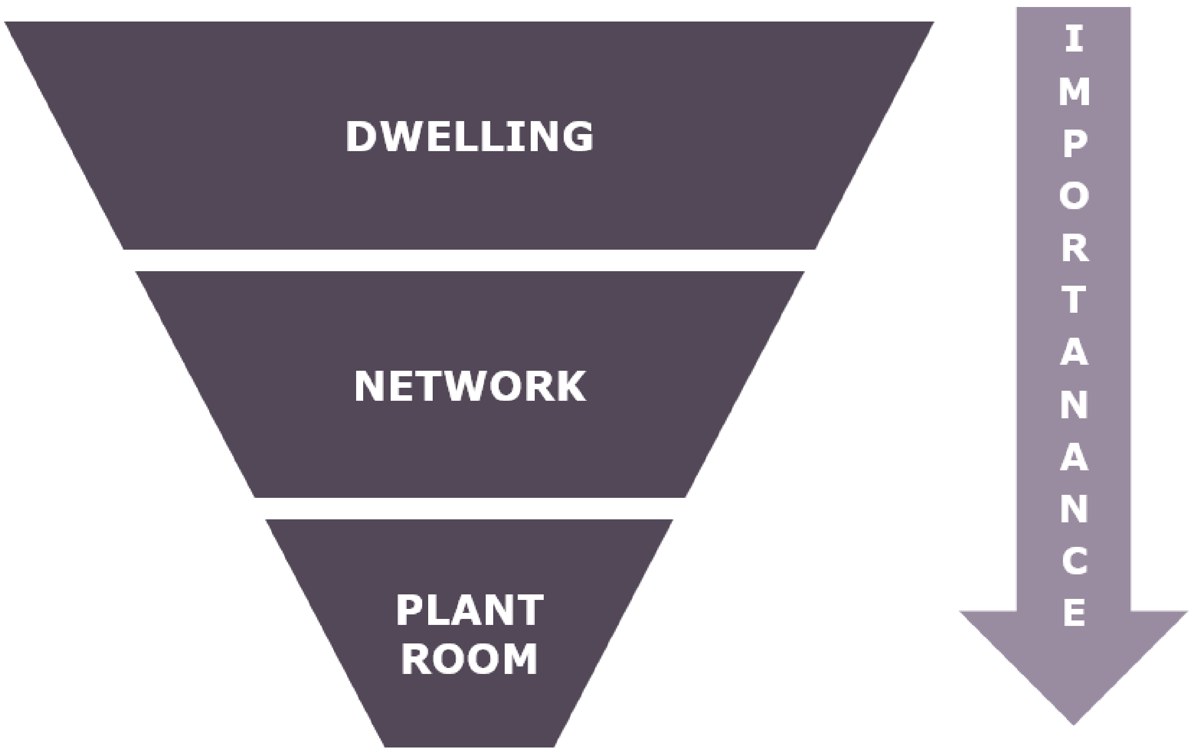


Figure 12 Optimisation Hierarchy for a residential heat network

1.4. Process for implementing heat network improvements

The below section highlights some of the typical interventions which can be undertaken to improve network performance. This is not an exhaustive list of interventions as each network will have its own unique considerations.

As stated previously (see Section 1.3), a phased approach is required to improve network performance. Each of the measures outlined below will typically fall into one of the distinct phases of heat network improvement: Stabilize, Easy Wins and Continuous improvement. However, this will vary on a site by site basis.

1.4.1. Stabilizing measures

The below measures are typically stabilisation measures due to their major impact on system performance and the end user's ability to access heat.

1.4.1.1. Reduce network flows

Uncontrolled network flow rates can directly damage the network and result in high pump energy consumption as well as higher heat losses.

Controlling network flow is typically an activity undertaken in the stabilisation phase of network improvement. This is due to the impact uncontrolled flows can have on the end-users ability to receive reliable heat.

The three main actions required to get network flow rates under control are:

- Removal of network bypasses (system and flushing bypasses).
- Elimination of end user bypasses (HIUs acting as a bypass).
- Control and/or replacement of pumps.

Often a small proportion of dwellings on the network are responsible for most of the flow on the network. This means only a small number of bypassing units can cause a significant problem for the whole network.

Reducing system bypasses is often more involved owing to systems being designed to have these bypasses. Therefore, specialist input is required for the following:

- Determine whether system bypasses are required to maintain flow temperatures.
- Determine whether minimum flow protection is required for pumps.
    - If not required, determine what is needed to implement pump control changes.
    - If required, review cost-benefit of installing local bypass to the pump vs pump replacement, then develop design approach once agreed.

1.4.1.2. Improve water quality

Poor water quality is a large cause of heat network failure within the UK and is also an area of immediate concern when stabilising heat networks. If systems suffer from regular heat outages as a result of poor water quality, then the effectiveness of subsequent improvement measures discussed in sections 1.4.2.1 to 1.4.2.5 are greatly reduced.

Incoming mains water has a high oxygen content which makes it unsuitable for use in heat networks due to increased risks of corrosion. Physically and/or chemically treating mains water is vital in minimising the risks of corrosion across heat networks.

Poor water quality results in:

- Reduced system reliability.
- Increased risk of equipment failure.
- Reduced plant and component lifetime.
- Increased replacement/ remedial costs.

1.4.2. Easy wins and continuous improvement

The below measures are typically part of the longer term improvement of a heat network. These measures will improve system efficiency and lower cost, however they have less of an impact on end user heat availability compared to the stabilisation measures outlined in the previous section.

1.4.2.1. Reduce return temperatures

Elevated return temperatures are a common symptom of a poorly performing heat network. High return temperatures have an impact on the cost of heat, reliability as well as overheating and are typically due to uncontrolled flow across the network leading to lower efficiencies and a poor end user experience.

The two areas of focus in order to reduce elevated return temperatures are:

- Improving the performance of dwelling systems.
- Removing network bypasses across the system.

1.4.2.2. Reduce flow temperatures

High flow temperatures are also a common symptom of a poorly performing heat network and lead to two key negative effects:

- Higher cost of heat.
- Overheating in communal and occupied areas.

These are negative effects due to network heat losses which are directly proportional to the flow temperature across the network. Therefore, reducing network flow temperatures will result in decreased heat losses and improve network performance.

Flow temperature reduction is limited by two main factors:

- Required temperature for heating and hot water (e.g. radiators sizes limit temperature reductions).
- Capacity of the system (reduction in temperatures can increase flow rates and therefore increase pressure losses and pump electricity consumption)

Flow temperatures cannot be dropped without sufficient understanding of the system. However, most existing heat networks are oversized which provides the capacity for flow temperatures to be reduced.

1.4.2.3. Reduce complexity and risk

A commonly encountered issue across heat networks within the UK is that they are overly complex, with excessive equipment that is not required in order for the network to function efficiently.

Examples of overly complex systems are as follows:

- Systems with separate distribution pumps for each block when one pump set serving all blocks would be feasible.
- Unnecessary hydraulic separation that is not required either to mitigate a pressure risk or for contractual reasons.
- Redundant equipment that has not been disconnected from the heat network and decommissioned

Increased complexity generally has a negative impact on long term system performance including:

- Reduced reliability.
- Increased cost of planned and reactive maintenance.
- Increased pump electricity consumption.
- Increased cost of replacing end of life equipment
- Poor system hydraulic control resulting in poor generation efficiencies
- All of the above factors result in an increased cost to end users and operators. By establishing a simpler system, with appropriate monitoring, it will be easier for operators to maintain the long term and optimise through the continuous improvement cycle.

1.4.2.4. Enhance insulation

Poor pipework insulation impacts the heat losses from the network, thereby resulting in an increased cost of heat to dwellings, as well as causing overheating within communal and occupied areas.

It is typically found that insulation thicknesses defined by Building Regulations (Part L) are not sufficient to mitigate heat losses, and systems should be insulated to thicknesses selected via a whole lifecycle cost assessment or following industry best practice as set out in CIBSE CP1 Heat networks: Code of Practice for the UK, 2020. Improved insulation can be relatively easy to implement as works do not cause service interruptions, whilst also typically resulting in short payback times.

1.4.2.5. Improve energy centre efficiency

Enables reduction to the cost of heat output from the energy centre. Typically, in order to improve the overall energy centre efficiency a well performing network is first required. This is due to the efficiency of heat generation equipment often being dictated by return temperatures from the system.

Low energy centre efficiency is typically evidenced by:

- High electricity consumption.
- High consumption of gas or alternative fossil fuel used by the heat generating assets.

- Low temperature differences between the inlet and outlet of the heat generating asset.

1.5. Approach to improvement

When sub-optimal performance has been identified, it is recommended that the following approach to assessing what approach measures are suitable are taken:

- **Repair**: the first consideration should be whether the equipment is faulty. If faulty equipment is identified then it should be If faulty equipment is identified, an assessment should be carried out to evaluate whether repairing the equipment will provide optimised performance. This may be done through a limited set of pilot works, particularly where the fault is identified in equipment that is installed in many locations (e.g. HIUs).
- **Recommission**: if the sub-optimal performance is not a result of faulty equipment, then the system should be recommissioned. As with Repair, undertaking the recommissioning in detail on a smaller number of pilot units would be beneficial to allow for assessment of the measures as it may be that, once full recommissioning has been carried out, the performance is still not considered adequate.
- **Upgrade/Improve**: once the equipment has been repaired and/or recommissioned, if the performance is still sub-optimal then an investigation should be undertaken as to whether the equipment could be upgraded or improved. This might be a smaller sub-element of a larger system that would reap large benefits, such as installing an inverter on distribution pumps.
- **Replace**: after all other approaches have been exhausted, if the system is still not performing sufficiently well then the equipment will need to be replaced.

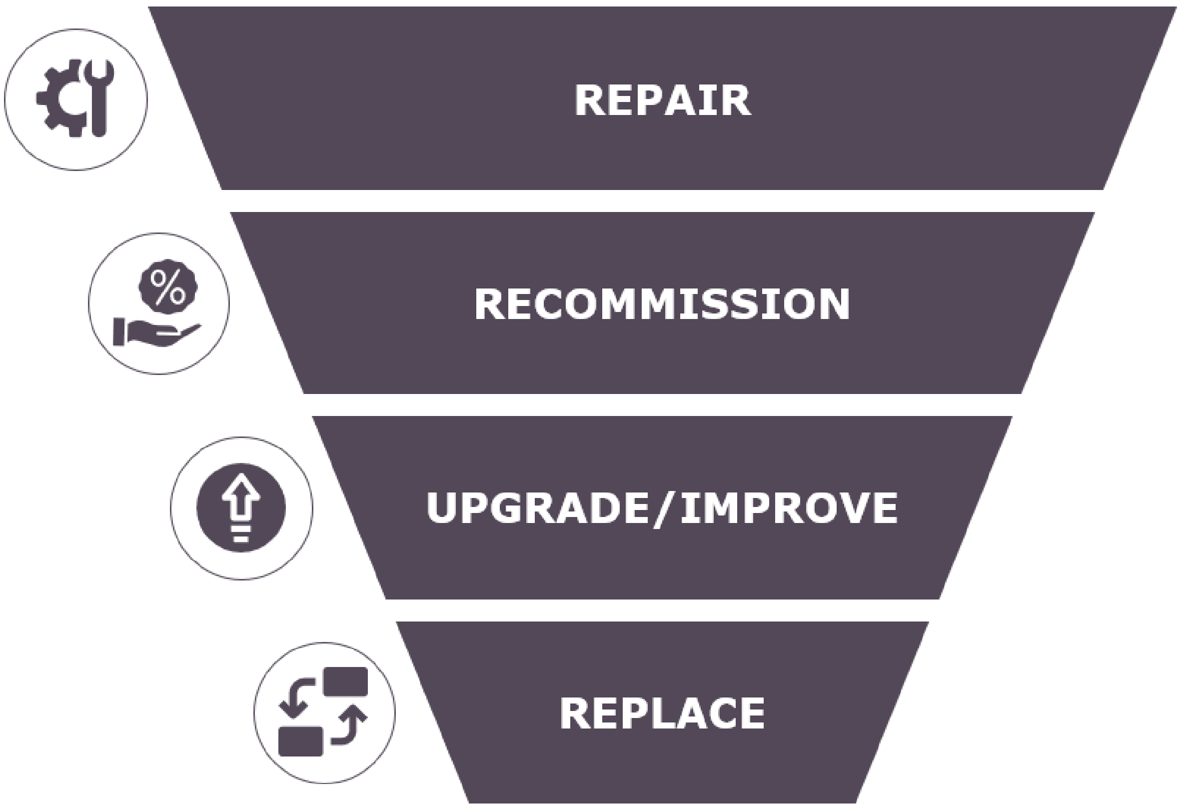


Figure 13: Approach to optimisation improvements

2. Overview of optimisation study process and outputs

2.1. Process overview

The key activities and outputs of each stage are highlighted in Table 1 and Section 2.2 below.

In most instances, the optimisation assessment will be conducted by a heat network specialist consultant, but these can also be conducted by the operator if resource and expertise allow. Regardless of the assessment author, the network operator has several key roles during the assessment and must remain actively engaged throughout to ensure that useful results can be delivered.

The key responsibilities of the network owner/operator throughout an optimisation study are:

- Inform all parties who attend site of all Health & Safety risks and mitigation measures
- Confirm scope of assessment
- Provide all available information requested regarding the heat network in question
- Liaise with internal departments and 3rd party providers (e.g. M&B agent) to secure further heat network information
- Provide site access and coordinate access to dwellings
- Confirm organisation objectives and key business case considerations
- Attend kick off, progress and close out meetings
- Confirm capital works appetite, objectives, budgets and strategy

Key stakeholder involvement throughout the optimisation study is shown in Figure 14 and an outline process flow diagram is presented in Figure 15 showing the main activities and responsibilities throughout the optimisation study process.

Pre-project		Phase 1: Initial investigation				Phase 2: Techno-economic options appraisal			Phase 3: Implementation plan	
	0. Define project	1. Information & data collection	2. Pre-audit analysis	3. Site audit	4. Technical review	5. Detailed technical analysis	6. Determine potential interventions	7. Cost benefit analysis	8. Costing of interventions	9. Final business case
Stage outcome	Understand Client aims & agree project scope	All relevant information on heat network identified	Initial understanding of system issues and potential causes	Sufficient understanding of system to complete optimisation assessment	Gain qualitative understanding of system issues	Quantitative assessment of performance against KPIs completed	Optimisation opportunities developed and modelled	Initial business case for optimisation opportunities completed	Detailed costing of interventions to inform final business case	Final business case for optimisation opportunities completed
Core tasks	Initial engagement Understand heat network typology and issues	Issue & return RFI Collect M&B and O&M data	Analyse all information returned from RFI Interview Client to understand issues from Client perspective Data gap analysis	Organise site visit and dwelling access Undertake site audit Measurements of key parameters (e.g. temperatures) Meeting and discussing performance with end users	Review of information site audit and pre-audit analysis Develop hypotheses regarding probably causes of performance issues Presentation of findings Discuss queries with manufacturers	Undertake root cause analysis Heat loss modelling Pump energy modelling Analysis of reliability and financial KPIs	Selection and design assessment of interventions Heat loss modelling Pump energy modelling Analysis of reliability and financial KPIs	Financial modelling of work packages Produce business case	Develop high level scope of works Engage with contractor and equipment suppliers to cost for works Undertake pilot of works if appropriate to assist with costing & confirming impact of interventions	Financial modelling of work packages Produce delivery plan Update business case
Information exchanges	High level summary of issues Scope and quote	Heat network documentation Heat meter data BMS data O&M logs	Queries raised during analysis	Requirements to ensure successful site audit RAMS	Findings of site audit		Client feedback on intervention options	Client inputs into financial model	Information for costing Data collected during and following pilot (if conducted)	Client inputs into financial model
Key outputs	Defined project scope Engagement to undertake optimisation study	RFI register & gap analysis	Draft system issue list Data gap analysis results	Completed site audit checklists	Initial investigation report Presentation of findings Decision on next steps	Heat loss model KPI analysis	Work package selection Heat loss model KPI analysis	Techno-economic options appraisal report Presentation of findings Decision on next steps	High level scope of works Detailed interventions cost planPost-pilot report	Implementation plan Presentation of findings Decision on next steps

Table 1: Summary of key optimisation study stages

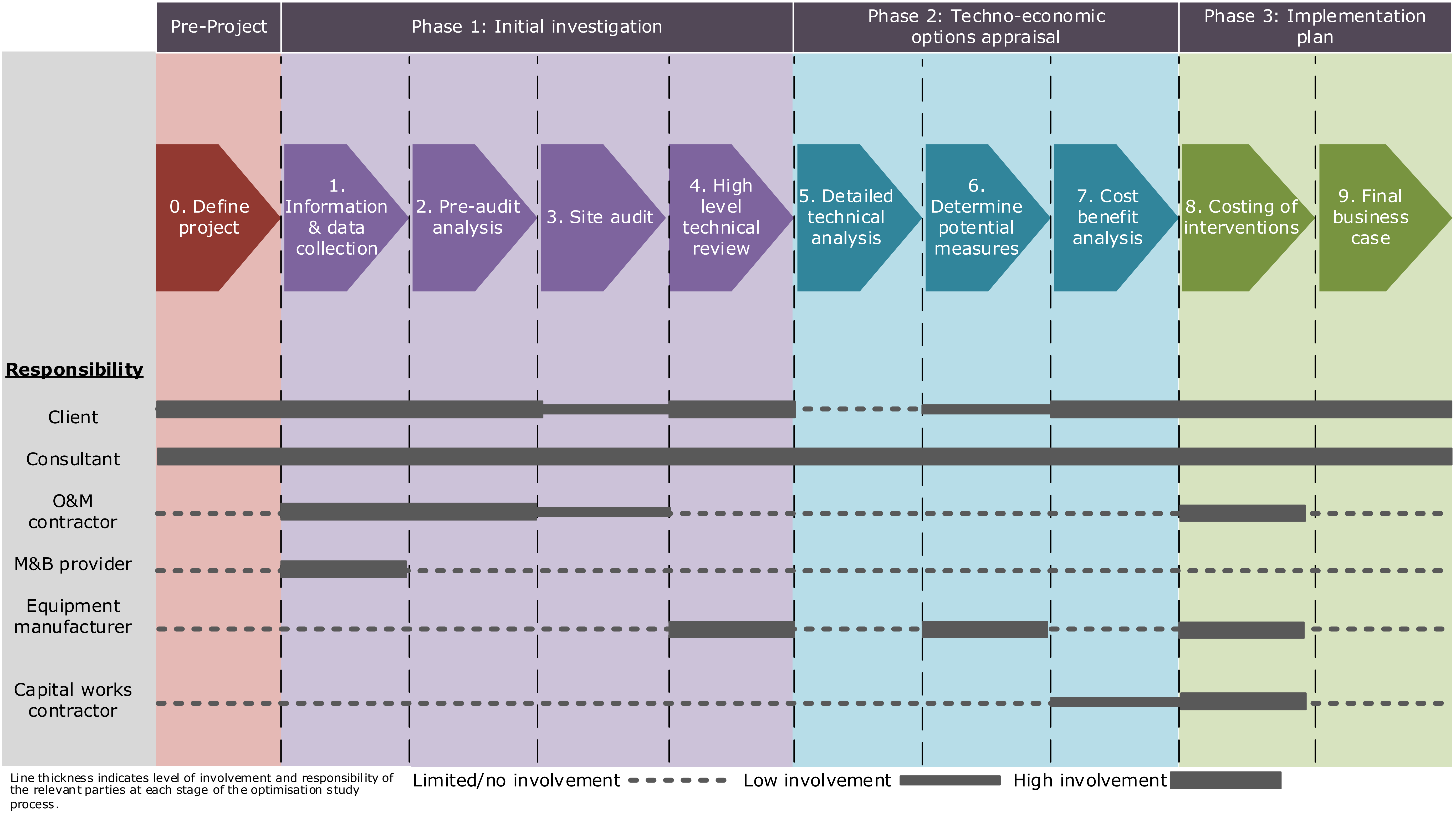


Figure 14: Key stakeholder responsibilities throughout optimisation study

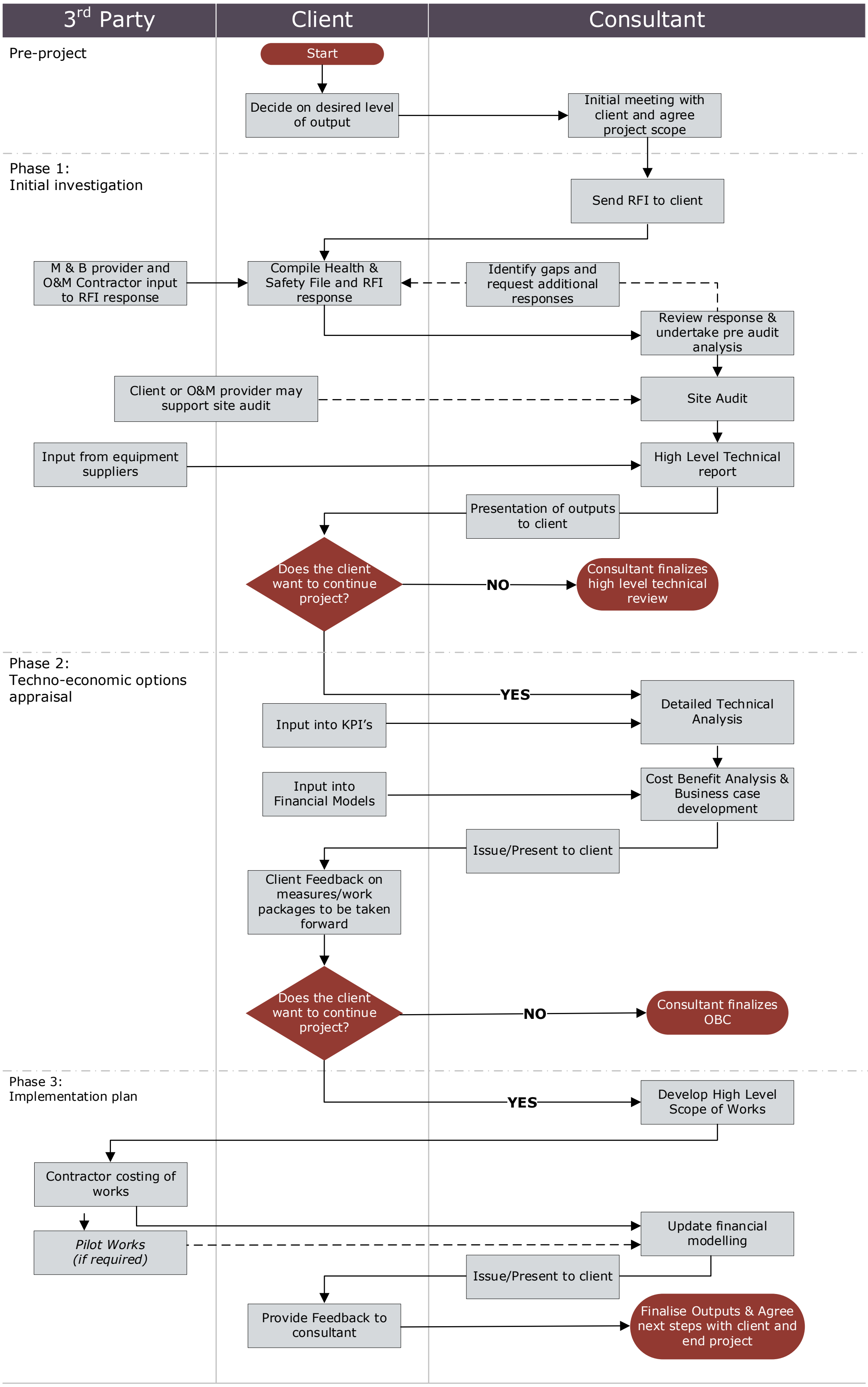


Figure 15: Process flow diagram for Optimisation Studies

2.2. Outputs overview

There are 3 main phases of the optimisation assessment process, and the key outputs of each phase are outlined below.

The decision on how many phases shall be undertaken shall be agreed between the client and consultant. This is dependent on several factors, the key ones being:

- Heat network size & complexity
- Available budget
- Project timescales

It should be noted that a decision on whether to proceed to the next phase of assessment can be made as the major deliverables of each phase are delivered – i.e. Phase 2 can be engaged following issue and review of the Phase 1 initial investigation report.

Recommended example scope documents that align with the three Phases of the Optimisation Study process are provided as a supporting document to this guide.

In some circumstances, it may be preferred to delay the delivery of a project phase, usually this would be known following the initial site audit. Typical reasons for this are:

- At sites with a severe lack of metering, the optimisation project may need to pause for a period to allow the installation of metering to improve the overall outputs from the Optimisation Study.
- Some sites may require accelerated delivery of stabilisation measures and/or quick wins where a network is in a failure state and action is required to resolve major performance or reliability issues (see Section 1.4). In these circumstances, the detailed technical analysis and business case for immediate works may be required in advance of longer term measures.
- Survey may undercover other building safety issues which need to be rectified prior to the optimisation study proceeding.
- Any required or recommended change identified during the project should be agreed between the relevant parties and change control implemented where required.

2.2.1. Phase 1 (Stage 1-4) assessment: Initial investigation

The aim of a Phase 1 assessment is to gain a full qualitative understanding of system performance and issues. This can involve heat meter data analysis if available but does not need to extend to a full KPI assessment of current performance.

The output of Phase 1 shall be an initial investigation report which includes the following information:

i. Major gaps in site information impeding further analysis
ii. Outcomes of data review and gap analysis
iii. Detail of plant room, network and dwelling level issues
iv. Rating of issue severity
v. Root cause analysis of issues
vi. Potential interventions to address issues

2.2.2. Phase 2 (Stage 5-7) assessment: Techno-economic options appraisal

The aim of a Phase 2 assessment is to gain a full quantitative understanding of system performance and issues, and the impact of addressing issues on system performance. This impact is compared against initial costing to indicate the business case of potential interventions.

The output of Phase 2 shall be a techno-economic options appraisal which includes the following information:

i. Root cause analysis of issues and determining potential performance improvement interventions

ii. KPI assessment of current performance and potential interventions

iii. Modelling of operational impact of potential interventions

iv. Initial costing and business case

2.2.3. Phase 3 (Stage 8-9) assessment: Implementation plan

The aim of a Phase 3 assessment is to gain a full understanding of costs of potential interventions to finalise the business case and to develop an implementation plan.

The requirement for full costing should be decided on a project by project basis, and shall consider the size of the heat network, extent of proposed interventions and accuracy of the initial estimates.

A pilot of works may be required as part of the detailed costing process, which should also be determined on a project by project basis. The benefits of conducting a pilot are:

- Increased certainty on project costs and programme
- Opportunity to analyse performance data pre- and post-pilot to increase accuracy of business case
- Opportunity to trial different methods of installation to determine the preferable option

For example, a whole network HIU retrofit could piloted by replacing a small number of HIUs. Delivering these works would give the client greater confidence in the cost of replacing all HIUs on the network, confirmation of the risks associated with HIU replacement at the site and verification of the performance of the replacement HIUs.

The output of Phase 3 shall be an implementation plan which includes the following information:

i. An outline scope of works

ii. Detailed costing of works

iii. Revised business case

iv. Revised KPIs and modelling of interventions following pilot (if applicable)

v. Project delivery plan

2.3. Knowledge and experience required

In order to ensure that the technical and financial analysis carried out during the Optimisation Study is undertaken to the required quality, a prerequisite level of knowledge and experience is required.

If you operate a heat network and are specifying a consultant to carry out an Optimisation Study for you, then you should ensure that the engineers undertaking the work have the minimum knowledge and experience as outlined in this section.

2.3.1. Required knowledge

Heat network Optimisation Studies require a combination of technical and analytical skills. Some of the essential skills required for this field include:

- Knowledge of thermodynamics: A strong understanding of thermodynamics is essential to understand the principles of heat transfer, heat loss, and heat recovery. This knowledge is necessary to carry out root cause analysis and to optimise their performance.
- Data analysis skills: Heat network optimisation studies require the analysis of large datasets, including heat meter and BMS data. The ability to analyse and interpret data using statistical and mathematical tools is essential for effective optimisation.
- Project management: Heat network optimisation studies involve multiple stakeholders and require effective project management skills to ensure timely completion and successful implementation of the optimisation recommendations.
- Communication skills: Effective communication skills are essential for presenting findings and recommendations to stakeholders. The ability to communicate technical information in an accessible manner is necessary.

2.3.2. Required experience

Some of the essential experiences required to carry out Optimisation Studies include:

- Engineering background: A degree in engineering, such as mechanical or chemical engineering and/or substantial work experience in engineering as recognised by a Professional Institution (e.g. EngTech, IEng or CEng).
- Project experience: Practical experience in project management, such as leading or participating in energy projects, is valuable for understanding the challenges and opportunities associated with heat network optimisation.
- Industry-specific experience: Experience in the heat network sector provides a valuable understanding of the unique challenges and opportunities associated with heat network optimisation.
- Analytical skills: Experience in data analysis and mathematical modelling is essential for effective heat network optimisation studies. This includes experience in statistical and root cause analysis.
- Communication skills: Experience in presenting technical information in an accessible manner is essential for successful heat network optimisation studies. This includes experience in developing reports, presentations, and other forms of communication for different audiences.

- Knowledge of regulations and policies: Knowledge of energy policies, regulations, and incentives is valuable for understanding the legal and regulatory framework surrounding heat network optimisation.

2.3.3. Roles and minimum requirements

Project Role	Project Activities	Minimum Experience	Minimum Qualifications
Study Engineer	Leads on site audit and responsible for managing the technical and financial analysis of the optimisation study	2+ years operational experience in heat network sector	Either Level 6 qualification (England, Wales and Northern Ireland) in engineering related discipline or Level 10 (Scottish Credit and Qualifications Framework) in engineering related discipline or Professionally registered as an Engineering Technician (EngTech) with the Engineering Council
Study Lead	Accountable for the technical quality of report, conclusions and recommendations	5+ years operational experience in heat network sector	Either Level 7 qualification (England, Wales and Northern Ireland) in engineering related discipline or Level 11 (Scottish Credit and Qualifications Framework) in engineering related discipline or Professionally registered as a Chartered Engineer (CEng) with the Engineering Council

Table 2: Minimum experience and qualifications for key specialist optimisation study role holders

2.4. Future technical regulations

Ofgem have been appointed as the Heat Networks Regulator for Great Britain. This regulation is expected to come into force in 2024[2]. As part of this, a technical standard for heat network design and operation is being developed. The standard, being developed by the Heat Network Technical Assurance Scheme, may include minimum technical requirements for existing heat networks, which will be a legal obligation for the heat network operator.

[2] As per Ofgem website 18/04/2023

3. Determining performance

Heat network performance should be analysed and determined quantitatively to enable detailed assessment of potential interventions and to enable heat network operators to compare performance across their portfolio and prioritise systems for improvement.

A set of KPIs is outlined in Section 3.1 for use during quantitative analysis of system performance. This list is not exhaustive, and operators may have additional KPIs they wish to review. This should confirmed when the project scope is initially defined.

The calculation methodology for all KPIs is detailed in Section 3.2.

Sufficient data may not always be available to allow all KPIs to be calculated. Data can typically be sourced from the BMS, standalone heat meter, HIU metering, built in equipment monitoring (e.g. data on pumps is often stored within the pump controller), O&M Records and utility metering (and bills).

Higher quality data used in measuring KPI's gives greater confidence in their calculation and therefore the likely benefits of delivering interventions. A key component in data quality, in the context of heat networks is metering frequency, since variables such as flow and return temperature vary over time and therefore high resolution monitoring is required to accurately record performance.

If data is of poor quality or is not available, as assessment shall be made as to whether reasonable assumptions can be made to enable the KPI to be estimated. For example, if 20 % of heat meter data is missing then trends from the 80 % of available data could be extrapolated to estimate network level KPIs.

Any KPIs relying on estimates or assumptions should be highlighted within the output reports for clarity.

In some instances, it will not be possible to make reasonable assumptions to calculate KPIs, in which case KPIs should be left uncalculated and data gaps preventing these calculations highlighted.

3.1. Key Performance Indicators (KPIs)

3.1.1. Energy centre performance KPIs

Energy centre KPIs relate to the efficiency and consistency of the provision of heat to the network by the generation equipment. The energy centre KPIs are defined as follows:

- Heat generation efficiency – the efficiency with which the heat generation equipment (e.g. gas boilers and/or ASHPs) produce heat for the network, measured using gas/electricity (subject to primary heat source) and heat meter data. This metric is indicative of the heat generation cost for the development.
- Average flow temperature – the average flow temperature provided to the network from the energy centre, measured from heat meter data. This metric is indicative of the consistency of supply to dwellings and expected heat losses from the network.
- Average return temperature – the average return temperature from the network to the energy centre, measured from heat meter data. This metric is indicative of the heat losses from the network and benefits the generation efficiency of condensing boilers.

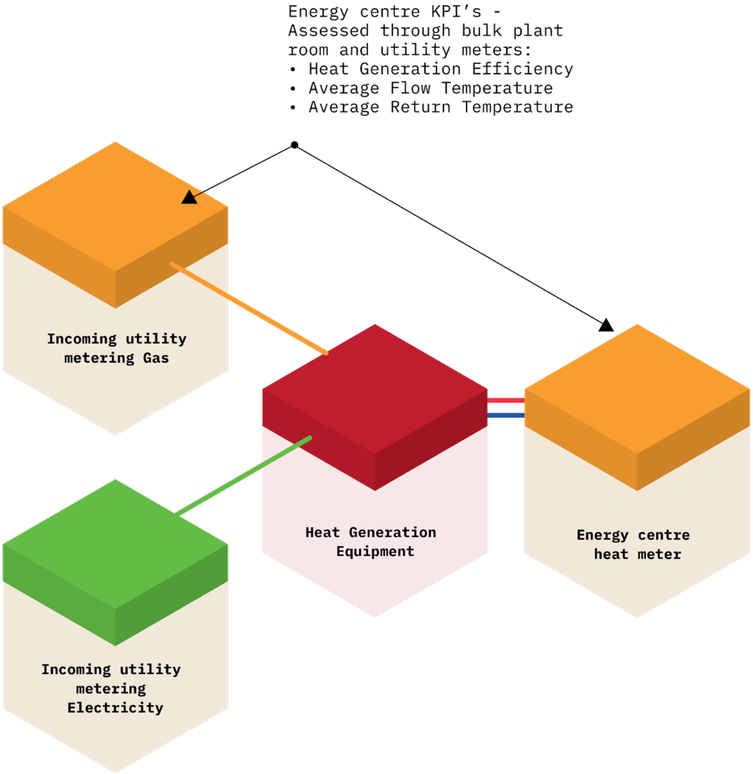


Figure 16: Graphic illustrating monitoring locations for Energy Centre KPIs

3.1.2. Heat network performance KPIs

Heat network KPIs relate to the efficiency of the operation of the network. The heat network KPIs are defined as follows:

- Heat network loss – the standing heat losses from the network, measured using energy centre and dwelling heat meter data or a model. This metric provides the magnitude of losses from a system and can be directly compared between networks. Note on larger systems the network loss KPI could be split into district distribution and communal distribution system losses to allow accurate comparison against industry standards (as set out in CP1 2020).
- Bypass flow rate – the percentage of flow leaving the energy centre that is not used to serve dwellings, measured using energy centre and dwelling heat meter data. This metric provides an indication of bypasses present on the system and unnecessary pump energy consumption.
- Average flow temperature – the average flow temperature provided to the network, measured using block level heat meter data. This metric provides an indication of the consistency of dwelling level performance.
- Average return temperature – the average return temperature from the network/each block, measured using block level heat meter data. This metric provides an indication of performance and heat losses across the network.

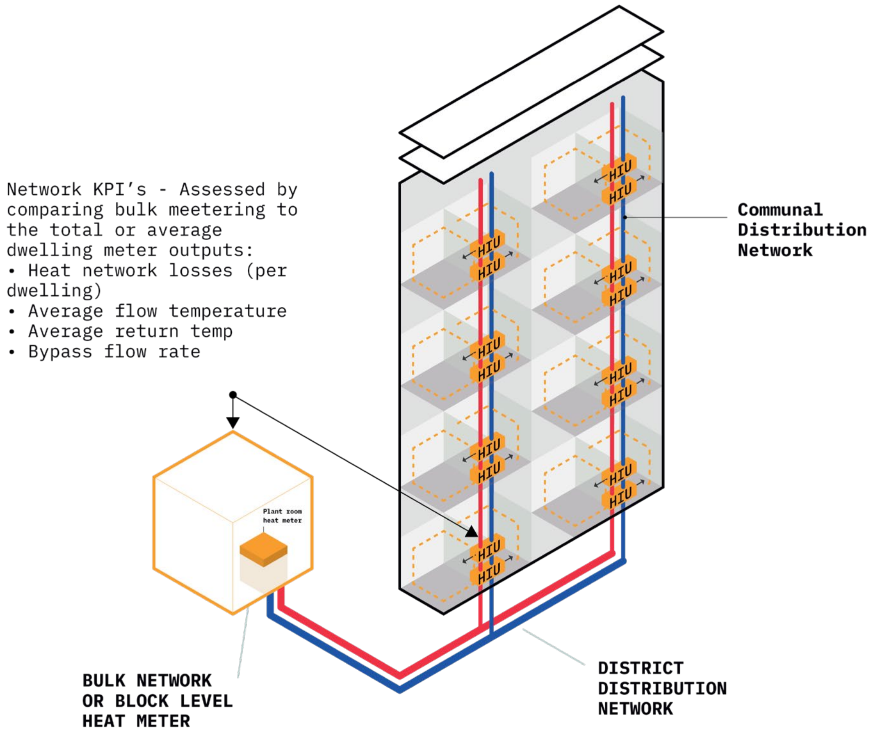


Figure 17 Graphic illustrating monitoring locations for Network KPI's.

3.1.3. Dwelling performance KPIs

Dwelling KPIs relate to the performance of the dwelling level heating infrastructure and the effects it has on the network. The dwelling KPIs are defined as follows:

- VWART during DHW delivery – the volume weighted average return temperature from dwellings during DHW delivery, measured using dwelling heat meter data. This provides an indication if the commissioning and performance of dwelling DHW production.
- VWART when no demand (i.e. standby) – the volume weighted average return temperature from dwellings during standby periods, measured using dwelling heat meter data. This provides an indication if the commissioning of keep warm functions and the presence of bypasses.
- VWART during space heating – the volume weighted average return temperature from dwellings during space heating delivery, measured using dwelling heat meter data. This provides an indication if the commissioning and performance of dwelling space heating delivery.
- Average VWART across all modes of operation – the volume weighted average return temperature from dwellings, measured using dwelling heat meter data. This provides an indication if the commissioning and performance of dwellings and can help identify dwellings in need of rectification works.
- As Figure 18 below shows, HIU return temperature should vary significantly depending on the mode of operation. By calculating the VWART for the different modes, it enables better understanding of overall HIU and dwelling heating system performance.

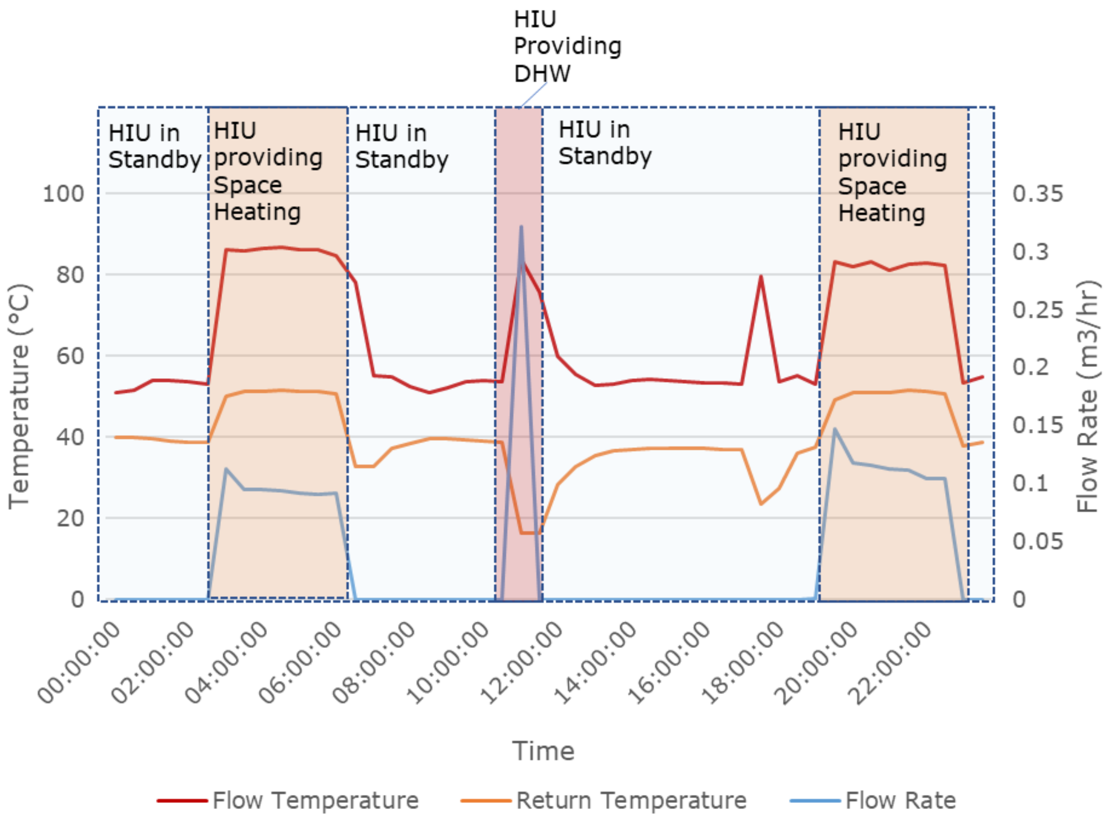


Figure 18 Example graphic illustrating how dwelling flow temperature and return temperatures changes with different operational modes.

3.1.4. Other KPIs

Reliability, financial and environmental KPIs relate to the reliability of heating supply to end users , the costs incurred in running the network and the carbon impact/air quality of the heating system. Example "other KPIs" are as follows:

- Time below minimum flow temperature – the amount of time (hrs) per annum that the network is operating below the sufficient flow temperature to deliver heat to end users, measured using heat meter data. This metric indicates the reliability of the system from an end user perspective.
- Flow temperature stability – the percentage of time the network operates within ±5 °C of the flow temperature set point, measured using heat meter data. This metric indicates the stability of the generation and distribution systems.
- Major outages – the number of times per 100 days that the flow temperature or differential pressure has fallen below minimum for over 4 hours or any other issue leading to >10% of end users not receiving heat for over 4 hours. This metric is indicative of the stability of the system and the reliability of maintenance response.
- VWAFT – the volume weighted average flow temperature to the network, measured using heat meter data. This metric ensures that specific issues such as those during high demand can be identified.

- VWART – the volume weighted average return temperature from the network, measured using heat meter data. This metric ensures that specific issues from network or dwellings can be identified.
- Reported interruptions and reductions – the number of reported interruptions or reductions per 100 dwellings per 3-month period. This metric is indicative of the reliability of the dwelling or other dwelling systems and maintenance.
- Maintenance frequency – the number of O&M visits to dwellings per 100 dwellings per 3-month period. This metric is indicative of the reliability of the dwelling or other dwelling systems and maintenance.
- Year 1 required heat tariff – the cost of gas and/or electricity used to generate a kWh of heat consumed by an end user. This includes heat lost during transmission and reflects the efficiency of heat generation and the distribution network. It does not account for the maintenance costs or ancillary electricity consumption from the process of generating or distributing heat (such as distribution pumps or pressurisation equipment).
- Carbon intensity of heat delivered – this reflects the carbon emissions associated with each unit of heat consumed by the end user. The metric considers only operational carbon associated with network energy consumption. The carbon intensity of heat can be used to compare the environmental performance of different systems and will be an important metric in scenarios where organisations have net zero carbon targets. Note that to use this metric effectively assessors should ensure that the carbon factors within the calculation are clearly identified.

3.2. KPI calculation methodology

The calculation methodology for all KPIs outlined in Section 3.1 is detailed in in Table 3.

Type	Area	KPI / metric	Calculation methodology
Performance	Energy centre	Heat generation efficiency	$= \frac{\sum kWh_{heat\ generated\ in\ energy\ centre}}{\sum kWh_{input\ fuel\ delivered\ to\ energy\ centre}}$ To be calculated for each item of heat generation equipment
		Average flow temperature	Average of all temperature readings over time – undertaken over 12 months if possible.
		Average return temperature	Average of all temperature readings over time – undertaken over 12 months if possible
	Heat network	Heat network loss	See Section 5.3
		Bypass flow rate	See Section 5.2.3.1
		Average flow temperature	Average of all temperature readings over time – undertaken over 12 months if possible
		Average return temperature	Average of all temperature readings over time – undertaken over 12 months if possible
	Dwelling	Average VWART (volume weighted average return temperature) across all modes of operation	See Section 5.2.2
Reliability	Energy centre	Time below minimum flow temperature	% time below minimum flow temperature required for heating and hot water supply.
		Flow temperature stability	% time within +/- 5 °C of set point
		Major outages (per 100 days, over 4 hours, non-PPM)	Output temperature below Minimum Flow Temperature for more than 4 hours OR

Type	Area	KPI / metric	Calculation methodology
			Differential pressure < dwelling minimum requirement for more than 4 hours OR Any other reported issue that leads to more than 10% of end users not receiving heating or hot water for more than 4 hours.
		Energy centre VWAFT (volume weighted average flow temperature)	See Section 5.2.2
	Dwelling	Reported interruptions and reductions (per 100 dwellings per 3 month period)	Number of property issues which are determined to be caused by issues with the heat network and/or HIU commissioning. Major outages excluded
		Maintenance frequency (per 100 dwellings per 3 month period)	O&M visits to properties / total properties x 100 Major outages excluded
Financial	End user	Year 1 required heat tariff	$= \frac{\sum(p/kWh_{input\ fuel} * kWh_{input\ fuel\ delivered\ to\ energy\ centre})}{\sum kWh_{heat\ consumed\ by\ end\ connections}}$ Calculated heat tariff to be compared to current tariff
Environmental	Heat Network	Carbon intensity of heat delivered	$= \frac{\sum(kWh_{input\ fuel} * kgCO_2/kWh_{carbon\ intenstiy\ of\ fuel})}{\sum kWh_{heat\ consumed\ by\ end\ connections}}$ Unit of output metric is either gCO2 per kWh or kgCO2 per kWh

Table 3: Heat network KPIs and calculation methodology

4. Site Audits

The aim of a site audit is to determine the condition and method of operation of all elements of the heat network. This, along with information gathered from data analysis and documentation review, can then be used during the root cause analysis process to determine key issues with the system and potential interventions to resolve these (see Section 6).

4.1. H&S considerations

Operational heat networks contain several hazards which present risks to operators and those auditing a system. It is the responsibility of the network owner and operator to:

- Ensure that the selected specialist has sufficient skills, knowledge, training and experience of heat network and existing building H&S considerations to undertake a site audit.
- Make the specialist aware of all site specific hazards and mitigation measures (e.g. minimum levels of PPE, processes to follow) prior to undertaken this audit.
- Provide all relevant H&S documentation for the site (e.g. relevant H&S file(s)[3], asbestos register).

It is the responsibility of the specialist:

- To ensure that all staff involved in the project have sufficient skills, knowledge, training and experience to operate safely on site and undertake site audit activities.
- Comply with all relevant risk mitigation measures in H&S documentation and on site processes defined by the network owner and operator.
- Produce a site specific Risk Assessment and Method Statement to confirm if additional risk mitigation measures are required.
- Report all hazards identified on site if it is unclear whether the owner or operator are aware of these
    - The purpose of the site audit is not to identify all H&S issues on site, so the owner and operator should be aware that the report provided by the specialist should not be considered as exhaustive.

4.2. Key information required

Prior to the site audit, it is essential to gain as much information on the heat network as possible. This helps to support information gathered during the site audit to gain a more complete understanding of the system. System documentation is also useful in instances where it is not possible to gather all information on site (e.g. if pipework is inaccessible in ceiling voids or behind walls).

It should be noted that design and O&M information is not always accurate, particularly on older systems where equipment may have changed. The information should be verified during the site audit where possible.

The consultant should gather key system information, listed in Table 4, prior to the site audit. The information listed below is extensive and may not be fully available from the

[3] There may be multiple H&S files for the site from the site owner and the O&M contractor.

system operator. In these circumstances the site audit can still proceed, but this may impact the effectiveness of the project.

Information
Health and safety file(s) (including asbestos register, if applicable)
Site specific hazards
Energy centre, network and dwelling schematics and layouts
Equipment schedules
Accommodation schedule/number of units
Description of operations
O&M manual
Mechanical services specification
Previous energy centre equipment servicing/replacement records
Previous records of end user complaints pertaining to the heating/hot water
Any previous internal or 3rd party reports
Historical heat meter data
Gas meter data
End user heat meter consumption data
Gas price
Electricity price
BMS remote access details (if available)
Current energy centre and dwelling maintenance costs (split by PPM and reactive)

Table 4: Key heat network information required prior to the site audit

When handling personal data (such as HIU heat meter data), organisations should be cognisant of their obligations under the UK's implementation of the General Data Protection Regulation (UK GDPR) with individuals working on the optimisation study given appropriate training.

The system owner (and operator if multiple parties are involved) have extensive experience and must be consulted prior to the site audit to provide further context to site history and any issues. This time can also be used to determine the key client aims and discuss how the outputs of the assessment can be tailored to suit these.

The list of questions requiring a response from the client prior to the audit is detailed in Table 5. The client may not be able to accurately articulate their objectives, therefore the below table provides some "prompted answers" to help guide the client's response.

Question for client	Prompted follow up questions & answers
What H&S risks are present on site and require consideration during the audit?	• Are site specific H&S files available? • How is the relationship between stakeholders such as client, O&M provider and end users? • Is asbestos present?
What are your main goals for this audit?	• Improve network performance • Reduce carbon emissions • Fix existing energy centre/network problems • Ensure connectivity and metering of all network sections • Reduce operating costs • Reduce overheating • Improve end user comfort • Resolve end user complaints • Reduce end user costs • Reduce arrears in scheme
Are there any known issues with the site?	• Has the client had feedback from the O&M provider. • Are there any urgent complaints to be aware of?
What end user complaints (if any) have you received?	• Lack of heating/hot water provision (consistently) • Lack of heating/hot water provision due to maintenance • Excessive bills • Overheating of building • System leaks.
Co-attendance with maintenance/company representative required or recommended?	• Who to contact to organise access to site? • Who will organise/facilitate access to dwellings? • How to access the site? • Who has strong technical knowledge of the site?
Budget/timelines for improvements?	• Is the client aware of potential external funding streams? • Are there constraints around financial year end?

Table 5: Key questions requiring a response from the client and system operator prior to the site audit

4.3. Pre-visit analysis

Prior to the site audit, all available information, data and client feedback shall be reviewed to determine potential causes of issues with the heat network. This review can then be used to tailor the site audit and ensure all required equipment is available as required. This ensures that all key aspects of the system are reviewed, which is especially key on larger systems where it is not practical to audit 100% of the heat network.

This pre-audit review does not need to be reported and should be seen primarily as a tool to increase the effectiveness of the site audit.

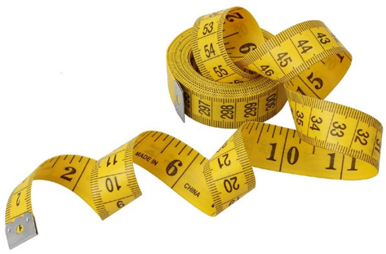
4.4. Equipment required

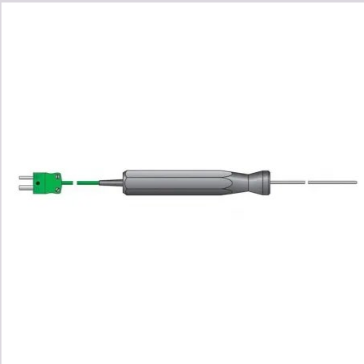
The list of equipment required during the site audit is listed in Table 6. This list is not exhaustive and the equipment relevant to a site audit should be reviewed on a site-by-site basis.

The temperatures and pressures present on heat network sites can cause significant physical harm and property damage if equipment is used incorrectly. Therefore, operatives should have experience and training on using equipment before using on a live heat network (or appropriate supervision if training is being undertaken) to ensure the safety of operatives, end users and others on site.

Secondly, if equipment is incorrectly used by untrained operatives, there is a heightened risk of inaccurate results being recorded which could negatively impact the quality of the overall project.

Equipment	Image	Uses
Thermometer		Measuring temperature of DHW outlets within dwellings.
Flow measuring cup		Allows measurement of water flowrate from outlets (e.g. hot water tap in dwelling).

Equipment	Image	Uses
Infrared temperature gun		Enables rapid measurement of heat emitter, energy centre equipment and pipework surface temperatures.
Clamp on temperature sensors		To be used to take pipe surface temperatures. Enables fast measurement of temperature differentials across different parts of heating systems.
Stopwatch		A common use is to measure domestic hot water response times for end users.
Tape measure		Measuring tool.

Equipment	Image	Uses
Callipers		Measuring tool enabling a greater degree of accuracy. Particularly useful for recording exact pipework dimensions.
Keys (as required for access to riser cupboards and access hatches)		Required keys to gain access to different locations on site will vary on a case by case basis.
Binder point temperature probe		Enables the temperature measurement of vessels and radiators. NOTE: Caution must be exercised when using invasive equipment on an operational heat network.
Water sample collection equipment		Enables the collection of water samples for initial inspection and for later testing if required. NOTE: Caution must be exercised when using invasive equipment on an operational heat network.

Equipment	Image	Uses
Differential pressure measurement kit		Enables differential pressure measurements. NOTE: Caution must be exercised when using invasive equipment on an operational heat network.
IR Camera		Enables capture of thermal imaging. Identification of high heat loss components. Temperature measurement supports quantification of heat losses. Location of pipework routing.

Table 6: Equipment required during the site audit

4.5. Minimum audit requirements

As a minimum the following areas should be audited as part of an optimisation study:

- All plant rooms/energy centres with heat generation plant.
- All substations associated the heating or hot water system.
- In exceptionally large networks this may not be possible. If the specialist deems this to be the case, an alternative approach should be agreed with the client prior to the site audit.
- In these circumstances at least 3 substations or 50% of the system (whichever is larger) should be inspected.
- If a substation is not physically audited, as a minimum operational data should be used to review performance of all substations. This should be conducted prior to the audit to identify key substations causing detrimental network performance which require further review on site.
- In domestic developments with more than one block, the communal distribution network of 3 blocks or 50% of the blocks (whichever is larger) should be inspected.

- In domestic developments, a minimum of 3 dwellings of each type should be inspected to give good understanding of dwelling heat demand. A type of dwelling is defined by the number of bedrooms/bathrooms or, type of HIU.

These requirements are a minimum, and it is imperative that consultants conduct a thorough survey of the energy centre, ensuring that all meaningful data is collected.

In larger or more complex heat networks more than one site audit may be required in order to fully understand and investigate the system. Additional audits may also be required to confirm the viability of works recommended within the initial technical review.

4.6. Key site audit activities

The recommended activities for each part of the network are detailed in the sections below.

These activities should not be considered exhaustive, as further activities will be required on all sites based on specific issues identified during the pre-visit analysis (Section 4.3 and site audit).

4.6.1. Energy centre & substations

All aspects of every energy centre and substations on a communal heating system need to be audited, as these are critical aspects of system performance and reliability.

The key activities to perform in each of these locations are detailed in Table 7.

Equipment	Measurement/data/information to collect
All equipment	Manufacturer, model & age of all equipment
	Temperature and pressure rating
	Equipment condition/estimate lifetime
	Can equipment be safely isolated, depressurised & maintained?
	Can equipment operate as per manufacturer guidance?
	Faults/error codes
	Presence, location and rating of safety relief valves
	Proximity of LTHW, HWS (if relevant) and BCWS systems
Heat generation equipment	Control mode & set points
	Is all heat generation equipment operational?
	Hydraulic arrangement
	Presence of thermal storage/low loss header/DHW calorifiers
	Evidence of flue corrosion

Equipment	Measurement/data/information to collect
Pumps	Are pumps capable of variable speed operation?
	Pump use case (BCWS, DHWS, recirculation).
	Control mode & set points
	Hydraulic arrangement
	Differential pressure across each pump
Pressurisation unit & expansion vessels	Set point
	Location of connection to energy centre
	Presence of isolation valves on pipework serving units
	Evidence of current or historic leaks
	Presence of leak detection and method of reporting
Water quality equipment	Presence and location of equipment
	Evidence of historic maintenance & water quality
	Visual water quality sample
Heat exchangers	Co-current or counter-current installation
	Presence and location of control valves
	Control mode & set points
BMS	Ability to interrogate unit (e.g. password requirements)
	Functionality of lamps & switches
	Confirm presence of remote monitoring of meters and sensors
Heat meters	Location
	Live system operating parameters
	Compliance with Regulations
Pipework	Material & size
	Evidence of pipework corrosion
Insulation	Material & thickness
	Coverage & damage
Temperatures	Operating temperatures at key locations
	Ambient temperatures within energy centre

Table 7: Key activities to perform within energy centres and substations during the site audit

4.6.2. Network

To gain a representative understanding of the network installation, commissioning and condition, 3 blocks or 50% of the system (whichever is larger) should be inspected. A sufficient portion of the accessible riser and lateral pipework should be audited within each of these blocks to gain a full understanding of the network.

This requirement applies for each part of the system where the installation is known to be different. If it is not known whether the installation varies between buildings, this should be investigated sufficiently until an answer can be determined.

The key activities to perform in each block where the network is inspected are detailed in Table 8.

Network location	Measurement/data/information to collect
All locations	Pipework material & size
	Pipework & ancillary equipment pressure and temperature rating
	Pipework and ancillary equipment condition
	Presence and specification of pipework expansion and support equipment
	Insulation material & thickness
	Insulation coverage & damage
	Evidence of leaks & corrosion
	Isolation valve locations
	Commissioning valve locations & settings
	Presence, location and specification of differential pressure sensors
	Proximity of LTHW, DHWS (in four pipe systems) and BCWS systems
	Number of floors/ height hydraulic system
	Hydraulic layout/schematic (connections between blocks, no. risers, no. flats per riser)
	Presence of any sub-metering
Top of riser	Presence and type of bypass or recirculation (in DHWS)
	Presence and specification of air vents
Base of riser/ building entry	Presence and location of heat meters
	Compliance with regs
	Presence and type of bypass
Laterals	Presence and type of end of lateral bypass
Temperatures	Operating temperatures at key locations

Network location	Measurement/data/information to collect
	Ambient temperatures within corridors and riser cupboards

Table 8: Key activities to perform when inspecting the network during the site audit

4.6.3. Dwelling

To gain a representative understanding of the dwelling system installation, commissioning and condition, a minimum of 3 dwellings of each type should be inspected.

A dwelling type is defined by:

- The HIU (or equivalent alternative) model
- Building design (where there are significant differences between blocks)
- Design heating system supply characteristics (for example underfloor heating vs radiators).
- Variation in other dwelling system characteristics with a major impact on operation.

This requirement applies for each part of the system where the installation is known to be different. If it is not known whether the installation varies throughout the network, this should be investigated sufficiently until an answer can be determined.

The key activities to perform in each block where the network is inspected are detailed in Table 9.

Location	Measurement/data/information to collect
All equipment (Pipework, HIU, valves, insulation and ancillaries)	Review pressure rating, temperature rating and condition of all equipment.
The HIU cupboard – installation	Pipework material & size
	Insulation material, thickness, coverage, condition and compliance with BS 5422
	Evidence of leaks & corrosion
	Isolation valve location
	Cupboard dimensions and accessibility
HIU – design	Type of HIU and connections (i.e. Direct or indirect space heating circuits, two pipe or four pipe heating system, cylinder or instantaneous hot water provision).
	Temperature, pressure and differential pressure rating of HIU (including specification of all temperature and differential pressure control valves)
	Presence and type of bypasses within or above unit
Metering	Presence, specification and operation of heat meter and billing system

Location	Measurement/data/information to collect
	Presence and specification of prepayment system
HIU performance – standby mode	Operating temperatures and flow rate through unit
	Components of HIU contributing to standby performance
HIU & dwelling performance – DHW mode	Time to deliver 45 °C at the kitchen tap and stabilised temperature Stabilised maximum bath temperature
	Hot and cold water flow rate at all outlets
	Operating temperatures and flow rate through unit
	Size and specification of hot water cylinders (if relevant)
Space heating system	Type of space heating system
	(If relevant) Size and specification of all radiators Radiator valve specification
	(If relevant) Model of UFH manifold, flow gauges and actuators. Presence and model of mixing pump, valves and protection device.
	Space heating pipework size and arrangement
	Size of all rooms
	Heat emitter balancing
	Operating temperatures and flow rate through unit

Table 9: Key activities to perform when inspecting each dwelling during the site audit

5. Baseline technical analysis

5.1. Aims

The documentation review and site audit are essential steps in identifying issues with a heat network. However, these activities provide little information with regards to historic performance. Therefore, as much performance data as available should be collated and reviewed to enable a more complete picture of system behaviour to be created. Where data is not available, there are also standard modelling techniques which can be used for this purpose. Key data analysis and modelling techniques to be used when analysing current system performance are outlined in the section below.

This analysis also establishes a baseline that can be used to model the impact of potential interventions during this stage of the optimisation assessment (see Section 6).

5.2. Using heat meter data

The conclusions that can be drawn from heat meter data analysis increase in number and certainty as the quality, frequency and amount of data available increases.

If there is opportunity to increase any of these factors prior to or during the optimisation study process (e.g. change AMR frequency from 30 minutes to 5 minutes or retrofit block level heat meters), then this should be strongly considered.

5.2.1. Live data review

By using live heat meter data (or reviewing a period of heating system operation) appropriately causes of poor network performance can be diagnosed.

Common conclusions which can be drawn from heat meter data are shown in Table 10. Note this list is not exhaustive and many more causes of poor network performance can be diagnosed from heat meter data.

Heat meter location	Heat meter data shows:	Potential Causes	Potential remedial works
HIU heat meter	High standby flow rates through HIU HIU return temperatures close to network flow temperature	HIU is bypassing (i.e. letting excessive flow through when on standby) Issue with HIU design, control, commissioning or maintenance causing a major bypass Faulty components within HIU	Repair HIU Recommissioning HIU HIU replacement
HIU heat meter	Low return temperature when DHW draw off occurs High return temperature and	Poor heating circuit commissioning. Space heating circuit flow rates are too high, for example if	Recommissioning space heating circuits. Replacing radiator valves with pressure independent

Heat meter location	Heat meter data shows:	Potential Causes	Potential remedial works
	flow rate when space heating is used.	radiators have not been commissioned correctly.	thermostatic radiator valves (PTIRVs)
HIU and Bulk Heat Meter	HIU standby flow rates relatively low. Network flow rates constantly high. High network return temperatures.	Network bypass – part of the network allowing water to flow directly from flow pipework to into return pipework.	Eliminate bypasses, preferably in such a way where operatives can't reintroduce the bypass at a later stage. Consider minimum pump flow rate requirements
HIU or Bulk Heat Meter	Flow temperature instability when heat load is consistent.	Poor energy centre control. Heat generation or distribution equipment is cycling.	Review energy centre control strategy and ensure equipment is sized appropriately.

Table 10: Common examples of how heat meter data can be utilised.

Heat meter data can identify potential causes of poor system performance, and therefore can used to determine where interventions are (or are not) required. Heat meter data can also be uses to support the selection of an appropriate intervention.

For example if a review of HIU heat meter data reveals that only a few HIUs have poorly commissioned space heating circuits then it may be appropriate to recommission the heating systems in these flats only, whereas if poorly commissioned space heating circuits are present in the majority of flats a programme of replacing radiator valves for Pressure Independent Thermostatic Radiator Valves (PITRVs) may be more appropriate. Where multiple interventions may be suitable, heat meter data can be used to inform modelling and financial analysis to support one intervention over another (discussed further in Section 6).

5.2.2. Volume weighted average temperature analysis

When analysing temperature data, volume weighted methodology shall be used rather than average temperature data, as large flow rate events have much larger impacts on overall system temperatures than low flow rate events.

To calculate a volume weighted average flow temperature (VWAFT) or return temperature (VWART), the following equation shall be used:

$$VWAT = \frac{\sum(T_t \times Q_t)}{\sum Q_t}$$

Where T is the measured temperature, Q is the measured flow rate and t is the time increment.

Ideally, data from the preceding 12 months should be used to give a full indication of annual and seasonal performance. If more data is available that this, then further analysis can be used to indicate changes in performance over time. If less data is available than this, this can still be used but any analysis should consider that the contribution of performance during heating and non-heating seasons will not be evenly represented. Further guidance on seasonal volume weighted average temperature (VWAT) analysis is detailed in Section 5.2.2.1.

The time increment of the data used in the calculations shall be stated in the report and be as short as possible. Once the time period between reads is greater than 30 minutes, the calculated VWAT may no longer be representative of system performance as there is insufficient granularity to measure the impact of HIU performance across different modes of operation. Data of this granularity can be used to indicate the rate of bypass though end units, but it is not possible to draw any further conclusions on performance based on this.

5.2.2.1. Seasonal analysis

In addition to annual VWAT analysis, seasonal analysis can also be used to provide further insight into performance during heating and non-heating seasons.

The heating season should be defined based on ambient temperatures over the last year, with a suitable period being selected to capture peak space heating use.

Similarly, the non-heating season should also be defined based on ambient temperatures over the last year, with a suitable period being selected to avoid capturing space heating use.

5.2.3. Flow rate analysis

Flow rates measured throughout the heat network via heat meters can provide key insights into end unit performance and bypass flow rates.

The flow rate calculations and analyses to be performed if data is available are detailed in the sections below.

5.2.3.1. Network bypass flow rate

A network bypass flow rate is a volume of network flow which does not pass through an individual HIU and is therefore circulated around the network without any useful heat being extracted for use within the dwelling.

If block level and dwelling flow rate data is available, the rate of bypass throughout the network can be calculated using the following equation:

$$Bypass\ flow\ rate = Network\ flow\ rate - \sum Dwelling\ flow\ rate\ downstream\ of\ network\ meter$$

There should be 0 l/s bypass flow rate through a well performing system (i.e. all network flow is to serve terminal unit demand requirements). If the calculation shows that bypasses are present on the network, these should be located and reviewed during the site audit. Typically this calculation should be undertaken over a period of time since instantaneous fluctuations in bypass flow rate can be significant.

5.2.3.2. Dwelling flow rate analysis

Analysis of average flow rates through a terminal units can provide a good indication into sitewide performance and the extent of any issues present. When taken over an extended period of time, the average dwelling flow rate is primarily an indicator of standby performance as HIUs are typically in standby mode for 85 % of the year[4], but is also influenced by performance during DHW and space heating mode.

To understand and visualise the range of average flow rates through terminal units on a system, these can be presented on a Pareto curve with cumulative average flow rate on the y axis against number of dwellings on the x axis. An example of this is shown in Figure 19, which shows that 10 dwellings on the network, approximately 16% of the total number of dwellings in this case, account for over 60% of the total cumulative flow across the network.

This implies that a small amount of targeted remedial action could present good value for money, as well as have a large impact on overall network performance.

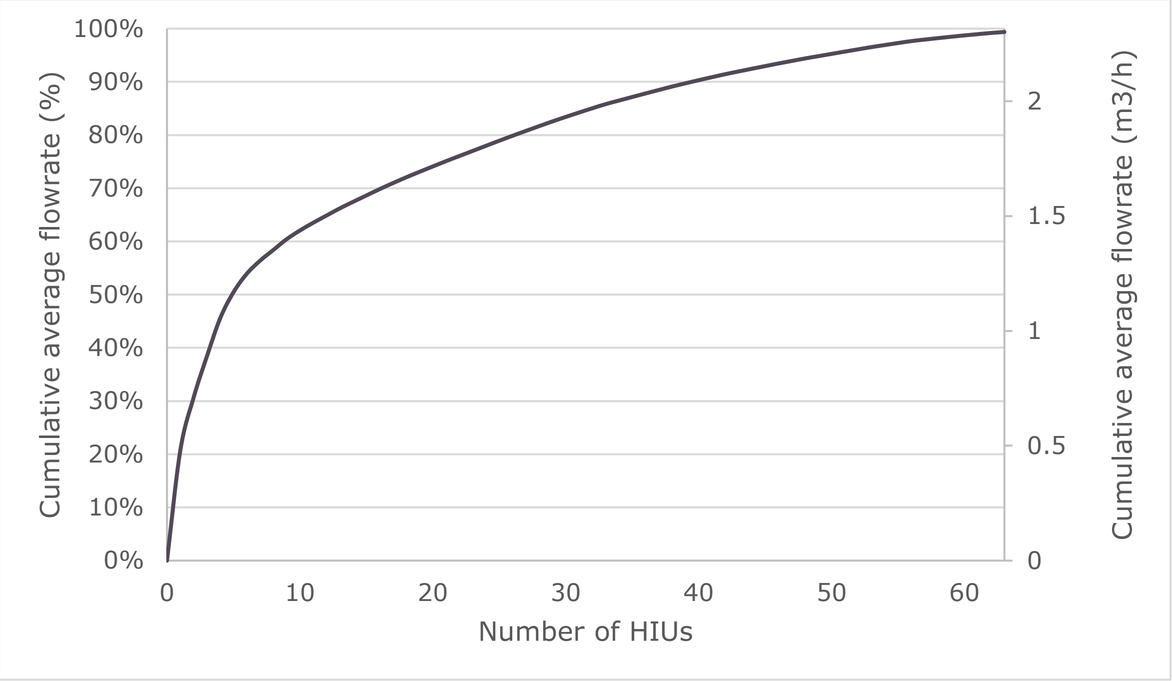


Figure 19: Example Pareto curve

Typical trends and resulting conclusions which can be drawn from a Pareto curve are shown in Table 11.

[4] Based on FairHeat SBRI VWART calculation for typical HIU, March 2016

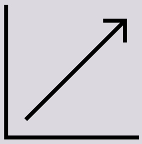
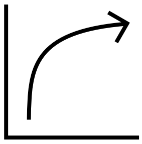
Graph trend	Potential conclusions
Linear trend 	Consistent performance of all HIUs on site. Gradient of trend provides information on whether performance is good or bad.
Logarithmic trend 	Variation in HIU commissioning, maintenance, and design (if multiple phases) throughout the system. Small number of units have a large impact on overall system performance. Targeted remedial action can present good value for money for system improvements. Example shown in Figure 19.

Table 11: Drawing conclusions from a Pareto curve

5.3. Heat loss modelling

The largest source of inefficiency within a heat network is heat loss from distribution pipework. As such, heat loss modelling is required to quantify network heat losses for the current network and the future network following the implementation of interventions. The energy savings from reducing heat losses will eventually feed into the business case used to justify heat network interventions.

5.3.1. Key inputs

The key inputs for a heat loss model are detailed in Table 12. It is expected that a majority of the inputs requiring on site observations only (e.g. pipe or insulation material) should be achievable in a large majority of site audits, with the exception of pipework installed underground where more assumptions may be required.

Input	Calculation methodology preferences
Flow temperature	1. Historic heat meter data 2. On site heat meter reads 3. Measurements via temperature probe
Return temperature	1. Historic heat meter data 2. On site heat meter reads 3. Measurements via temperature probe
Pipe size	1. On site measurements 2. Schematics
Pipe length	1. On site measurements 2. Length measured on layout drawings 3. Length of assumed route measured on a map

Input	Calculation methodology preferences
Pipe material	1. On site observations 2. Design information
Insulation material, thickness, and coverage	1. On site observations 2. Design information
Terminal unit standing losses	1. Temperature specific manufacturer testing data 2. Pipework modelled & PHE losses based on temperature specific manufacturer testing data
Ambient temperature	1. Historic temperature sensor data 2. On site observations

Table 12: Heat loss model inputs

5.3.2. Methodology

5.3.2.1. Initial modelling

The approach to calculating heat losses from a pipe is standardised in ISO 12241. A scheme specific heat loss model shall be created to model baseline heat losses, and this model can also then be used to model the impact of interventions. It should be noted that there are free online tool available to assist with creating a model.

To ensure model accuracy, the impact of different dwelling and commercial end consumer types and bypasses throughout the network needs to be incorporated. The relative impact of these will vary at different points based on the overall volume weighted operating temperatures of each item.

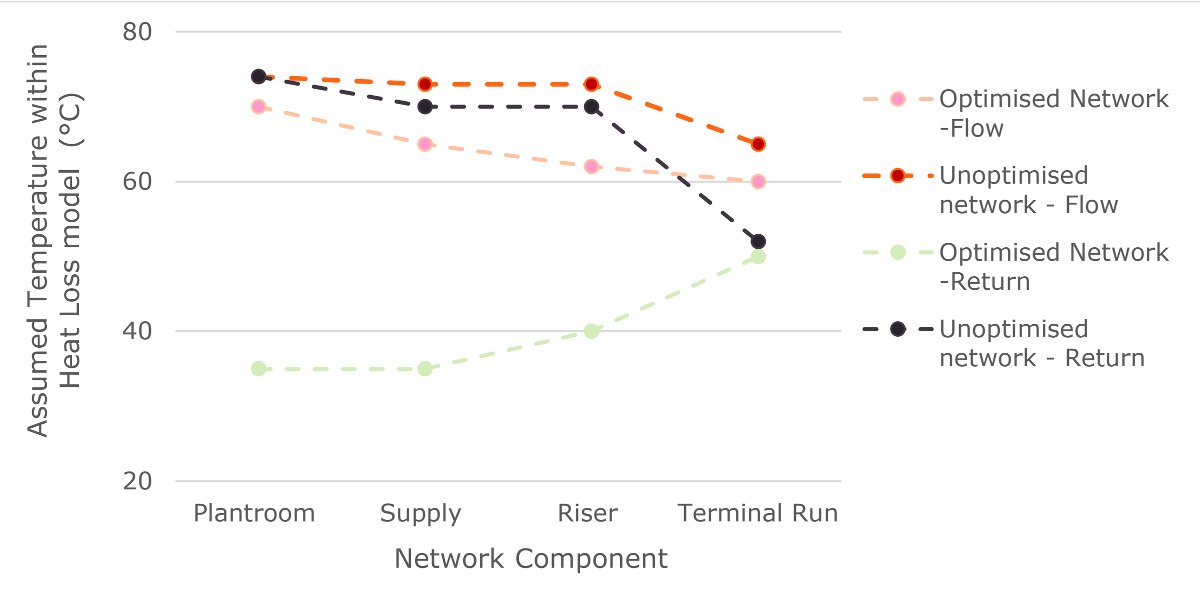


Figure 20: Graphic showing example variation in average operating temperatures for an optimised network against an unoptimised network of a heat network. Figures are notional and should not be considered as reference values.

Varying seasonal operating conditions shall also be incorporated into the heat loss model if appropriate for the system (e.g. if weather compensation has been implemented). This must be applied for all operating temperatures and should also be applied to ambient temperatures if data is available.

Both these items are also essential features to be able to accurately model the impacts of interventions to heat losses.

5.3.2.2. Model validation

Once the model has been created, it should be verified with system data as far as possible to ensure the model is accurate. Heat losses can be calculated using system data using the following formula:

$$kW_{Heat\ losses} = \frac{kWh_{Heat\ generated} - kWh_{Heat\ consumed}}{Hours}$$

If data is available, this calculation should be performed over the 12 previous months to verify the model. If more data is available, heat losses should be compared overall years that they can be accurately calculated to identify any trends and provide further model validation. If data is not available over this time period, as much data as available should be used with the limitations of this calculation highlighted within the end deliverable.

The preferred calculation methodology for the kWh inputs in this equation is detailed in Table 13.

Input	Calculation methodology preferences
$kWh_{Heat\ generated}$	1. Heat generation equipment heat meter readings 2. Gas/electricity meter readings with assumptions on generation efficiency
$kWh_{Heat\ consumed}$	1. Heat meter readings from all end consumers 2. Heat meter readings from a majority of end consumers. Missing readings assumed to be equal to median consumption 3. Standard dwelling heat consumption figures assumed or calculated by consultant. Typical values for modern high-rise residential block in London would be c.2,920kWh per year (BESA HIU Test Regime, 2018). When using theoretical or benchmark values assumptions should be clearly justified and reference established industry documents such as the BISRIA HIU Test Regime Standard or SAP calculations. Note the assumed/calculated heat demand should account for the fabric of the building, number of bathrooms per dwelling and number of occupants per dwelling.

Table 13: Calculation methodology for system heat generation and consumption

The primary purpose of the validation model is to give confidence in the outputs of the initial heat loss model. In some sites data may not be available to undertake validation. In these circumstances the limitations of the modelling must be highlighted to the client.

5.3.3. Presenting outputs

The following information shall be provided as a minimum when presenting the outputs of the heat loss model:

- Total system heat losses (in kWh/annum, kW, kWh/annum/dwelling & W/dwelling)
- Breakdown of heat losses between flow and return pipework
- Breakdown of heat losses from the different sections of the network including:
    - Energy centre, pipework (and plant) within the energy centre;
    - District distribution pipework, pipework from the energy centre to the entry point to at each building;
    - Communal distribution pipework, including:
        - Riser pipework, vertical pipework between floors;
        - Lateral pipework, horizontal pipework in corridors from riser cupboards to dwelling entry;
        - Terminal run pipework, the final run of pipework serving only one dwelling
- Breakdown of losses between buildings (if there is a notable difference throughout the system due to scheme size and performance)
- All inputs and assumptions

The outputs shall be presented in table format and graphically to enable ease of interpretation. There are several options for representing these results graphically, but it is recommended that a Mekko chart is used as this also enables clear comparison between the base case and potential interventions. An example of this is shown in Figure 21.

The outputs shall also be compared to benchmark heat losses for well performing systems. For example, CIBSE CP1 2020 states that residential heat network losses should be less than 100 W/dwelling, excluding the heat loss that is measurable by the dwelling heat meter (which is due to HIU keep warm operation and should be less than c.40 W/dwelling).

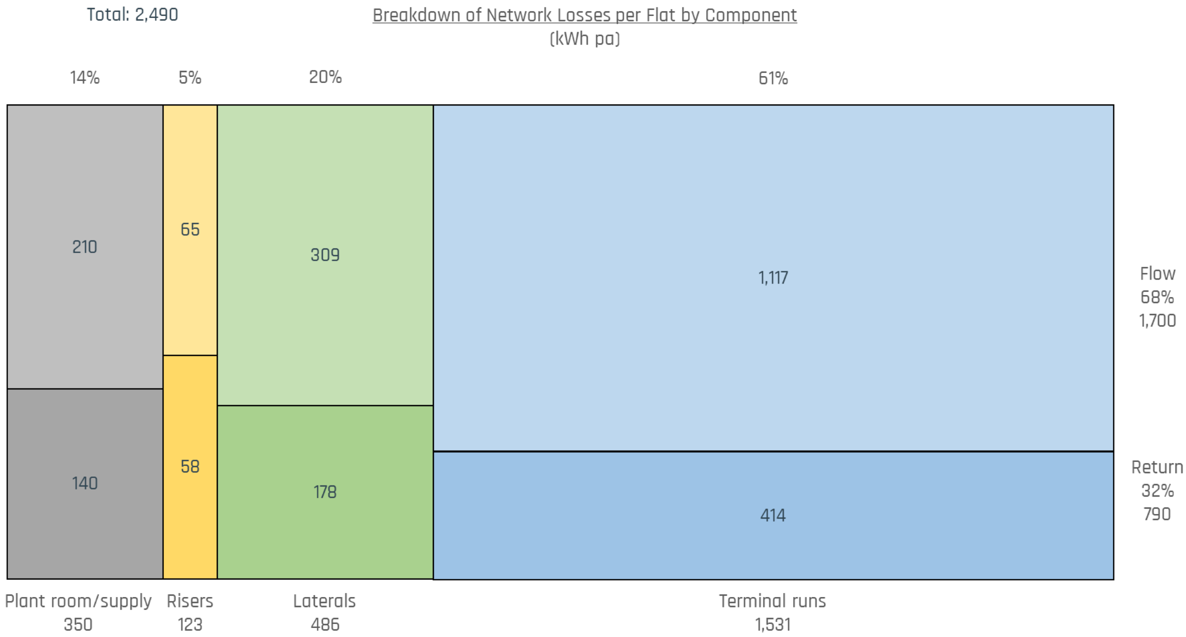


Figure 21: Example Mekko chart presenting outputs of a pre-project heat loss model

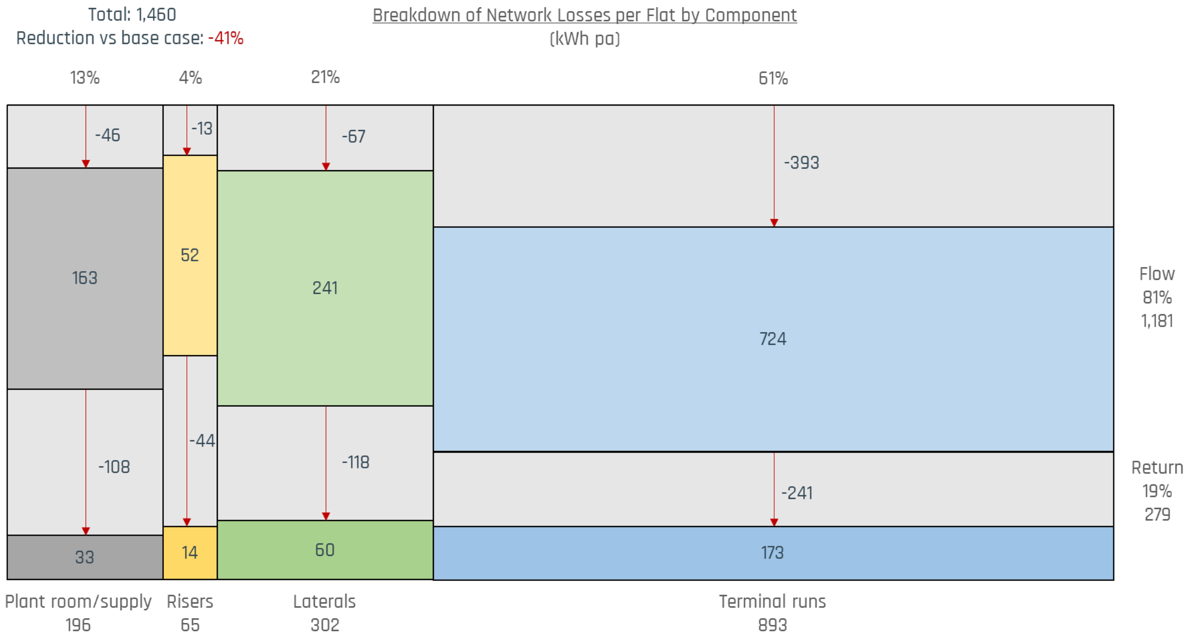


Figure 22: Example Mekko chart showing possible reduction in heat losses as a result of optimisation works

5.4. Pump energy

Pump energy is the main source of ancillary electricity consumption on a heat network and is also the most influenced by network performance. Pump energy consumption therefore needs to be considered when modelling current network operation.

5.4.1. Types of operation

Pumps on a heat network typically have one of the following usage characteristics:

- Variable speed
    - Typical for network distribution pumps under control on a system operating with variable flow
    - Variations in pump energy consumption with flow rate throughout the year which need to be considered
- Fixed speed
    - Typical for pumps set to 'hand' operation, network pumps on a system with multiple bypasses or energy centre circulation pumps
    - Minor variations in power consumption over time so can be assumed to be constant
- On/off
    - Typical for heat generation equipment shunt pumps
    - Operates at fixed speed when operational but controls only sequence pump online when required

5.4.2. Calculating electricity consumption

For many modern pumps, current and historic pump electricity consumption can be determined from the pump software or via the BMS. If this data is available, it should be prioritised over electricity consumption calculations during the baseline technical analysis.

If pump energy needs to be calculated, this can be performed using the following equation for a pump operating at fixed speed:

$$Pump\ energy = Pump\ power\ at\ operating\ speed\ x\ Time\ pump\ is\ operational$$

For a pump operating at variable speed, the following equation is applicable:

$$Pump\ energy = \sum Pump\ power\ at\ given\ speed\ x\ Time\ pump\ is\ operational\ at\ given\ speed$$

It is not practical and often not possible to determine the time a pump spends at each speed, so these speeds can be grouped to simplify the calculation. The number of groups should be large enough to ensure the energy savings at lower pump speeds are captured, but not large enough that the calculation isn't too onerous. For example, the following brackets could be used:

- Time spent between 0-25 % of the system peak load operating point
- Time spent between 25-50 % of the system peak load operating point
- Time spent between 50-75 % of the system peak load operating point
- Time spent between 75-100 % of the system peak load operating point

An example of pump speed distribution of a heat network with good pump controls is shown in Figure 23.

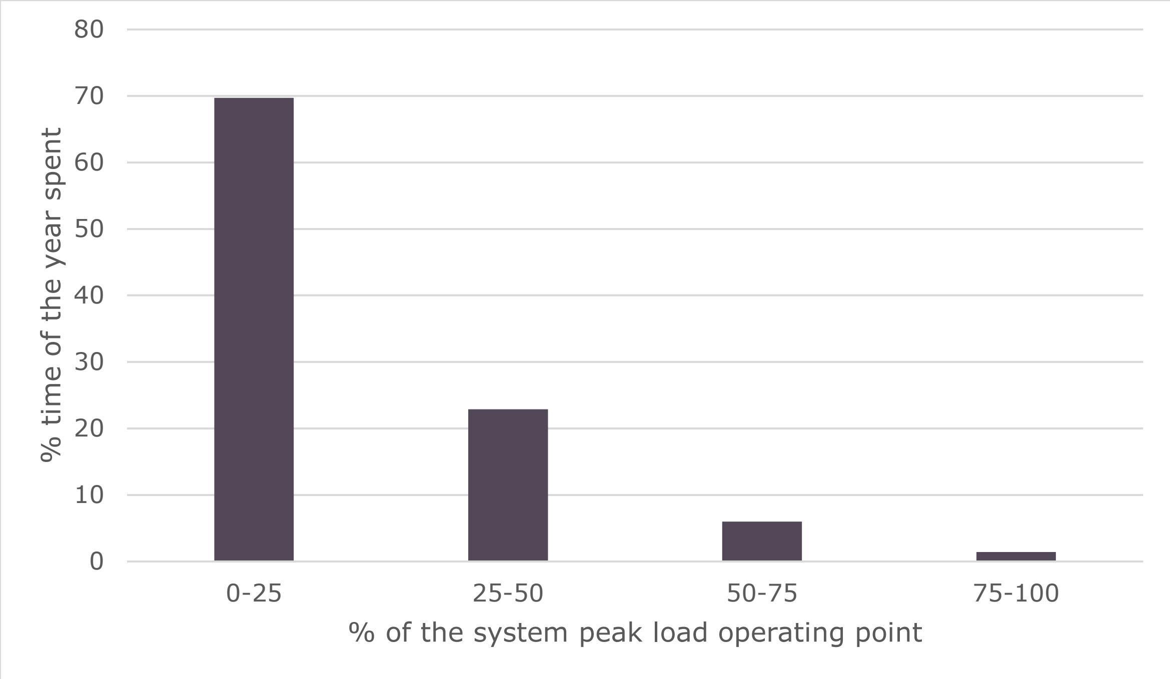


Figure 23: Example performance of a well operating pump scheme

To ensure that electricity consumption is not underestimated, pump power should be determined at the upper end of each group. In the example above, this means that power would be determined at 25, 50, 75 & 100 % of the peak load operating point.

It should be noted that where pump energy is excessive (for example due to high pump speed or oversizing), a percentage of pump electricity would be converted to thermal energy, marginally warming the network water. While this is inefficient, the energy is not entirely wasted. In best practice, this heat rejection from pumps into network water should be considered to avoid overestimating the negative impact of poor pump performance, but only if it is possible to accurately quantify this value.

6. Determining & modelling interventions

6.1. Root cause analysis

Root cause analysis is commonly used across STEM fields when investigating faults or issues and places a much greater focus on understanding the underlying causes of issues rather than just focusing on treating the issues themselves.

This process may be followed to help determine the issues causing poor performance of heat networks, which can then inform potential interventions to improve heat network performance. These business case for these interventions should then be analysed using the techniques outlined in Section 7.

The key steps to this process are:

1. Address and contain issues if required (e.g. fix leak)
2. Establish all facts and information relevant to the issue, including a timeline from normal operation to the issue occurring
3. Use knowledge of issue to establish likely causes
4. Undertake system tests to verify actual root cause(s)
5. Implement remedial action to address root cause (e.g. close bypass valve)
6. Implement preventative action to prevent recurrence of issue (design of remedial action, signage, locking of valves)
7. Implement preventative action to prevent occurrence of similar issues (applying lessons learned/training of operatives)

An example of how this can be applied to heat networks is detailed in Table 14 below.

#	Stage	Detail
-	Issue	Cold water during peak demand
1	Containment	Service end units of end users who have complained
2	Relevant facts/information	What end user equipment is installed? How many users are impacted? How are pumps and boilers controlled? Have there been historic issues with water quality? Are there any open bypasses on the system?
3	Likely causes	Localised dwelling commissioning issue Issue with differential pressure across the system due to a combination of blocked strainers/open bypasses/poor pump control Issue with control leading to a drop in network operating temperature during peak demand
4	Tests & results	Interrogate & update controls strategy

#	Stage	Detail
		Close open bypasses Clean network strainers Recommission all end units in a block with multiple complaints
5	Remedial action	e.g. bypasses identified as the root cause issue Resolve all network and dwelling bypasses across the system
6	Action to prevent recurrence	Physically remove bypasses where possible Remove or lock valve handles where not possible Affix signage to key valves to instruct operatives to not open Update O&M documentation
7	Action to prevent occurrence	Train maintenance operatives on importance of closing bypasses and how to identify open bypasses Undertake pilot dwelling recommissioning exercises and quality assurance of full servicing programme

Table 14: Example of root cause analysis application

In order to ensure that the likely causes of issues being identified through this process are root causes rather than symptoms, the '5 whys' technique can be used to thoroughly interrogate the subject. For example:

- Issue: complaints of cold water at peak load
    - Why? – Heat network flow rate through the HIU is not sufficient to meet dwelling demand
    - Why? – there is insufficient differential pressure at the dwellings impacted during peak demand
    - Why? – the network pumps are operating at full speed and cannot increase speed to meet additional demand
    - Why? – there is a high base flow rate through the system
    - Why? – because bypasses are open (root cause)

It should be noted that some issues will have multiple root causes, so this process should be repeated until all potential root causes are identified.

6.2. Dependency of interventions

The impact of potential interventions highlighted by the root cause analysis process cannot be modelled in isolation, as several of these interventions interact with each other and multiple interventions are commonly required for the benefits to be realised.

For example, in order to improve the generation efficiency of a condensing boiler, the boiler inlet temperature needs to be reduced below 55 °C. This requires the network temperatures to be reduced below this point, and the energy centre hydraulic arrangement to be reconfigured to achieve these low temperatures. Therefore, splitting a low loss header in the energy centre alone will not enable boilers to condense. This must be done in conjunction with network improvements (e.g. dwelling recommissioning and network bypass closing) for the impact to be realised.

In order to account for this complexity, only groups of interventions can be modelled as distinct 'work packages'.

In addition to dependency between interventions, the impact of interventions on system design constraints needs to be considered. The key constraints here are:

- The minimum flow temperature requires the following to be reviewed:
    - Minimum dwelling operating temperatures and forward approach temperatures throughout the system. This is impacted by:
        - Dwelling hot water set point
        - Dwelling space heating system required operating temperatures. This is dependent on:
            - Dwelling heat loss
            - Radiator output adjusted for flow temperature using an appropriate radiators manufacturer's characteristic curve as per BS EN 442
        - Presence of hydraulic breaks in dwellings and throughout the network
        - Forward approach temperature at each hydraulic break
        - Velocity constraints of fluid flow through installed pipework
        - Pump operation under proposed operating conditions
- Decommissioning/combination of equipment requires system calculations to ensure that all equipment can operate within its maximum capacity under the proposed operating conditions. This typically applies to the following activities:
    - Combination of pump sets serving separate circuits
    - Combination/decommissioning of heat exchangers. This impacts the following items:
        - Pumps
        - Pressurisation units & expansion vessels
        - Side stream filtration units
        - System operating pressures
    - Combination of pipework running in parallel

Where more extensive interventions are being made to the system, manufacturer input should be sought to provide further assurances that equipment is suitable for the proposed operating conditions.

6.3. Modelling impact on system

Once potential intervention work packages have been identified, the impact of these on the system shall be modelled. This provides a comparison of KPIs between the base case and potential optimised conditions, and also feeds in as an input to financial modelling as part of the business case (see Section 7). The key impacts to be modelled are detailed in Table 15.

Item to be modelled	Reason	Modelling methodology
Heat losses	Interventions reducing operating temperatures, increasing insulation provision or replacing end of life pipework will impact heat losses	See Section 5.3
Energy consumption	A reduction in flow and return temperatures can lead to an increase in heat distribution and generation efficiency	Manufacturer's data
Pump energy	A reduction in system flow rates and variable control of pumps reduces electricity consumption	See Section 5.4
Maintenance	Reducing wear on equipment by decreasing run hours and/or operational parameters (speeds, pressures, velocities), improving system reliability, as well as removing redundant equipment, all impact planned and reactive maintenance works. Reactive works also require operator employee time, which is time lost that could be spent on other business activities.	Analysis of maintenance logs to determine root cause of reactive maintenance requirements Assessment of changing system complexity on planned maintenance requirements
Sinking fund	Changing the amount of operational equipment on the system impacts future replacement costs	Assessment of changing system complexity on end of life equipment replacement
Carbon	Reductions in fossil fuel and electricity consumption reduce the carbon impact of the system	The Green Book (2022)
Overheating	Overheating carries a social cost to it by impacting end user comfort and even health in extreme circumstances	Multiple methodologies could be used (e.g. avoided costs of cooling or ventilation)

Item to be modelled	Reason	Modelling methodology
Air quality	The impact of local emissions from combustion of fossil fuels carries a social cost to the surrounding area	The Green Book (2022)

Table 15: Key parameters to be modelled when determining impact of potential interventions

6.4. Considerations for decarbonisation

Heat networks are not included in the list of sectors currently taxed on their operational carbon emissions. However, legislation was passed in 2019 which requires the UK greenhouse gas emissions to be brought down to net zero by 2050. Therefore, as 2050 approaches, more financial and regulatory frameworks will inevitably be put in place to push operational heat networks to decarbonise their operation.

Currently the majority of heat networks use natural gas boilers as the primary source of heat generation. To decarbonise heat networks, a new low carbon heat source will be required. In the short to medium term the following options are available:

- Install a heat pump on site
- Connect to an external heat source (i.e. a district scale heat network). These are increasingly converting to utilising industrial scale heat pumps and waste heat sources as their primary heat sources.

By using heat pumps as the primary source of heat generation (either on site or off site), a heat network would decarbonise its operation as the electricity grid continues to increase its share of renewables. As heat pumps operate more efficiently at lower output temperatures, there are several considerations which can be made now to prepare the operation of the heat network for a future installation of low carbon generation technology.

In addition to the immediate benefit of reduced heat losses from the network, investing in interventions to enable the system to operate at lower flow temperatures now, will also reduce the scope of works required in the future if retrofitting the system production with a heat pump installation.

From a perspective of preparing the system for a future heat pump installation, network flow temperature should be no higher than 65 °C to ensure compatibility with most heat pumps and to achieve the highest possible heat pump SCOP. It should be noted that some heat pumps (e.g. CO_2 heat pumps) can operate at higher flow temperatures; however, there are other constraints that must be considered such as compatibility with higher return temperatures. In any case, lowering network flow temperatures should be considered a low regrets action as ultimately it will improve system losses and supports the decarbonisation of heat.

To ensure systems are futureproofed for decarbonisation, Optimisations Studies should review the most likely route to a decarbonised heating network in a short Decarbonisation Plan. This will allow networks consider low cost, low regrets, opportunities which would support the switch to a low carbon heat source. Activities could include:

- Lowering energy centre and network flow temperature.

- Installing suitably sized blanked connections (with appropriate isolation and space allocation for a substation) to facilitate connection to an external heat network.
- Maximising thermal storage capacity on site to support the future operation of heat pumps.

By implementing these actions earlier, the long-term cost of decarbonising can be reduced and the heat network can be ready for the switch to a low carbon system once the current heat generation equipment reaches end of life.

7. Business case

7.1. Analysis techniques & standard outputs

There are two main suggested methodologies which can be used to analyse the financial impact of potential interventions: simple payback and net present value (NPV).

Simple payback for an intervention is calculated using the following formula:

$$Simple\ payback = \frac{Capital\ cost\ of\ interventions}{Year\ 1\ annual\ saving}$$

This formula is easy to interpret and communicate so should be reported in the business case.

However, the simple payback does not account for the difference in current and future value of money, especially in higher cost interventions where the payback time is longer. In order to take these factors into account, the Net Present Value (NPV) of potential interventions should also be reported.

Alongside the NPV, the Internal Rate of Return (IRR) should also be reported. The IRR is the discount rate at which NPV=0. IRR results should be sense checked following calculation, as the IRR formula can return multiple results if there are negative cashflows within the assessment period after the initial capital investment.

These metrics help to give an indication of the magnitude of savings against the cost of interventions. A high NPV or IRR indicates that large savings can be achieved for a given investment, and a low NPV or IRR indicates that low savings can be achieved for a given investment. If a negative NPV or IRR is calculated, this indicates that the sum of the discounted savings does not outweigh the initial capital cost.

7.2. Inputs to consider

7.2.1. Discount rate

The discount rate is a key input into the NPV calculation and should be specified by the network owner. The higher the discount rate, the less significance is given to future costs/savings compared to short term costs, which in the context of heat networks means that interventions need to deliver higher savings for a given investment to have a positive NPV.

Typical discount rates for key heat network owners are shown in Table 16.

Organisation type	Typical discount rate
Public sector	3.5 %[5]
Housing association	3.5 %[5]
Private developer	8-12 %

Table 16: Typical discount rates

[5] As per HM Treasury Green Book Guidance.

7.2.2. Project Lifespan

The project lifespan determines the length of time over which savings can be considered against the cost of interventions. There are several potential organisational reasons that can influence this (e.g. decarbonisation targets, maximum forecasting timescales), which should be confirmed by the heat network owner.

Project lifespan (alongside the discount rate) is key input when undertaking financial analysis since it feeds into key financial metrics such as the Net Present Value (NPV) and Internal Rate of Return (IRR). In the majority of circumstances, only measures which payback within the project lifespan will be taken forward for delivery.

7.2.3. Capital Expenditure - CAPEX

Accurate capital costs for potential interventions should be secured via contractor quotes as far as possible during the optimisation study. These quotes should be compared against costs for similar projects and industry benchmarks to ensure that costs are reasonable for the works proposed. In order to assist with contractor pricing, a pricing schedule and high level scope of works should be provided to the contractor.

Alongside contractor costs, allowance for the following project costs should also be included in the overall capital costs:

- Contractor preliminaries
- Design
- Project management (internal and external)
- Quality assurance
- Updates to O&M documentation
- Applicable surveys (e.g. asbestos & structural)
- Builders work (e.g. firestopping, removing and replacing ceilings)
- Contractor OH&P
- Procurement (including legal fees, framework costs, professional fees for tender development)
- Engineering support and quality assurance
- Contingency
- Risk
- Optimism Bias (if appropriate depending on project scope and complexity)

These costs will be impacted by the selected procurement route for the works and availability of suitable internal resource. Therefore, these factors should be discussed the network owner/operator when calculating the overall project CAPEX to ensure they are accounted for accurately.

7.2.4. Operating Expenditure - OPEX

The information listed in Table 17 is required in order to apply a financial value to the key operating parameters in Table 15. Financial model inputs should be discussed with the network owner to confirm alignment with their own working practices. For example, organisations will commonly have different approaches to modelling indirect costs depending on their strategic objectives (see Section 7.2.6 for further discussion).

Input	Reason
Cost of energy	To apply a cost to heat generation and pump energy
Cost of O&M	To determine the impact of improving reliability/removing equipment on O&M costs PPM and reactive maintenance costs should be used if available
Cost of operational carbon	To apply a financial value to the operational carbon emissions
Cost of overheating	To apply a financial value to overheating caused by the heat network
Air quality costs	To apply a financial value to the impact of combustion on local air quality
Embodied carbon	Premature replacement of equipment or installation of additional equipment increases the embodied carbon of the system

Table 17: Operating costs to be modelled

7.2.5. Replacement Expenditure - REPEX

For larger plant items, such as boilers pumps and HIUs periodic replacement is required as plant reaches the end of its economically viable life. The replacement expenditure (REPEX) associated with these items are usually relatively large compared to regular O&M activities but occur infrequently. For example, boilers have an economic life of c.20 years.

The technical and financial impact of replacing end of life equipment within the project lifespan requires consideration. It is important to fully define the required end of life works within the base case and each work package. This is to ensure fair comparison of the base case and each work package.

For example, if it is proposed to replace end of life cylinders for HIUs in a work package, then the assumed base case end of life replacement would be a like for like cylinder replacement, whereas replacements in work packages would be for new HIUs.

Alternatively, if the cylinders were ten years from end of life. The base case scenario would need to account for the cost of like for like cylinder replacement in year 10 of the financial model. This can be modelled by using a CAPEX cost and adjusting appropriately for the discount rate.

Replacing end of life plant may also impact operating costs by impacting the factors in Table 15, which should be considered on a case by case basis.

It should be noted that only the replacement of equipment that impacts operating costs needs to be modelled, as all other costs will incur the same cost in the modelling of all options.

7.2.6. Direct and indirect costs

Section 7.2.4 details the key operating costs which can be modelled on a heat network. However, not all these costs are direct costs i.e. items which incur an actual financial cost. For example, the cost of carbon, overheating and air quality do not represent an actual cost, but are indirect costs which are used to express the operational impact in financial terms.

The heat network owner may prefer to evaluate work packages based upon an NPV calculation which includes indirect costs (referred to as social costs in HM Treasury The Green Book (2022)). This is to ensure that their projects are maximising both social and financial outcomes.

The preferred financial KPIs should be agreed with the network owner and should always be reported as part of the optimisation study.

It should also be noted that a majority of the direct costs modelled are not typically incurred by the network owner, as energy and maintenance costs are passed on to end users. The owner will typically only start incurring costs when operating costs are so large that subsidies are required to end user payments to cover total costs. Therefore, the owner may wish to perform additional analysis comparing the reduction of subsidised costs only against the cost of interventions.

7.3. Risk items

There are several potential interventions that do not have a direct impact on performance but reduce operational risk. Key examples of this are installation of water quality equipment, resolving issues with pipework expansion and mitigating system pressure risks.

7.3.1. Risk Identification

As part of the Optimisation study an appropriate risk register can support the identification and evaluation of risk items. A risk register will typically consider the likelihood, proximity and impact of a given risk occurring. The impact of a risk occurring can be measured both financially and non-financial metrics (such as days of system downtime or reputational damage).

This allows the identification of high likelihood and high impact risks which should be mitigated urgently.

7.3.2. Risk mitigation

Identified risks can often be mitigated to reduce either the likelihood or impact of a risk occurring. Some common high impact risks and potential mitigation measures associated with heat networks are identified in Table 18 below.

The interventions required to mitigate operational risk typically do not have a performance payback. However, they do serve to reduce system outages, the risk of premature system failure and reduce the H&S risk on site.

The benefit of undertaking risk mitigation activities can be modelled using NPV analysis. For example, improving system water quality could extend network component lifespan and would reduces the equivalent annualised replacement costs (since the cost of replacing plant is spread over a longer period of time). This REPEX saving can be compared against the cost of improving and maintaining system water quality to justify investment.

It is often not appropriate to do this alongside performance modelling due to the uncertainties around impact to system lifespan and the costs associated with system failure.

For example, improving system water quality will likely increase the lifespan of pipework, and reduce long term replacement costs. In contrast, upgrading pipework insulation will certainly reduce heat loss if installed correctly, reducing system fuel costs.

For this reason, it is typically clearer to report the costs and benefits of risk mitigation activities separately to the performance NPV modelling.

Some interventions, for example where there are significant H&S risks to be mitigated, will need to be delivered regardless of project business case. The specialist should highlight all essential risk mitigation measures as part of the project deliverables.

Regardless of how risk items are presented, it should be confirmed which mitigation measures must be implemented in order for performance modelling assumptions to be realistic. For example, if major risks to system lifespan are identified, it should be clarified that the modelling and payback of any performance works assumes these risks have been sufficiently mitigated.

Risk	Potential impacts	Potential Mitigation
Access	Inaccessible equipment cannot be suitably maintained which could lead to premature plant failure and prolonged system outages. Poor energy centre access increases complexity of reactive maintenance works and equipment replacement.	Review replacement strategy for existing (and proposed plant).
Asbestos	H&S risk to residents and operatives. Control of asbestos risk a legal duty under the Health and Safety Executive.	Ensure site management adheres to duties outlined under the Control of Asbestos Regulations 2012. Engage with asbestos specialists to review risk and provide recommendations on mitigation measures.
Fire	H&S risk to residents and operatives.	Engage with fire specialist to review risk and provide recommendations on mitigation measures.
Flue & Ventilation	Failure of energy centre components (flues, gas pipework, heat pump) can result in noxious and flammable gases (including heat pump refrigerants) being released into the energy centre.	Review of energy centre ventilation requirements and strategy. Specialist equipment review where required
Legionella	Legionella bacteria can form in stagnant parts of heating systems which are maintained at between	Specific action depends on cause of Legionella risk. Broadly, it should be ensured the system adheres to relevant HSE guidance

Risk	Potential impacts	Potential Mitigation
	20–45 °C for extended periods of time. H&S risk to residents and operatives. Control of Legionella risk a legal duty under the Health and Safety Executive.	such as the Approved Code of Practice L8.
Mould	Can contribute to/exacerbate mould issues within buildings.	Ensure adequate monitoring of system leaks.
Pipework failure	Exposes residents and operatives to potentially high pressure and temperature water. Can result in severe leaks and/or prolonged system downtime.	Proactive replacement of pipework.
Refrigerants	Each refrigerant type has associated risks to resident and/or operative H&S and system operation	Undertake a refrigerant specific risk assessment
Scald/burn	High DHW temperatures can cause scalding to the end user.	Ensure TMV's are installed on bath outlets and ensure HIUs are correctly commissioned
System Pressure	Excess pressure: Component failure, H&S risk to residents and operatives and/or system shutdowns. Low system pressure: air drawn into system. Top of riser flats not receiving adequate heat.	Ensure all components are operating below their rated pressure. Ensure system pressures has been set appropriately.
Water quality	Premature deterioration and failure of network components.	Install appropriate water quality monitoring and control.

Table 18: Key risk areas. Note this list is not exhaustive and other risk items may be encountered.

7.4. Interpreting outputs

All modelled interventions that provide a positive NPV represent a net profit, while ones with a negative NPV represent a net loss. If interventions have a positive NPV and an IRR that is equal to or above the selected discount rate, this technically represents a favourable investment as the savings over the project lifespan are larger than the owner's requested rate of payback.

The option with the largest NPV may not necessarily have the largest IRR as low-cost options can address the simplest interventions and provide a quick payback, which may not be matched by more extensive interventions despite these offering the largest overall improvement to operating costs.

In addition to the financial impact, the impact to end users should also be considered when interpreting model outputs. For example, an option with a slightly lower financial benefit but greater reduction in cost of heat may be preferable depending on the owner's objectives.

7.4.1. Sensitivity analysis

The inputs into the business case all rely on underlying assumptions, meaning there is uncertainty within the outputs, especially as the modelled project length increases. As such, sensitivity analysis shall be carried out to provide further understanding on the impact of this uncertainty. The key inputs this should be carried out for as a minimum are:

- Capital costs
- Discount rate
- Fuel cost
- Electricity cost
- Carbon cost (if applicable)
- Overheating cost (if applicable)
- Air quality cost (if applicable)

7.5. Delivery plan

The analysis within the Optimisation study will aid understanding of the underlying issues with a network and support the development of potential work packages (considering the dependency of interventions). The Business Case also needs to consider how to procure and deliver upgrades.

A delivery plan should be developed to confirm the potential packages of work required to optimise network performance. The delivery plan should propose a phasing/grouping of works depending on a number of factors, including:

- **Following the principles for improving network performance**. As discussed in Section 1.3.2, heat network improvement works are typically phase in the following steps:
- Stabilizing actions may be required immediately to rectify or avoid heat network failure. For example, the optimisation study may identify failed plant which is contributing to poor network performance.
- Easy wins should be pursued following network stabilisation, since these interventions will offer fast improvements in performance for limited cost
- Continuous improvement of networks will occur in the medium to long term and will be implemented to gradually improve network performance.
- **Availability of funding:** The delivery of interventions will depend on the availability of internal or external (such as grants) funding. As such, high cost activities may need to be delayed until funds are available.
- **Procurement:** Each organisation will have its own procurement routes and frameworks, which will impact how it can engage both consultant and contractors to deliver projects. For example, some organisations may be able to directly award

projects directly to their existing supply chain, whereas some will have to undertake a more formal tender and procurement process.

- **Lifecycle considerations:** Should plant be reaching the end of economic life, there may be opportunities deliver multiple related interventions simultaneously.
- **Portfolio planning:** Commonly heat network operators are responsible for multiple sites, as such the delivery plan for a given site may need to factor in the value of the proposed works within the wider portfolio of heat networks. For example, it may be preferable to pilot the efficacy of a specific intervention on a single site before rolling out the intervention across a wider portfolio of buildings or networks. Alternatively work packages may be scheduled to prioritise sites requiring stabilization works or which have a larger number of easy wins.

The formation of the delivery plan will require close co-operation between client and consultant due to the mixture of technical and organisational input required.

8. Typical failure states

An extensive review of New Build projects (20+) and operational heat networks (40+) has been undertaken to identify key failures which occur during the lifecycle of heat network development. These are categorised into 16 key failure themes, as outlined in Table 19.

Number	Key failure theme
1	Insufficient consideration of heat network requirements at concept design stage
2	Incorrect sizing
3	Unnecessary complexity
4	Unsuitable hydraulic arrangement
5	Poor insulation specification and installation
6	Poor planning and civil works for underground pipework
7	Poor underground pipework installation
8	Insufficient monitoring and data collection
9	Inappropriate design and commissioning of consumer connection and/or heat system
10	Lack of consideration to system pressures
11	Lack of consideration to maintainability
12	Poor installation and commissioning practices
13	Inefficient control
14	Uncontrolled network flows
15	High return temperatures
16	Poor water quality

Table 19: Summary of key failure categories

Within each category, the key failures are detailed in Table 20 alongside their:

- Frequency
- Impact
- Ability to optimise on an operational network
- Cost to optimise on an operational network
- Analysis of underground pipework failures is not detailed in this section, as this is typically not assessed during optimisation studies as it cannot be accessed and any measures are highly likely to be cost and disruption prohibitive. If issues regarding underground pipework integrity or reliability are suspected, this should be investigated separately with an underground pipework specialist.

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
1	Lack of architectural consideration for the following: 1. Spatial requirements within risers and corridors to ensure insulation requirements 2. Building / floor plate layouts to accommodate multi-riser communal distribution networks	High	High	Low	Very high
1	No network routing assessment undertaken to minimise pipework length	High	High	Low	Very high
1	Inappropriate selection of network temperature profile	High	High	Medium	Medium – very high
1	Spatial requirements for equipment not accurately determined	Medium	High	Low	Very high
2	Incorrect methodology used to estimate peak demand and annual heat consumption	High	High	High	Low – high
2	Incorrect methodology used to size pipework, resulting in oversized pipework	High	High	Medium	High
2	Oversizing of equipment	High	High	High	High
2	Equipment selected without considering minimum load and equipment turndown	High	High	High	Medium - high
3	Unnecessary hydraulic breaks (substations which are not required for either contractual separation or pressure breaks)	High	High	High	High

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
3	Unnecessary energy centres (e.g., separate energy centre in each block of a residential development rather than single plant)	Low	High	Medium	High
3	Consumer heat system (DHW generation and heat emitter) selection complex. For example: DHW cylinders or recirculation systems where instantaneous DHW generation is appropriate	Low	High	Medium	High
3	Unnecessary number valves or ancillary equipment	Medium	Medium	Medium	Medium
4	Inappropriate thermal store design, which includes: 1. Four connections (rather than two) 2. Plumbed in parallel No diffusers/baffle plates to aid stratification	High	High	Medium	Medium
4	Low loss headers within energy centres	Medium	High	Medium	High
4	Complex/novel hydraulic arrangements	Medium	High	High	High
4	Incorrect plumbing during installation, for example pipework plumbed into incorrect PHE connections	Medium	High	High	Medium
4	No reverse return or mechanism to ensure even flow between modules	Medium	High	High	Medium
5	Insulation material specified and installed not sufficient to meet heat loss requirements	High	High	Medium	Medium

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
5	Insulation thickness specified and installed not sufficient to meet heat loss requirements	High	High	Medium	Medium
5	Poor installation workmanship, including: 1. Missing insulation 2. Damaged insulation 3. Overtightened pipe supports Vapour seal not complete	High	High	Medium	Low
5	Lack of coordination of pipework and services resulting in reduced insulation thickness	Medium	High	Low	Very high
5	Inappropriate use of pipe supports: 1. Direct pipe supports used, and when used BS 5970 non-preferred option for insulation not followed 2. Incorrect material used 3. Non-pre insulated pipe supports used	Medium	High	Medium	Low
8	Insufficient number and/or location of heat meters	High	High	High	Medium
8	Infrequent or unavailable meter readings	High	High	High	Medium
8	Unavailability of AMR and remote readings	High	High	High	Medium
8	No water meters on water connection	High	Medium	High	Low

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
9	Inappropriate selection of DHW generation technology (e.g., DHW cylinders, recirculation systems)	Low	High	Medium	High
9	Inappropriate selection of DHW and CWS distribution in dwellings (e.g., not utilising manifold approach to reduce delivery times)	High	Medium	Low	High
9	Inappropriate selection of heat emitters and ancillary equipment (e.g., radiator valves, wet towel rails, UFH bypass, UFH mixing pump)	Medium	High	Medium	Very high
9	Incorrectly sized consumer connection (e.g., DHW and space heating PHE)	High	High	High	High
9	Consumer connection and heat system not commissioned as per design intent	High	High	High	Low
10	Incorrect sizing of expansion and pressurisation provision	Medium	High	High	Medium
10	Working pressure exceeding pressure rating of equipment	Medium	High	High	Medium – very high
10	Differential pressure exceeding pressure rating of equipment	Low	Medium	High	Medium – very high
10	No mitigations for high pressure pipework within dwellings	Medium	High	High	Medium – very high
11	Insufficient sensors for BMS control and monitoring (e.g., pressure sensors, temperature sensors, ambient temperature sensors)	Medium	High	High	Low

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
11	Commissioning sets installed when not necessary	High	Low	High	Low
12	Network (pipework, equipment etc.) not installed to the design specification	High	High	Low	Very high
12	Commissioning practices not undertaken as per industry guidance	High	Medium	High	Low
13	Poor controls design and/or implementation Description of Operations	High	High	High	Low
14	Open permanent flushing bypass	Medium	High	High	Low
14	Distribution network bypasses present, and open or controlled in a way which increases network flow rate. This includes: 1. Top of riser bypasses 2. End of lateral bypasses 3. Energy centre or substation bypasses	High	High	High	Low
14	Bypasses at consumer connections as a result of poorly performing consumer connection (e.g., faulty components).	High	High	Medium	Low - high
15	Poorly implemented controls increasing return temperatures (for example, PHE control)	High	High	High	Low - high
15	High return temperatures from consumer connections as a result of:	High	High	Medium	Low - high

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
	1. Open flushing bypasses 2. Poorly performing consumer connection (due to poor control, commissioning, or faulty equipment)				
15	Consumer heat system performance resulting in high return temperatures. Examples include: 1. Equipment selection (e.g., wet towel rails, DHW cylinders) 2. Poorly commissioned heat emitters	High	High	Medium	Low - high
16	Insufficient water quality equipment specified and installed, including: 1. Strainers 2. Air vents 3. Drain cocks 4. Side stream filtration units 5. Dosing provision 6. Air and dirt separator 7. Vacuum degasser	Medium-High	High	High	Low - high
16	Dead legs present on system	High	High	High	Low

Theme	Key Failure	Frequency	Impact	Ability to optimise on operating system	Cost to optimise on operating system
16	Poor water quality management during operation (lack of sampling, analysis and issue identification and rectification)	High	High	High	Low - medium

Table 20: Key failures, frequency, impact and feasibility of optimisation on an operational heat network