The Future of District Heating and Cooling Networks

UKERC Working Paper

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Introduction to UKERC

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Executive Summary

Fourth Generation District Heating (4GDH) has gained wide acceptance as a means to decarbonise heating, by distributing heat from low carbon sources to end-user buildings. It differs from earlier generation district heating technologies by operating at lower nominal temperatures – less than 70 °C as an annual average. This means that heat can be distributed with lower thermal losses compared to earlier generations and that heat from primary fossil fuel consumption can be replaced with lower temperature and lower carbon alternative heating sources.

Within the category of 4GDH, several configurations exist with respective advantages and disadvantages, including so-called 'Cold' *Ultra-Low Temperature District Heating (ULTDH)* and *Combined Heating and Cooling (CHC)* configurations, the latter of which permit provision of cooling as well as heat by virtue of their low operating temperatures. Cold district heating differs from more conventional or 'Warm' 4GDH configurations in that they require the use of decentralised heat pumps to raise or lower temperatures at the point of use.

The advantages of cold networks include even lower thermal losses, scope to use cheaper uninsulated pipework and potentially improved heat pump performance by avoiding large temperature lifts. There is also a degree of 'future proofing' afforded by such networks – since cooling demands in buildings are estimated to rise significantly in the coming years.

Disadvantages can include the need for higher mass flows and larger diameter pipes, as well as the cost and disruption caused by the installation of decentralised heat pumps for individual end users. Moreover, as an emerging technology Cold district heating is currently fragmented, with many different design and operating configurations reported in the literature. As a result, unlike conventional networks for which industry standard guidelines are available, best practices have not yet been established for Cold networks.

Based on some notable examples of Cold networks, the following key points are highlighted:

- Ultra-Low heating networks can be retrofitted to become Cold CHC networks.
- Cold networks can be expanded modularly to incorporate new waste heat sources, heating demands and cooling demands.
- In comparison to separate district heating and cooling networks, Cold CHC can achieve far superior environmental and economic performance.
- Highest performance is achieved when heating and cooling demands are approximately equal.
- The electrification of heating through decentralised heat pumps, together with local heat storage, presents a significant opportunity to provide demand side response services.

However, taking the United Kingdom as a case study, whilst it remains to be seen whether any given 4GDH configuration will ultimately prove to be superior, imminent policy changes to move away from stand-alone gas central heating, as well as decarbonisation efforts in other energy sectors, may cause technological lock-in to a particular configuration at the expense of others. The notion of path dependence, in which small actions are positively reinforced over time through increasing return effects, may ultimately prove more important than the respective lifetime economic and environmental costs of the different 4GDH configurations.

The following initiating measures have therefore been identified to help prevent Cold networks from being overlooked as a viable alternative to conventional 4GDH configurations:

- The widespread capture of low-temperature waste heat should be mandated or at least strongly incentivised;
- Affordability and consumer expectations of building integrated heat pump installations need to be improved, possibly via innovative ownership models;
- The installation of heat network pipes should be considered independent of heat production, improving accessibility and customer choice; and
- Power system flexibility services tailored to heat pump demand side response need to be widely publicised and accessible.

Within our own research, we are developing capability in modelling, simulation and optimisation of these novel systems, such that questions around performance, optimal configurations and demand response capacity can be answered on a site-specific basis in future.

1. Introduction

For many countries around the world, heating and cooling represents a significant proportion of overall energy use. Globally, almost half the amount of energy consumed within buildings is for space and water heating, whilst nearly 16% of electricity consumed within buildings is used for space cooling [1], [2]. In the UK, heating and cooling consumes 667 TWh of energy annually [3], nearly half of overall national energy consumption [4]. Space heating and water heating accounts for 463 TWh of this consumption, of which 83% is derived from burning fossil fuels (73% gas and 10% oil) [3]. Clearly this heavy reliance on burning fossil fuels for heating needs to be reduced if a net-zero carbon dioxide emissions target is to be reached – the latest figures suggest that as much as 23% of total carbon dioxide equivalent emissions in the UK are due to heating buildings [5]. Meanwhile, whilst the official figure for cooling is 39 TWh [3], a comparatively small proportion of UK energy consumption, it does not include current domestic cooling. This value is likely to rise in the coming years due to rising global temperatures, enhanced building fabric standards and growth in sales of domestic cooling systems for currently unmet demand [6]. For instance, from a starting point of virtually no residential cooling in the UK in 2020, this is estimated to increase to 5 TWh by 2050, possibly rising to as much 15 TWh by 2100 [7]. Meanwhile, the cooling demand of buildings in all sectors could potentially double, or even triple, in a business-as-usual carbon emissions scenario with an estimated 4 °C global temperature rise by 2100 [6].

Considering these figures, the problem of how to decarbonise heating and cooling in buildings has been receiving increased attention. Renewed focus has been placed on district heat networks powered by electrical heat pumps, since these can both recover waste heat and utilise renewable electricity to satisfy heating demand [8].Whilst neither of these technologies are new, the way in which district heating may be designed and operated in the future represents a marked departure from most existing networks in operation over the last forty years, with decarbonisation and better integration into a smarter, more flexible energy system at their core.

Most district heat networks in operation today are *Third Generation District Heating (3GDH)* networks (see the following section for an explanation of the different district heating generations), in which heated water is transported from a centralised energy production centre out towards buildings via supply pipes. Operating temperatures typically exceed 60 °C to supply domestic hot water and space heating via radiators, with return temperatures of around 40-60 °C. The main disadvantage of 3GDH systems is that they exhibit high thermal losses from network piping due to the high temperature gradient between the fluid and the ground, reducing the overall system efficiency. High supply temperatures are usually achieved by extracting heat from gas combustion in boilers and combined heat and power plants, which until recently were deemed to be relatively low-carbon options for producing heat. Electrical heat pumps, on the other hand, operate with reduced coefficient of performance (CoP) when providing a large temperature lift, limiting their competitiveness as a replacement for gas-fired heat production in 3GDH networks. High temperatures also prevent high utilisation of low-temperature heat sources, such as renewable solar thermal, geothermal or low-grade waste heat from commercial/industrial cooling processes.

Hence, the desire to decarbonise heating has led to the development of innovative low-temperature configurations in district heating, collectively known as *Fourth Generation District Heating (4GDH)* [8]. The IEA Technology Collaboration Programme on District Heating and Cooling (IEA-DHC) [9] have used the broad definition of 4GDH being *'...all new technological features and concepts using low temperatures, which are considered best available from 2020 onward... The corresponding technology comprises all heat distribution technologies that will utilise supply temperatures below 70 °C as the annual average'*. A period of early adoption, in which various technologies are tried and tested, is still ongoing in 4GDH, with the result that design and operation configurations are currently fragmented [10].

An aim of this paper is to examine the merits of various 4GDH configurations, with particular emphasis on networks which operate below the supply temperatures required for building heating, referred to as 'Cold' *Ultra-Low-Temperature District Heating (ULTDH)* [9]. These systems distribute a heating medium at temperatures below 50 °C between producers and consumers of heat, meaning that low-temperature waste heat may be recovered and redistributed within the network, such as the heat that is rejected when meeting a cooling demand. When both heating and cooling demands from residential and/or commercial buildings are served by the same network, heat is exchanged bi-directionally in a *Combined Heating and Cooling (CHC)* configuration. Proponents of CHC networks to supply both heating and cooling cite numerous advantages over other 4GDH configurations, which are operated at slightly higher temperatures (50-70 °C) and have a more traditional network configuration consisting of uni-directional heating supply and return pipes [11]. It is currently unclear which 4GDH configuration(s) will eventually prove the most successful. Therefore, a subsequent aim of this paper is to discuss the future deployment of heating and cooling networks, considering potential outcomes with reference to path dependence [12], using the UK as a case study.

In Section II, the evolution of district heating and the concept of technological generations is briefly outlined before discussing the features, advantages and disadvantages of various 4GDH configurations. Following this, Section III identifies several key areas which could determine the nature of 4GDH network deployment in the UK, specifically whether Cold District Heating or higher temperature configurations of 4GDH will become the dominant technology.

2. Developments in District Heating

2.1 Prior District Heating Generations

The use of technological generations to classify different types of district heating was used by Lund et al. [8] when introducing the 4GDH concept (see Fig. 1). Generations are identified by:

- The presence of a dominant district heating technology over several decades.
- Continuously increased energy efficiency between generations.
- Continuously reduced supply temperatures between generations.
- Breakthrough technologies, including new manufacturing and construction methods.
- The ability to utilise new energy sources.

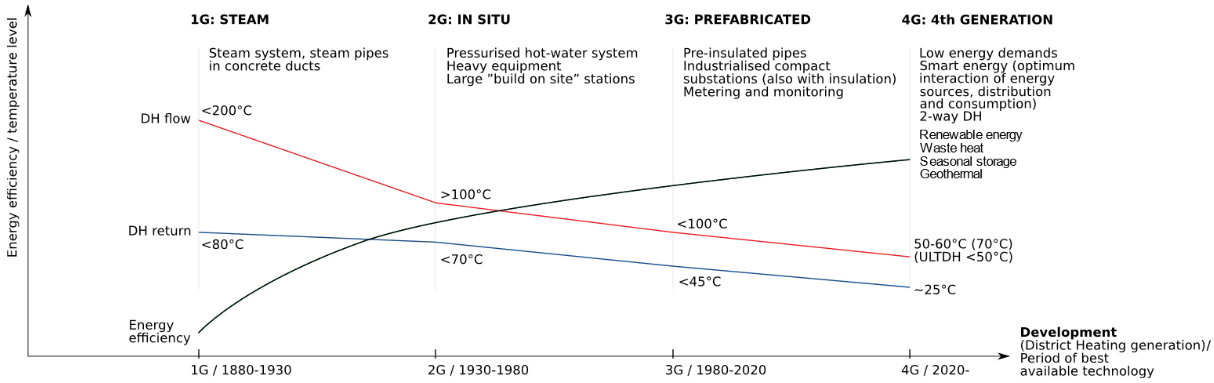

Figure 1. District heating generations, based on [8]

First Generation District Heating (1GDH), established in the 1880s, is characterised by the use of coal as a fuel source to create pressurised steam which, having been transported via positive pipe pressure gradients to its point of use, would deliver heat through condensation [8]. Although there are still active steam-based systems today, notably the Con Eddison district heating system in New York, and the Paris Urban Heating Company system in Paris, the period in which 1GDH represented the dominant technology ended in the 1930s [9].

Second Generation District Heating (2GDH) next became prominent, using pressurised high temperature water (above 100 °C) instead of steam to distribute heat. Increased deployment of cost-efficient combined heat and power plants drove expansion of heat networks during this period, such that security of supply and operational efficiency were not primary concerns. Notable technological differences compared to 1GDH include the use of shell and tube heat exchangers at substations and central circulation pumps to provide the network pressure required for transportation [8].

The move to 3GDH was primarily driven by the desire to improve efficiency and reduce costs, following two international oil crises in the 1970s. Therefore, temperatures of the pressurised water heat carrier were lowered, plate heat exchangers were introduced for improved heat transfer, prefabricated, pre-insulated pipework enabled cheaper installation and the use of expensive fuel oil was displaced by cheaper alternatives such as natural gas, biomass and waste incineration.

Decarbonisation and better integration with other smart energy systems are the primary influences in the development of 4GDH systems [8]. The rationale for defining a new generation, initially, was to be able to distinguish between traditional high-temperature heat networks and new low-temperature heat distribution concepts [9]. Now there is an expectation that 4GDH will continue the trend for increased efficiency, lower temperatures, breakthrough technologies and utilisation of new energy sources which characterise the development of previous generations.

2.2 Fourth Generation District Heating Configurations

The descriptions of 4GDH provided in Section 1 permit a wide range of possible topologies and supply temperatures; the IEA-DHC identify six different 4GDH subcategory configurations based on these two attributes [Annex 10.1][9]. The categories are primarily grouped as being either ‘warm’ or ‘cold’. These are the *Warm-Classic, Warm-Modified Classic, Warm-Multi-Level, Warm-Combined Heating and Cooling (CHC), Cold-Ultra-Low,* and *Cold-CHC* configurations [9].

The Warm – Classic configuration (Fig. 2) uses the traditional topology and technology associated with 3GDH networks, i.e. heat is produced at a centralised location and distributed to end-users via supply and return pipes. The assumption for this configuration is that the use of hot water tanks and hot water circulation within buildings require supply temperatures no lower than 60-65 °C to avoid Legionella bacterial growth. To lower the supply temperatures, the Warm – Modified Classic configuration (Fig. 3) avoids this risk by using heat exchangers within network substations for the instant supply of hot water. Heat exchangers feature longer thermal lengths for improved heat transfer and an additional pipe is used to separate circulation and return pipes, such that return flows are not warmed by mixing with circulating supply flows; temperatures may be lowered by around 10 °C compared to the Classic configuration. Passive heating substations are required for these configurations (see Fig. 4).

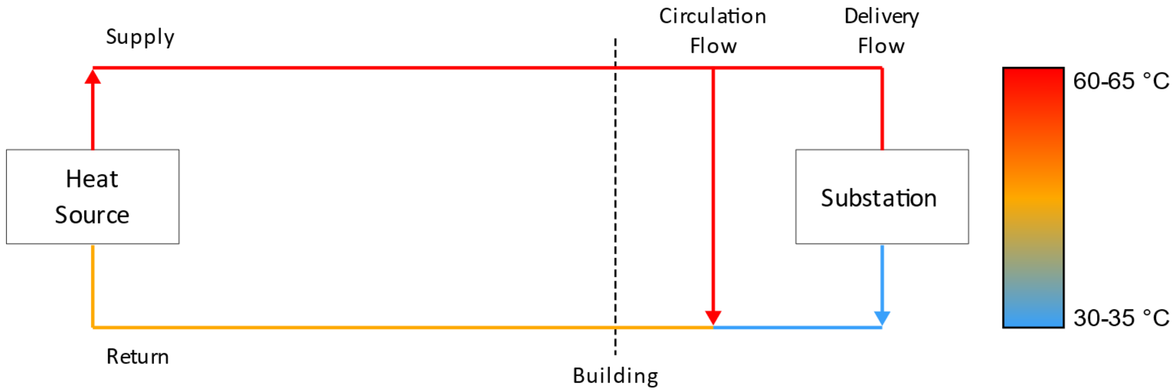

Figure 2. Illustrative layout for the Warm – Classic configuration, redrawn from [9]

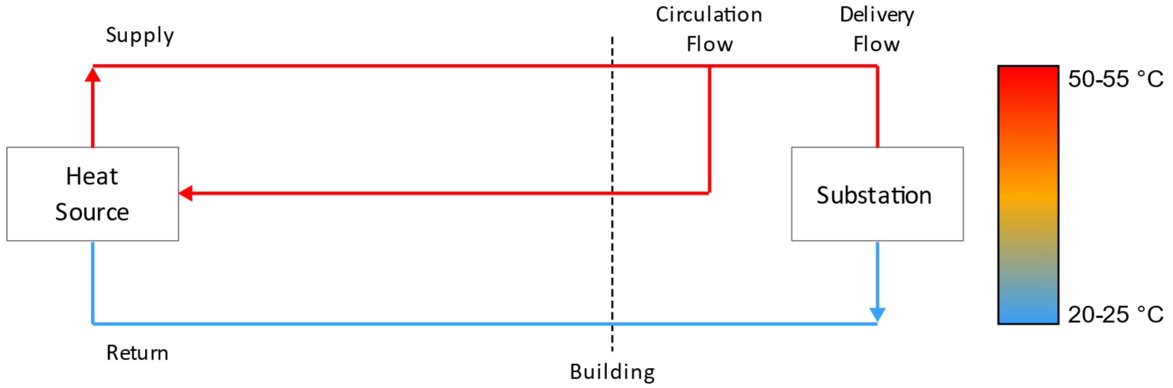

Figure 3. Illustrative layout for the Warm – Modified Classic configuration, redrawn from [9].

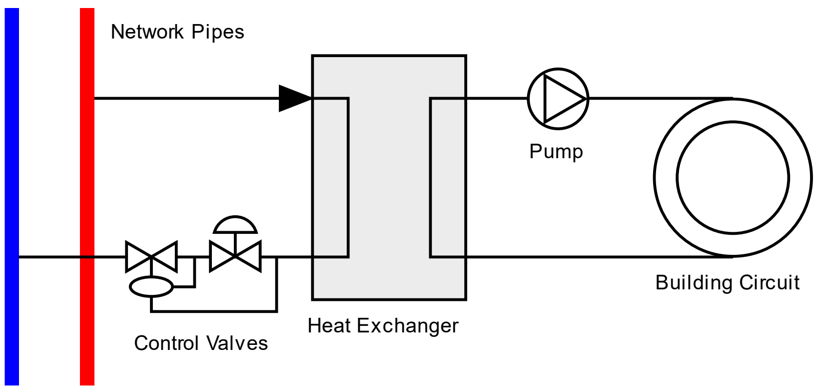

Figure 4. Basic substation layout for indirect passive heating using a heat exchanger, based on [9]. Directions are reversed on the primary side for passive cooling

The Warm – Multi-Level configuration (Fig. 5) is intended to maximise matching of high temperature heat to high temperature demands, with return flows at lower temperatures matched to lower temperature demands. This cascading approach is achieved using multi-level supply and return pipes at intermediate temperatures, connecting passive end-user substations (Fig. 4) between these levels to match buildings' supply and return temperatures to those of the network. The principle behind this configuration is to minimise the loss of exergy when supplying both high and low-temperature demands.

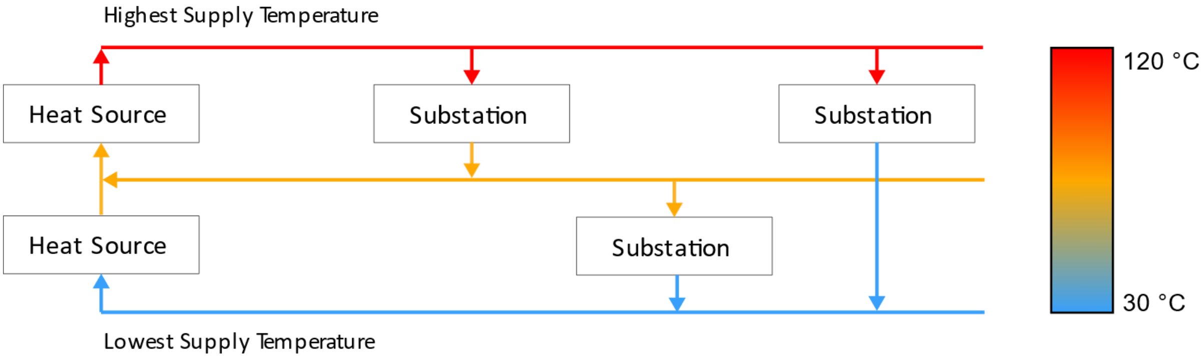

Figure 5. Illustrative layout for the Warm – Multi-Level configuration, redrawn from [9]

Traditional district heating and cooling networks are combined via shared, centralised heat pumps in the Warm CHC configuration (Fig. 6). Powerful heat pumps use the cooling network return as a heat source when producing heat to supply the heating network, in turn providing a cooled supply to the cooling network. The interchange of heat between buildings is therefore enabled in this configuration, albeit indirectly. No decentralised, powered devices are required to upgrade the supplied heat in this configuration, meaning that passive heating and cooling substations may be used (Fig. 3).

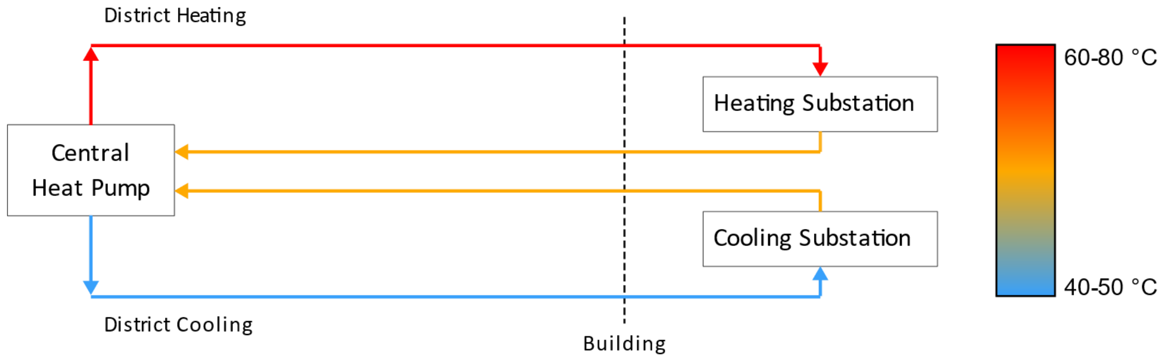

Figure 6. Illustrative layout for the Warm – CHC configuration, redrawn from [9]

Thermal losses can be reduced to negligible levels in the Cold – Ultra-Low configuration (Fig. 7), since supply temperatures are well below those required at the point of use for heating and may even be at ambient temperature. The network follows the traditional topology with supply and return pipes; however, additional heating is required at substations to upgrade heat for end use (see Fig. 8). Low supply temperatures also enable greater utilisation of low-grade heat, such as from renewable or waste heat sources.

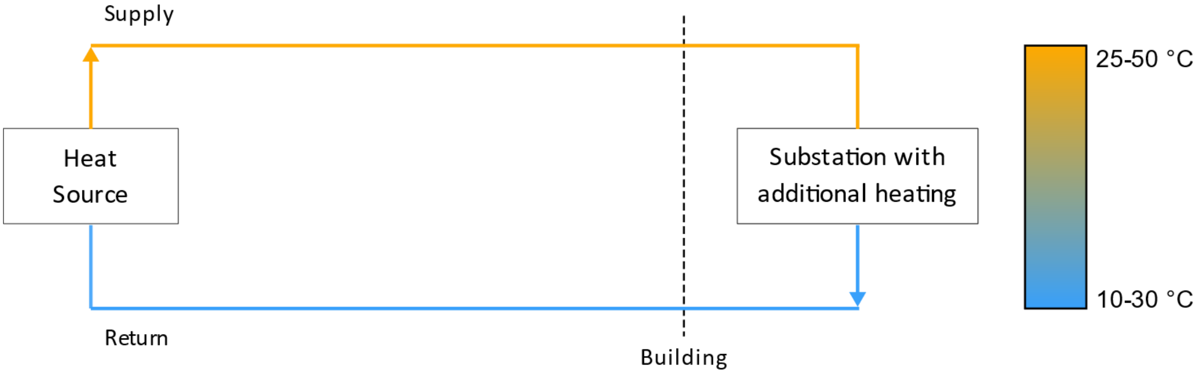

Figure 7. Illustrative layout for the Cold – Ultra-Low configuration, redrawn from [9]

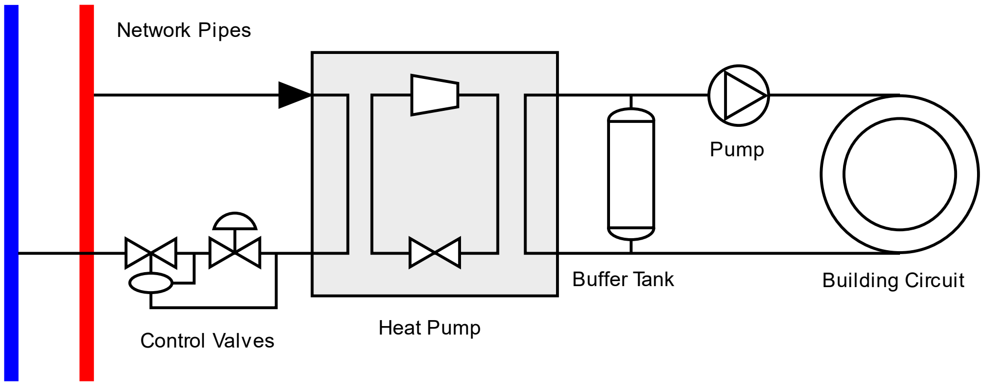

Figure 8. Basic substation layout for active heating using a water-source heat pump and buffer tank

In the Cold – CHC configuration (Fig. 9), as well as heating and/or cooling produced centrally, each end-user substation may also act as a 'prosumer' of heat, extracting or injecting heat to meet local demands and in doing so balancing the heating or cooling requirements of other substations. Therefore, the normal consideration of supply and return pipes do not apply; instead, a warm side and cold side are considered. An exception to this is when only one pipe is used (not shown in Fig. 9), either as an open loop [13] or to continually circulate heat between substations in a closed loop [14]. In the two-pipe case, decentralised circulation pumps are required to discharge the heating medium back into the network pipe(s). If network temperatures are unsuitable for achieving heating and cooling delivery temperatures, then substations require heat pumps for heating and cooling; if heating and cooling demands are coincident at a given substation then dedicated heating and cooling heat pumps may be needed (see Fig. 10). Alternatively, network temperatures in warm side pipes may be sufficiently high to meet heating demands without decentralised upgrading of heat and similarly cold side temperatures may be low enough to permit direct heat exchange for the satisfaction of cooling loads (see Fig. 11). If demands are not coincident, then a reversible heat pump may be used (see Fig. 12) or a combination of heat pump and passive heat exchange may be suitable, depending on network temperatures (see Fig. 13).

Heating and cooling demands from buildings are partly balanced in real time by the district network. However, seasonal variations will cause either heating or cooling demands to dominate at different times. Therefore, some form of large thermal storage to manage seasonal balancing is typically used, e.g. aquifer or bore-hole storage. If cumulative heating and cooling demands are not balanced in a given year then additional heating or cooling must be supplied by dedicated plants, to prevent the depletion of seasonal storage over time.

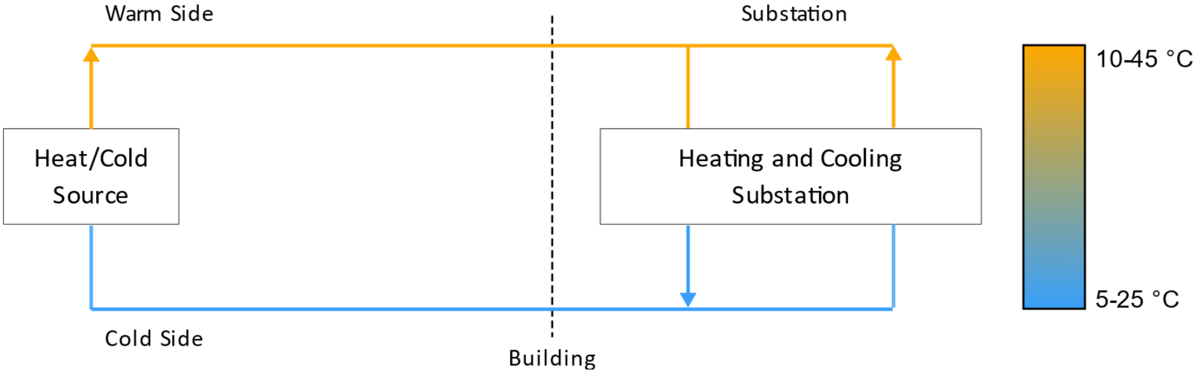

Figure 9. Illustrative layout for the Cold – CHC configuration, redrawn from [9]

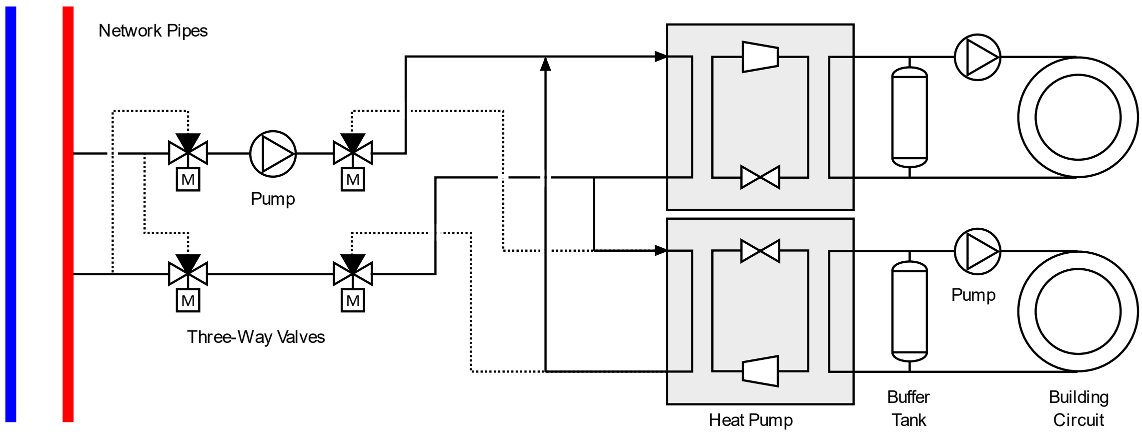

Figure 10. Basic substation layout for active heating and cooling using dedicated water-source heat pumps, buffer tanks and bi-directional network exchange via three-way valve arrangement. The layout permits direct interchange of heat between heat pumps

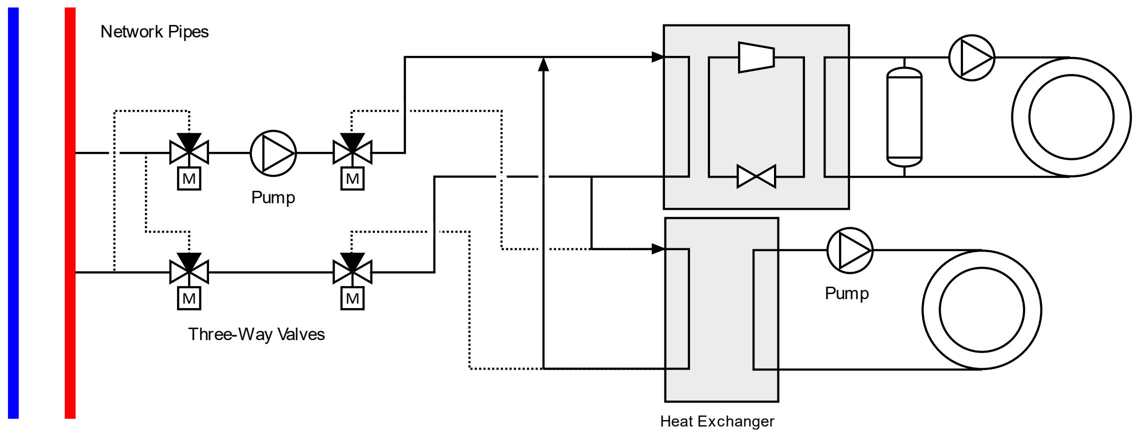

Figure 11. Basic substation layout for active heating using a dedicated water-source heat pump and indirect passive cooling using a heat exchanger. A buffer tank and bi-directional network exchange via three-way valve arrangement also feature. The layout permits direct interchange of heat between heating and cooling loads. A similar layout would be used for active cooling with passive heating.

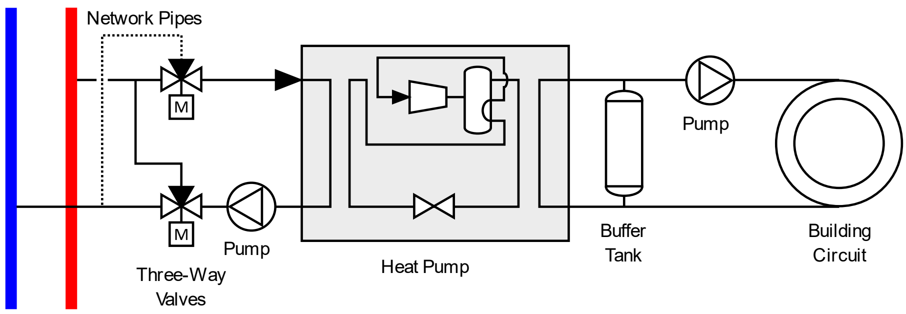

Figure 12. Basic substation layout for active heating and cooling using a reversible water-source heat pump with four-way valve, buffer tank and bi-directional network exchange via three way valve arrangement

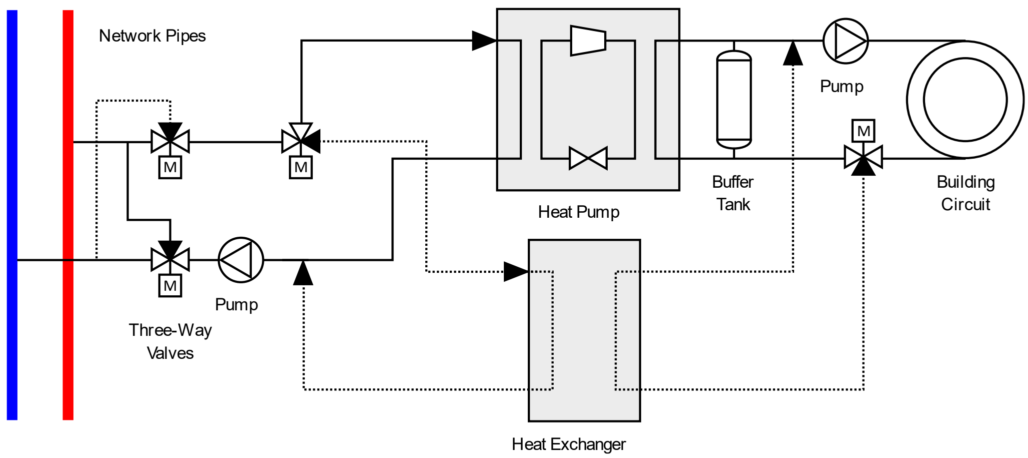

Figure 13. Basic substation layout for active heating and passive cooling for cases where loads are not coincident. Features a water-source heat pump, heat exchanger, buffer tank and bi-directional network exchange via three-way valve arrangement. A similar layout would be used for active cooling with passive heating

The different configurations are summarised in Table 1, along with their advantages and disadvantages. Also included in this table are various names that have been applied to each configuration in the literature. There is clearly a need for consolidation of terms and agreement amongst stakeholders, as the application of names thus far is likely to cause confusion:

- Some names have been applied to markedly different configurations;
- the term 4GDH is often used to imply certain configurations but not others;
- the use of ‘low-temperature’ as a comparison to 3GDH is non-specific;
- the term ‘ambient’ implies that network temperatures are uncontrolled, which may not be the case; and
- the use of *Fifth Generation District Heating and Cooling (5GDHC)* should be reserved until 4GDH technologies have become established and then later superseded [15].

The IEA-DHC 4GDH configuration names could also be improved, since the terms ‘Warm’, ‘Cold’, ‘Classic’ and ‘Ultra-Low’ are only meaningful in relation to prior generations of district heating. For the Cold – Ultra-Low heating only configuration, a succinct description is *a district heating network that operates at temperatures that are not suitable for direct heating purposes* [11]. Therefore a more informative name to reflect this could be ‘Below-Supply-Temperature District Heating’ networks. Similarly, the Cold – CHC configuration is minimally described as *heating and cooling from a single network* [15]. In this case a more suitable name could simply be ‘Bi-directional Heating and Cooling’ networks, since this highlights the necessarily bi-directional interaction of end-users with a single network and implies temperatures low enough for efficient cooling. However, the terms Cold – Ultra-Low and Cold – CHC (collectively Cold District Heating networks) are retained here since they have already been introduced in the literature [9], [10], [15] and their meanings have been described above.

Table 1. Comparison of 4GDH configurations, based on [9]

Configuration	***Warm – Classic***	***Warm – Modified Classic***	***Warm – Multi-Level***
Also known as	Low Temperature DH; 4GDH	Low Temperature DH; 4GDH	LowEx (Low Exergy); Multi-Conductor DH; Cascading DH
Topology	Supply and return	Supply and return	Multiple supply and return
Pumping	Centralised	Centralised	Centralised
Temperatures °C	60-65 / 30-35	50-55 / 20-25	50-120 / 30-80
Temperature Boosting	No	No	No
Cooling Enabled	No	No	No
Advantages	Commercially available technologies with well understood installation; possibility to repurpose 3GDH infrastructure.	Legionella risk significantly reduced; delivery return flow not warmed by mixing with circulating supply; improved heat exchange for further lowering of temperatures.	Efficient heat transfer with appropriate heat exchanger approach temperatures; Lower return temperatures than Classic configuration despite high supply temperatures.
Disadvantages	Limited reduction in thermal losses due to Legionella risk; mixing of delivery and circulation flows increases return temperatures.	Requires redesign of current substations for retrofit; heat exchangers with long thermal lengths not commercially available.	Flow balancing is challenging; additional pipes need to be installed; high temperature demands need to be located close to high temperature source to minimise thermal losses.

Configuration	***Warm – CHC***	***Cold – Ultra-Low***	***Cold – CHC***
Also known as	Low Temperature DH and Cooling; 4GDH and Cooling (4GDHC)	5GDHC; Balanced Energy Networks; Cold DH; Anergy Networks; Low Temperature Networks; Ambient Loops; Shared Ground Loop (SGL) Arrays	5GDHC; Balanced Energy Networks; Bi-directional Low Temperature Networks; Cold DH; Anergy Networks; Ambient Loops; Reservoir Networks; SGL Arrays
Topology	Supply and return (two networks)	Supply and return	Warm and cold or single pipe
Pumping	Centralised	Centralised	Decentralised
Temperatures °C	60-80 / 40-50 (heating)	25-50 / 10-30	10-45 / 5-25
Temperature Boosting	No	Yes	Yes
Cooling Enabled	Yes	After retrofit	Yes
Advantages	May be used in conjunction with existing 3GDH infrastructure; use of a single centralised heat pump for heating and cooling may reduce capital costs.	Supply temperatures not dictated by the highest temperature demand; low thermal losses permit application in areas with low heat density; possibility to install cheaper plastic pipes; a locally available heat source is not a necessity.	All advantages for Ultra-Low configuration; direct heat recovery from cooling processes is possible; advantageous when cooling demands are relatively high; substations can operate with high flexibility.
Disadvantages	More electricity is required to achieve the temperature lift from the cooling network return to the heating network supply; thermal losses restrict application to only high heat density areas; requires heating and cooling networks to have equivalent annual demands.	The cost of decentralised heat pumps may be more than an equivalent centralised heat pump with disruptive installation/ maintenance; require higher mass flows and larger diameter pipes; reduced benefit in areas with high heat density.	All disadvantages of Ultra-Low configuration; requirement for seasonal storage which may be restricted by site conditions; flow balancing is challenging in two pipe networks.

Within the Cold group there is further fragmentation for which additional sub-categorisation is needed [11], [15]. The further distinctions are for networks with:

- Closed loop or open loop pipes;
- uni-directional or bi-directional mass flows;
- one, two, or three pipes;
- self-balanced loads or thermal sources/sinks which are centralised or distributed; and
- fixed or variable nominal pipe temperatures.

Each of these imply materially different designs and control philosophies, resulting in different systems with varying performance. There is no consensus thus far on which represents the optimal design; each have their merits and the optimal choice is likely to be site-specific.

The following section examines known successful early-adopter implementations of Cold networks, to establish the conditions which led to their development, identify their specific configuration and motivate the discussion in Section 3.

2.3 Existing ULTDH Networks

2.3.1 `Mijnwater Grid', Heerlen, Netherlands

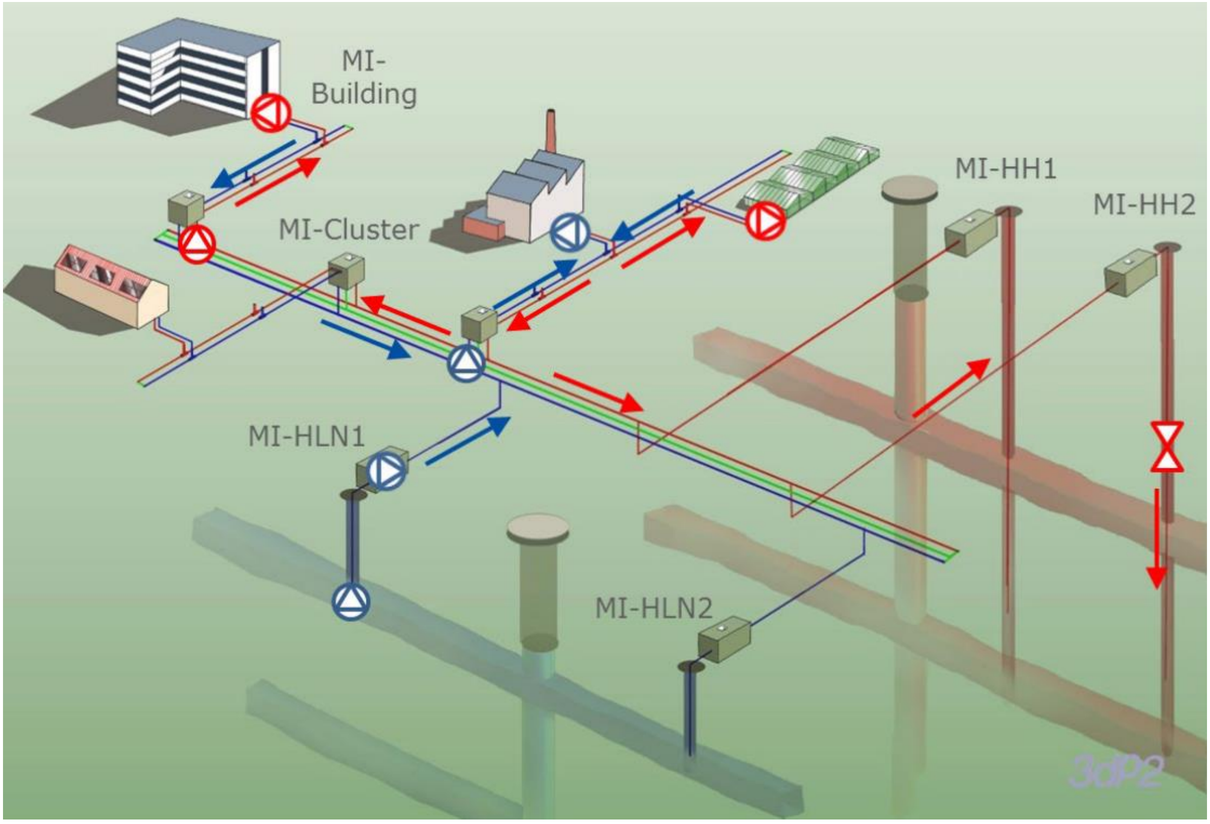

Figure 14. Illustration of the Mijnwater Grid, from [16]

The Mijnwater Grid in Heerlen, Netherlands, started in 2005 as a pilot project intended to use water from flooded mines as a geothermal source for a commercial building and a social housing project (Fig. 14). A warm source (28 °C) and a shallower cool source (16 °C) were used to deliver heating and cooling via a three-pipe system, consisting of warm and cold-side headers with a common return header to an intermediate temperature well [9]. The configuration was essentially an Ultra-Low 4GDHC network and separate cooling network, with no direct exchange of heat between buildings. However, the geothermal resources were slowly depleted using this approach, since conduction effects were not sufficient to prevent the temperatures in the wells from homogenising [16].

A subsequent upgrade was made in 2012 to facilitate the simultaneous exchange of heat between heating and cooling customers, repurposing the mine water system as warm and cold seasonal storage facilities. The common return pipe was also isolated at this time, remaining in place in case of emergencies [16]. An ambition of this new Cold CHC network was to reduce wasted energy by ensuring energy exchange, first at the building level, then between buildings at the neighbourhood level and finally at the city level. Customers are connected in geographically dispersed, locally balanced clusters with connection to the main mine water headers. Thus, the network embraces a decentralised approach, in which circulation of heat is kept to a minimum and only directed where needed [9].

The ratio of heating to cooling demand in the system is approximately equal, with high levels of direct energy exchange - 64% in the most balanced cluster, with an annual average across clusters of 44% [17]. Heating and cooling of buildings can occur passively or actively using heat pumps, depending on available pipe temperatures (heating 27-50 °C; cooling 8-20 °C); domestic hot water is supplied by dedicated booster heat pumps. To maintain sufficient exergy in the mine storage wells, temperature limits are imposed on water re-injected into the warm (>29 °C) or cold (<15 °C) wells, enforced by contracts with end-users to ensure that water is sufficiently heated or cooled before being returned to the network [16]. There is therefore no need for non-electrical based thermal production; thermal energy is derived from energy exchange and decentralised building heat pumps, allowing the entire system (including circulation pumps, etc.) to be powered by three solar photovoltaic installations [17].

The Mijnwater grid is still expanding, highlighting the benefit of this modular, decentralised approach. When connecting new buildings to the grid, if heating demands are required at too high temperatures, these are ‘insulated down’ to an appropriate temperature for grid supply, rather than dismissing them for connection [18]. Buildings are connected to the cluster grids via heat exchangers, supplied using variable speed circulation pumps and 3-way valves on the primary side, all owned and operated by the Mijnwater Corporation [16]. Currently, building owners then supply any additional heating or cooling, either actively or passively, using their own managed equipment and pay a standard charge for the grid connection.

2.3.2 ‘Anergy Grid’, ETH Zurich Hönggerberg Campus, Switzerland

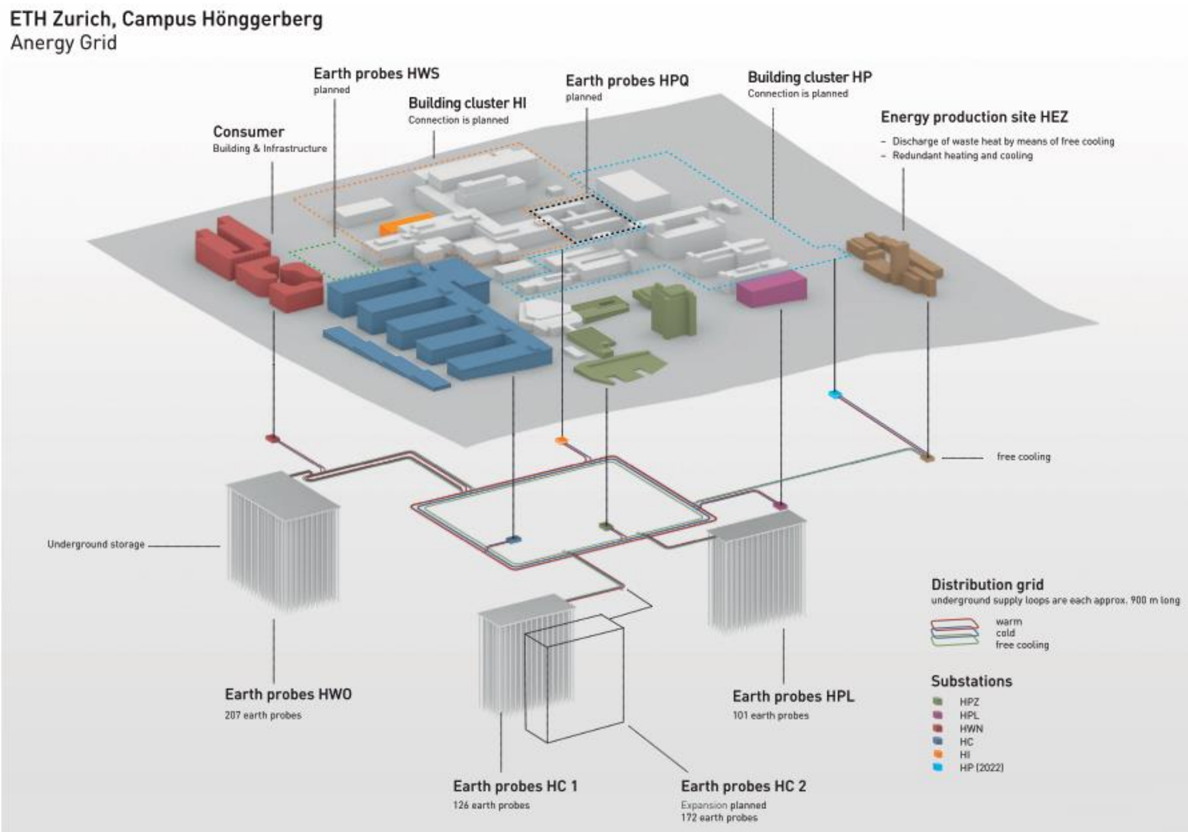

Figure 15. Illustration of the Anergy Grid, from [19]

Warm and cold-side loops connect building clusters at the ETH Zurich Hönggerberg campus, a Cold CHC network operated in parallel to pre-existing separate district heating and district cooling networks since 2013, known as the ‘Anergy Grid’ [19] (Fig. 15). The warm-side loop operates at temperatures between 8 °C and 22 °C, providing a heat source to decentralised heat pumps, whilst the cold-side loop operates at 4 °C lower, enabling passive cooling. Substations in the network consist of heat pumps and heat exchangers, which are able to self-balance where possible, utilising cold water from heat pumps within air-conditioning systems. As a result, water is only circulated in the network when an imbalance is present within a building cluster; borehole fields located near each cluster provide seasonal storage for any surplus or deficit of heat that cannot be balanced internally. The separate conventional heating and cooling networks, respectively powered by a central gas boiler and an electric chiller, permit relatively straight forward annual balancing of the borehole storage fields to ensure they are not depleted [20]. Thus, around 81% of the useful heating demand and 87% of the useful cold demand was supplied by the Cold CHC network in 2016, with the remaining covered by the pre-existing parallel networks [19].

During monitoring, an overall 72% decrease in carbon dioxide emissions was achieved versus conventional heating and cooling networks [20].

2.3.3 'Balanced Energy Network (BEN)', London South Bank University, UK'

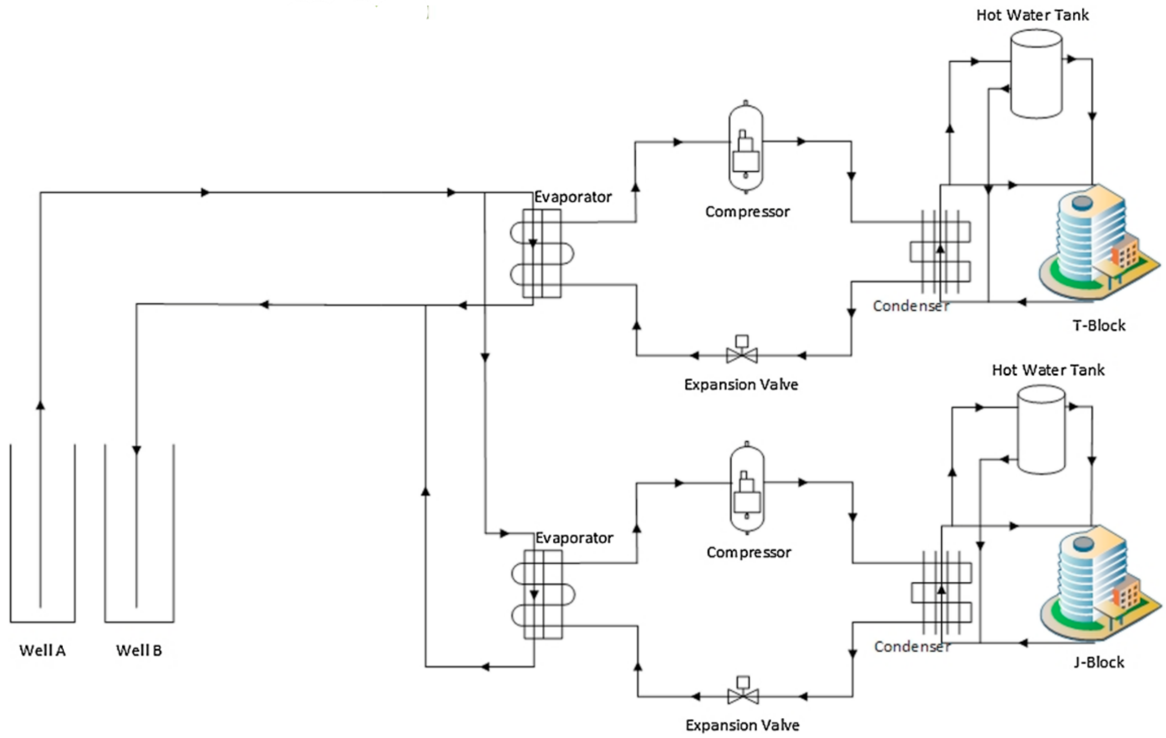

Figure 16. Schematic of the Balanced Energy Network, from [21]

The Balanced Energy Network is intended to establish the first Cold CHC network in the UK [21]. The first stage of the project was to connect two large academic tower blocks in central London to two geographically separate chalk aquifer borehole wells (Fig. 16). Water at steady annual temperatures of around 13-15 °C is extracted from the boreholes, providing circulating water that could either act as heat source or sink for heating and cooling loads in the buildings. Initially the circulating water is to act predominantly as a heat source, since both buildings are heat dominated, and is an Ultra-Low open loop network without a water return [22].

Each building was previously served by four gas boilers, supplying heat for distribution via heat emitters with 70/60 °C supply and return flows. The design intention was to retain these boilers and tie-in to the system on the common supply header. This required high temperature lift heat pumps, capable of operating with a CoP of around 3 at these higher output temperatures. Heat from the heat pumps would also be stored locally in 10,000 litre capacity hot water storage tanks. These tanks provide rapid charging by heating the top section first and expanding the heated volume downwards over time, making use of the thermocline within the tank [23].

A cloud-based energy aggregator links these devices to provide demand side response capability to the power system, including Fast Frequency Response, Short Term Operational Reserve and Use of System services [24].

Modelling of the BEN indicates that, in comparison to the original boiler only system, over 70% reductions in the energy used for heating are achievable [13] and that demand side response can provide cost savings of around 9% [24]. This is in spite of necessary changes to place pipework above ground along the edges of buildings, as the original underground trench route was obscured by utility services, and downgrading of the reversible injection borehole interface packages to be uni-directional, due to prohibitive costs, preventing the use of boreholes for long term storage [22]. With the option to expand the network to add cooling loads, possibly improving heat pump CoP, or even upgrade the borehole injection wells in future, the BEN could yet achieve higher levels of performance.

The above examples highlight some key points regarding the adoption of Cold networks which are relevant to the discussion in Section III. These are summarised as follows:

- Ultra-Low heating networks can be retrofitted to become Cold CHC networks.
- Cold networks can be expanded modularly to incorporate new waste heat sources, heating demands and cooling demands.
- In comparison to separate district heating and cooling networks, Cold CHC can achieve far superior environmental and economic performance.
- Highest performance is achieved when heating and cooling demands are approximately equal.
- The electrification of heating through decentralised heat pumps, together with local heat storage, presents a significant opportunity to provide demand side response services.

However, the fragmentation of Cold networks versus more conventional district heating configurations is likely to hinder their adoption, a consequence of learning effects (discussed in Section III) which favour technologies with the greatest market share. Too little is known about how each variation affects capital investment costs, heat pump performance, circulation pumping requirements and thermal losses, which each dictate the levelised cost of energy for a given network. Unlike conventional heat networks, for which an industry design guide [25] and code of practice [26] have been published in the UK, no such best practice guidance is available for Cold networks. To address this situation, simple to use tools for modelling, simulation and optimisation of Cold networks are needed. Such software tools would improve familiarity with these networks, facilitate understanding of their respective merits, and allow feasibility stage economic comparisons between these and more conventional 4GDH configurations to be made on a case-by-case basis. Ideally component-based, bottom-up approaches should be developed, so that the various configurations could be modelled using a single tool.

In addition, whilst there is clearly an opportunity to provide demand response given the interaction with Cold networks and the power system, together with availability of relatively cheap thermal storage, the actual available capacity for flexibility from one of these networks of any given size is not known. Some services may generate higher revenue than others and certain services are likely to be incompatible due to the need to guarantee availability and recovery of capacity within a limited timeframe. There will also be a trade-off between equipment size and the ability to provide flexibility which will result in different payback periods. The capacity for demand response from any given Cold network would also be better understood with the help of model-based tools.

With greater understanding of their design and operation, there may be a stronger case for recommending networks with decentralised heat pumps over more conventional 4GDH configurations. However, as discussed in the next section of this article, there will likely be many factors beyond the techno-economic case for Cold networks which will ultimately determine their contribution to the future of heating and cooling in the UK.

3. Heat Network Deployment in the UK

Heat networks are not a new technology in the UK, indeed there are around 5,500 district-scale and 11,500 community-scale heat networks in operation, serving around 500,000 residential and non-residential customers [27]. However, this represents only around 2% of overall heat demand in the UK and most of these networks are supplied by gas-powered CHP plants - only 1% are supplied by heat pumps [27]. The dominance of gas-based heating is not restricted to heat networks either, with gas central heating systems also installed in the majority of UK homes.

The UK Government has indicated that the immediate development of a market for low-carbon heat networks will be a ‘no-regrets’ action to help decarbonise heating and move away from gas [5], citing the Climate Change Committee's recommendation for 18% of heat to be supplied via heat networks by 2050 [28]. To achieve this, £338 million of investment has been pledged as part of the Heat Network Transformation Programme (over 2022/23 to 2024/5) and a Heat Network Zoning policy has been proposed for introduction in 2025 [5]. A Heat Network Zone is an area for which heat networks are deemed the lowest cost, low carbon option and the policy would stipulate that certain buildings within a zone must connect to a local heat network within a reasonable timeframe. This is thought to provide visibility and certainty to the process of heat network development, de-risking investment decisions and promoting heat network growth [29]. It is therefore reasonable to suggest that the UK is at a critical juncture in terms of heat network deployment. Yet, whilst the immediate increased adoption of heat networks might be considered a ‘no-regrets' action, there are numerous competing technological approaches which could be adopted, as highlighted in Section II, and regrettable development paths could still be a possibility.

Technology development paths towards a long-term market outcome are influenced by increasing returns. Technologies which exhibit increasing returns are those that improve, or represent an increasingly preferable option, as their adoption increases [30]. Several categories of increasing return can be considered [12]:

- Large set-up costs - increased incentive to stay with a particular technology or eco-system to maximise the benefit from initial sunk costs.
- Learning effects - lower costs and improved performance of a technology driven by learning and repetition as its market share grows.
- Coordination effects - increased investment in supporting infrastructure or compatible technologies as adoption increases, improving the perceived value.
- Adaptive expectations - increased consumer confidence in a technology due to high adoption rates and therefore familiarity, causing self-fulfilling expectations of future market leadership.

In a market of competing technologies which each exhibit increasing returns, the following properties are observed [30]:

- Unpredictability - a technologies' potential and the preferences of adopters are not sufficient to accurately predict market share in the long-term.
- Inflexibility - the introduction of financial incentives for a certain technology cannot influence its future adoption once another competing technology becomes 'locked-in'.
- Path-dependence - market outcome is dictated by small historical events which are not 'forgotten' and preceding steps along a path cause further movement in the same direction.

Increasing returns can therefore lead to circumstances where a technology achieves a monopoly due to historical events, even though this technology may have inferior long-term potential. As an example, it is worth returning to another significant juncture in the development of national heating infrastructure in the UK. In 1977, the UK Government completed the transformation from town gas to natural gas, intended to exploit North Sea natural gas resources. In the four decades that followed, the proportion of homes with gas central heating systems doubled from 46% to 96% [31], resulting in the current situation for which decarbonisation is a major, national-scale challenge with high potential for disruption to the general public. However, over the same period, the building heating market share for district heating in Sweden grew from less than 20% to around 55%, the share of heat pumps increased to around 20% (from 0 in the 1990s), whilst the share of natural gas for direct heating is currently less than 5% [31]. Between the two nations, Sweden is therefore in a much stronger position to decarbonise its heating supply.

The type of heating network which may eventually become the dominant technology in the UK could also be influenced by path dependence and increasing returns effects, rather than solely by the merits of individual configurations. In the following sections, several areas are considered for which decisions will be taken in the coming decade which may influence heat network market outcomes for many decades to come.

3.1 Regulations for low-temperature waste heat recovery

There is significant potential to recover low temperature waste heat in EU countries, estimated at 10% of total overall demand for heat and hot water, from data centres, metro stations, service sector buildings and wastewater treatment plants [32]. However, whereas countries such as the Netherlands and Norway have introduced regulatory frameworks to make surplus waste heat capture a priority for businesses, UK policy has previously required only voluntary appraisal of waste heat capture opportunities [33]. Other challenges for waste heat recovery include discrepancies in the perceived quality (volume and temperature) of waste heat between the provider and heating network operator, as well as the risk that a waste heat provider will cease activities [32].

These challenges can be managed most effectively when using Cold configurations, since low grade waste heat can be utilised in these networks and their ability to expand modularly, connecting many small prosumers, improves resilience against loss of heat sources. This is unlike traditional 4GDH configurations in which the network is designed around large centralised heat sources and anchor loads. Therefore, if in the future there are stronger incentives, or even mandatory requirements, for businesses to capture surplus waste heat in the UK, this may initiate a coordination effect, whereby it becomes more viable to install Cold networks due to their compatibility with waste heat capture. The proposed heat network zoning policy is one way in which businesses may be encouraged to capture more waste heat in future [34].

3.2 Heat pump installations within buildings

All 4GDH networks are likely to feature electrically driven heat pumps in some way, by virtue of their high efficiency and ability to use renewable electricity. The main distinction between Cold and other configurations is the heat pump location relative to the customer. Heat pumps are integrated within customer buildings to actively raise the temperature of heat extracted from (or injected to) the network in Cold designs, whereas in other configurations heat pumps are more likely utilised by designated heat providers, with customers instead equipped for passive heat exchange (see Fig. 2). Therefore, the likelihood that customers will be willing, and able, to manage their own building heat pump installation will be a determining factor in the prevalence of Cold configurations.

The UK Government intends to build the market for heat pumps, aiming to achieve cost parity to gas boilers and facilitate the installation of at least 600,000 heat pumps per year by 2028 [5]. Learning effects form a major part of this strategy, with the Government hoping that initial subsidies and regulations to end installation of new fossil fuel heating systems will provide the catalyst for a 30-fold increase in UK production by 2030. The heat pump market is already steadily increasing globally and IEA projections for a net-zero scenario (see Fig. 17) suggest that there will indeed be a significant ramp up in production by 2030, which is likely to bring costs down and improve customer acceptability.

However, the UK Government's £288 million Green Heat Network Fund (GHNF) began funding rounds in 2021 [35], before any of these learning effects are likely to materialise and at a time when large, high output heat pump installations at energy centres are often viewed as the most cost effective solution. Furthermore, the GHNF will not fund tertiary equipment located 'behind the meter' within a customer's premises [36], leaving a funding gap for Cold networks relying on decentralised heat pumps [37]. This may result in preference for conventionally configured 4GDH heat networks in the short term and, if these designs become established, reductions in heat pump costs will provide most benefit for the centralised energy centres serving these networks.

The UK Government has also recently launched the Boiler Upgrade Scheme, which provides a significant subsidy on the capital cost of heat pumps and a means to address the funding gap for customers but does not address possible concerns around long term performance [38]. Moreover, the scheme's stipulation that building insulation must first be installed for a property to be eligible is likely to act as a barrier for many customers, given the potentially high cost and disruption of retrofitting insulation. To address this and improve the customer proposition of building integrated heat pumps in the short-term, manufacturers of small water source heat pumps that are compatible with Cold networks could consider leasing schemes. This has shown to be effective for increasing the market share of battery electric vehicles in the automotive sector, where high up-front costs and uncertainty around the performance of electric vehicles is a significant barrier to outright ownership [39].

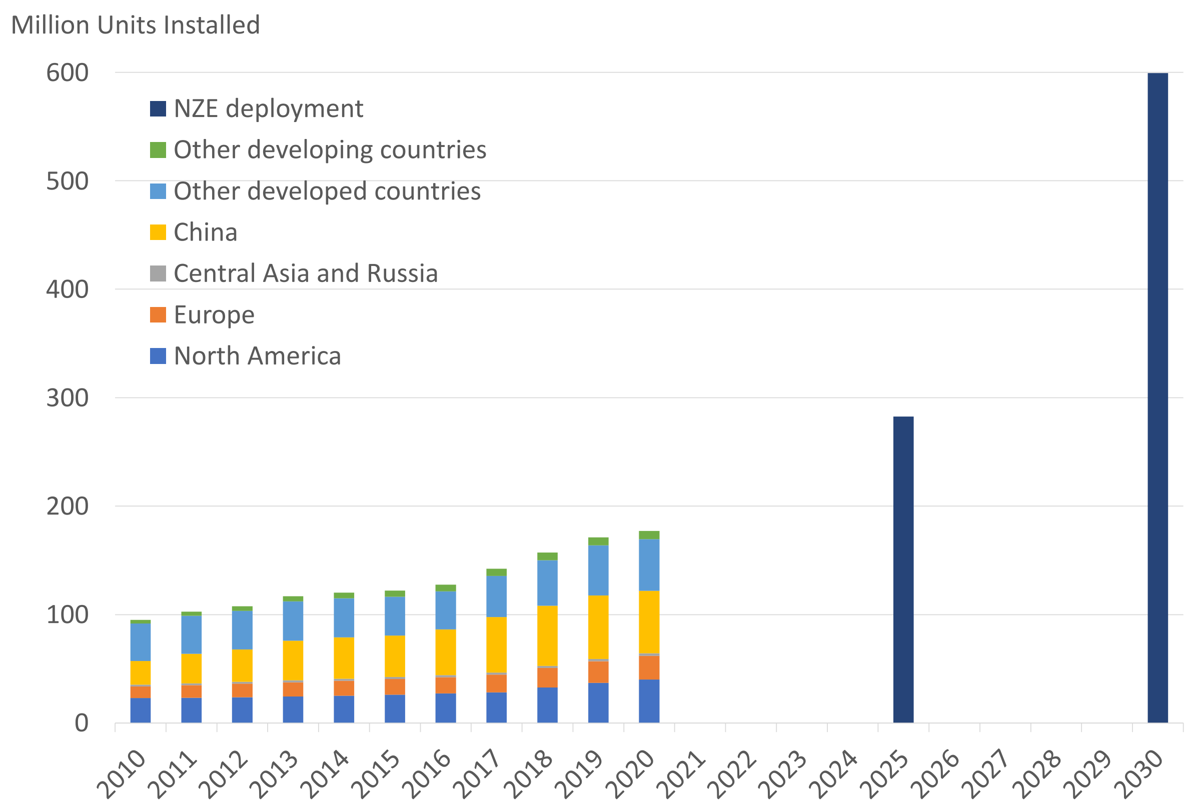

Figure 17. Installed heat pump stock by region and global Net Zero Scenario deployment, 2010-2030, redrawn from [40]

Alternatively, so-called Heat-as-a-Service (HaaS) business models could be employed, which include not only leasing of the heat pump but also indoor comfort management and pricing via a set heat plan, rather than payment per kWh [41]. A trial of such a service in the UK highlighted that customers felt more confident of switching to low-carbon technologies, such as heat pumps and district heating, if comfort levels could be maintained [42].

An additional feature of HaaS models is that technical risk is taken on by the service supplier, i.e. for maintenance and repair of equipment [43]. Whilst this improves the customer proposition for building integrated heat pumps, if the HaaS provider has ownership of both the network and heat pump, it may be more preferable for them to locate the heat pumps centrally, to minimise both the difficulty in carrying out maintenance and disruption to the customer. However, this assumes that comfort relates only to keeping buildings warm, rather than also preventing them from overheating; if demands for cooling increase significantly, Cold CHC configurations would become the preferred option for a HaaS provider, since otherwise separate cooling provision would have to be supplied anyway. Nonetheless, the ownership of component parts in a 4GDH system will influence the preferred approach, as discussed in the next section.

3.3 Split responsibilities for heat production and distribution

In power system operations, the responsibility for generation, transmission and distribution of electricity has typically been split across different entities to promote competition and improve performance, whereas in heat networks, assets for both heat production and distribution are typically owned and managed as a single system [44]. This is logical since in traditional configurations the production plants would be designed and operated specifically to serve the heat network and its connected customers. However, the recent trend towards increased capture of waste heat from decentralised sources should move the focus away from production, towards the distribution and trading of heat [44]. From this perspective, it makes sense for a district heating network to exist as an independent utility, similarly to power or gas distribution networks, to which individual prosumers can choose to connect, rather than mandatory connection being forced on customers [34]. This paradigm creates coordination effects that favour the prosumer-centric Cold CHC configuration, via which heat can be exchanged bi-directionally, providing a platform for heat trading. Heat network expansion to connect greater numbers of heating loads to low temperature heat sources is also made simpler for the Cold configurations – uninsulated pipe runs can cover a larger area without problematic heat losses [11] and many smaller networks can be connected in a modular fashion, as demonstrated by the Mijnwater Grid [16].

Strategic investment is needed for this to occur, i.e. investments in heat network pipes ahead of demand availability. District heating industry stakeholders mostly reject the notion of strategic investment, although it may be considered when there is strong municipality backing and suitable regulation [45]. The implementation of heat network zoning could once again prove pivotal in this regard, in particular the role of the 'Zoning Coordinator' in the ownership and procurement of heat networks [29].

The Zoning Coordinator role will either be fulfilled by local or central government and their involvement in the delivery of heat networks within a zone could either be high, i.e. public sector delivery, or minimal in the case that delivery is determined by an open market model. The paradigm described above is most likely to be achieved through public sector delivery. The Zoning Coordinator would take ownership of the scheme and could exercise the greatest control over expansion planning to meet local needs, not burdened by the level of financial returns expected in the private sector. It would be able to focus on connectivity, allowing competition for heat supply into the network to drive down prices and improve outcomes for customers. This would require regulatory oversight and system balancing mechanisms to be in place [29], and suggests that the future heat market regulator would also need to take a strategic role in heat network planning.

Alternatively, the Zoning Coordinator could procure a third party to deliver the network and may specify a concession such that a single network operator has exclusive rights to connect buildings in the zone. Strategic investment is less likely under this scenario, since there are strong financial incentives to size strictly according to contracted demand [45]. On the other hand, the Zoning Coordinator may stipulate network expansion or over-sizing as part of conditions to operate or a concession arrangement.

Finally, with an open market model the Zoning Coordinator would have minimal strategic input into heat network development as network developers would contract directly with heat consumers [29]. In this scenario, the ability for existing network operators to expand their operations within a zone or for private entities to develop networks supplying their own estate, is highly likely to favour continuation of more established supply and return heating networks with centralised energy production. Learning effects and prior investments in traditional networks would encourage only incremental lowering of temperatures by existing operators, meanwhile strategic investment would be difficult to justify in a competitive market. Developers of smaller private or community owned networks would also only opt for Cold networks if locally available heat sources or cooling requirements warranted such an approach.

The nature of heat network ownership and the level of government oversight are therefore likely to impact the path of heat network development in the UK.

3.4 Active participation in power system flexibility markets

Peak electricity demand in Great Britain was approximately 59 GW in 2020 and is expected to double by 2050 if large parts of transport, heating and industry decarbonise through electrification [5]. To avoid problems of network congestion and frequency excursions, power systems can benefit from demand-side management schemes, in which the flexibility of devices or systems that consume electricity is exploited to provide a range of ancillary services. Transmission level ancillary services currently comprise of [46]:

- Dynamic Containment, fast-acting frequency response service to proportionally increase or decrease demand in relation to rapid frequency deviations, restoring nominal system frequency;
- Fast Reserve, which includes the ability to turn down demand to counteract decreasing system frequency and restore the balance of active power, sustained over several minutes;
- Short Term Operating Reserve (STOR), which involves the ability to turn down demand by a lesser amount, over a sustained period of several hours.

The Balancing Mechanism (BM) is another route through which flexibility can be exploited, in which offers to reduce demand in half hourly periods are submitted to the power system operator and may be accepted at close to real time to balance supply and demand. Distribution network operators also tendered over 3.5 GW of equivalent flexibility services (called Sustain, Secure, Dynamic and Restore) in 2021/2, with minimum capacities in the range of 10-100kW [47]. Finally, through real-time pricing, indirect demand side management can be achieved in which flexible assets are operated in response to market price signals, thus capitalising on energy arbitrage opportunities.

The value of energy system flexibility in Great Britain has been estimated to be £9.6-16.7 billion/year of cost savings in a net zero scenario by 2050 [48]. The amount of power used by heat networks, together with their inherent thermal inertia and access to thermal storage, makes them ideal systems to capitalise on this opportunity for providing demand-side response [49]. Indeed, both the Mijnwater and BEN projects discussed in the previous section involve plans to provide demand-side response capability. Modelling for the BEN project reveals that almost a quarter of overall heating costs could be saved by implementing fast reserve, STOR and real-time pricing types of demand response, over and above the savings made by installing the Balanced Energy Network itself [24].

Flexibility in district heating systems originates from three sources of thermal inertia: the heating medium fluid within network pipes, the fabric of supplied buildings and from dedicated thermal storage [49]. The combination of inherent and dedicated thermal storage in district heating systems could be utilised for power system demand side response, by manipulating the power demands of heat pumps and network circulation pumps.

The potential storage capacity of Classic district heating network pipes can be accessed by allowing the network temperatures to rise 10 to 20 °C above the nominal supply temperature [49], [50]. The storage capacity of network pipes in the Danish district heating system is estimated to be about 5 GWh, considering a 10 °C rise – around 10% of the storage capacity from water tanks installed at the network level [51], [52]. However, whilst this significant capacity could be beneficial for peak shaving, such cycling of pipe temperatures could increase material fatigue rates in steel pipes [49]. Furthermore, the management of this storage capacity is complex, with ramp rates limited by temperature propagation through the network [53] and discharging dictated by the actions of end users [54].

For a Cold CHC network supplying both heating and cooling demands, the approach to storage depends on whether net heating or cooling is being supplied by the network, with a reduction below nominal temperature in the cool line necessary during cooling dominated periods. A study for a Cold CHC network in the South of Spain [55], demonstrates how heating or cooling to maintain temperatures within prescribed limits can increase utilisation of locally generated excess electricity from solar photovoltaic panels by 41.2%. However, employing a specific storage strategy by overheating or overcooling the network only contributed additional cost reductions of 2.1%. Nevertheless, the authors note that this could be improved in a larger network with a more diverse supply of renewable energy, as might be the case when supplying flexibility to the main power grid, and that the impact on building integrated heat pump CoP values was not studied.

Similarly to using network pipes as an additional storage capacity, the load profile of individual buildings can be manipulated by allowing indoor temperatures to vary within an acceptable comfort range [49]. The storage capacity of individual dwellings in Belgium have been estimated to be between 12-30 kWh for radiator heated buildings and 16-66 kWh for those with underfloor heating; this is assuming a comfort range of 2 °C and a demand response event lasting 4 hours [56]. In a study of buildings equipped with air-source heat pumps in the UK, the magnitude of flexibility from a single dwelling was determined to be considerably less, with changes of a few kilowatts over 2 hours, though this could be aggregated over 1000s of dwellings via a commercial aggregator [57]. These results highlight that thermal capacitance, and therefore thermal inertia, can vary significantly across housing stocks, due to differences in buildings' thermal mass. Both studies also identified that the available storage capacity varies temporally, whilst [57] noted that the ‘payback’ power required to re-establish indoor temperature after a demand response event could reach 10% over the business-as-usual peak for low inertia buildings, albeit at a later point in time.

Dedicated thermal storage provides the simplest route for providing flexibility for demand side response, since it can be designed for a specific power level and event duration, with stratified hot or cold water tanks being relatively low cost options which are widely used for short-term storage [58]. Water tanks have also been shown to offer the best flexibility characteristics versus comparably sized thermochemical material and phase change material tanks, providing around 17 kWh of storage capacity to increase or decrease power consumption from a 0.5 m^3 tank [59]. Water tank storage can be deployed at the network level, as is typical for traditional large-scale district heating networks [54], or as buffer storage at the building level, which may be aggregated similarly to the capacity of building fabric [60]. Long-term or seasonal storage options, such as boreholes, tank pits and aquifers are less relevant since their charge and discharge cycles are much longer than the typical durations of demand response events (hours or less).

Hence, there is considerable thermal storage which could potentially be made available for flexibility and a significant proportion of electricity which is currently used for heating or cooling purposes – around 30% and 40% in the residential and commercial sectors, respectively [61]. In a scenario where access to flexibility markets is simple and financially rewarding, possibly contracted through a commercial energy aggregator or distribution system operator, the switch over to Cold networks could provide a valuable revenue stream to customers, either through the BM, ancillary services or energy arbitrage. Unlike in traditionally configured 4GDH networks, for which passive consumers of heat would have no ownership of electrically driven heating equipment, the requirement for a heat pump on the customer premises in Cold networks represents a flexible asset which could facilitate participation. In traditionally configured networks, centralised heat pumps could also be operated flexibly and this could be used to lower costs for customers. However, this would be at the discretion of the network operator, with customers having little power to negotiate, particularly once connected to the network.

Consumer participation in the energy system could therefore influence outcomes for heat network development in this respect. As familiarity grows with other smart grid technologies, such as vehicle to grid schemes, smart meters, smart appliances, home energy storage and solar photovoltaic generation, a more engaged customer would seek to also leverage their heating system for participation in flexibility markets. In which case, attitudes towards Cold networks, offering greater choice and energy independence, are likely to be increasingly positive when compared to traditionally configured 4GDH networks, for which there is a producer-consumer relationship.

4. Concluding Remarks

There is currently a renewed focus on heat networks, both in government policymaking as an effective means of decarbonising heating and cooling, and in the academic literature due to recent innovations in Fourth Generation District Heating (4GDH) networks.

In the first part of this report, the technological differences between prior generations of district heating and these latest networks configurations were discussed and some specific examples of Cold networks were presented. Whilst there will inevitably be cases for which Cold networks do not represent the optimal configuration of 4GDH, they do provide high flexibility, robustness against future increases in cooling demand, capability to capture low temperature waste heat and a means for customers to enter into flexibility markets. At the least then, Cold networks should be encouraged through favourable conditions for their development.

In the latter part of this report, key areas affecting the development of heat networks in the UK have been discussed with reference to path dependence. Given prior experience of classical heat network configurations, it is conceivable that Cold networks could be overlooked as a potential alternative. Hence, the following initiating measures have been identified that could be crucial in the coming years if the type of increasing returns which could support Cold networks in the long term are to be realised:

- The widespread capture of low-temperature waste heat should be mandated or at least strongly incentivised;
- Affordability and consumer expectations of building integrated heat pump installations need to be improved, possibly via innovative ownership models;
- The installation of heat network pipes should be considered independent of heat production, improving accessibility and customer choice; and
- Power system flexibility services tailored to heat pump demand side response need to be widely publicised and accessible.

In the meantime, there is further research still required to fully understand Cold networks and their future role. There are many variations of the Cold network concept, both in existence and proposed in the literature, representing a fragmented technology area when compared to conventional heating and cooling networks which do not require decentralised heat pumps. There are no general rules to determine network operating temperatures or optimal heating to cooling load ratios, with a range of temperatures reported in existing examples and adjustments to cooling loads made during a project's lifetime to try and achieve the most efficient operation. The ability for flexibility service provision via Cold systems is also a property which should be quantified and considered when comparing their levelised cost of energy against competing technologies. These are areas which we hope to address in our own future research involving modelling, simulation and optimisation of these novel systems.

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