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# Sustainability and carbon neutrality in UK's district heating: A review and analysis

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ABSTRACT

The UK is currently approaching a critical point in the fight against climate change. To achieve carbon neutral by 2050, it is crucial that the way in which buildings are heated are reviewed to determine the most suitable solution. The UK government has acknowledged that district heating (also referred to as heat networks) forms an important part of their plan for future sustainability in heating homes as well as improving energy costs. At present, there are five generations of district heating with distinctive improvements between each. However, research shows a lack of progression with only minor improvements to efficiencies and carbon emissions in the past two decades. Therefore, this paper aimed to review the key technologies and design principles of the low-impact network which shall be implemented into future networks to ensure sustainability and carbon neutral. Furthermore, data were utilised from UK government's 'Heat Network Project Pipeline' documents which cover a wide range of projects supported through the development stage by the UK Heat Network Delivery Unit. A statistical analysis was also undertaken to identify popular heat source technologies currently being implemented into the UK networks. Information such as technologies, size and costs were analysed to establish the intercorrelations, which may influence the type of technologies being selected. The results show that 56% of total networks contained Combined Heat and Power (CHP) as a primary heat source, of which over 40% were gas fired CHP, displaying the current dominance of the technology. Overall, it is evident in the UK that, the new networks have been improved from previous generations with a high concentration of renewable energy technologies and heat recovery methods being used. However, there is still a high reliance on natural gas, which does not fulfil the characteristics of a low-impact heating network.

## 1. Introduction

### 1.1. Environmental concerns

In 2021, worldwide $CO_2$ emissions were estimated at 34.6 Gigatonnes, which matched the all-time high record in 2019 [1]. Guterres [2] explained that there is currently an ambitious task for countries to urgently become carbon neutral, with an aim to achieve this by 2050 to mitigate global warming. Ensuring this target requires a substantial amount of commitment from a wide range of sectors to modify their policies, expenditures, regulations and technologies. A landmark turning point on the fight against climate change is the creation of The Paris Agreement, a legally binding international treaty which currently has 195 parties enlisted [3]. The Paris Agreement's main goal is to limit global warming to below 1.5 °C (2 °C Maximum) in a collaborative effort to implement long term strategies, utilise technologies and provide financial aid to vulnerable countries.

A large contribution to $CO_2$ emissions is from heating buildings in the UK. In 2016, the UK Parliamentary Office of Science and Technology [4] estimated that 98% of greenhouse gas emissions are within commercial and domestic settings, of which 13% for industrial, derives from the process of heating space and water. In 2021, statistics in the 'UK Energy in Brief Report' [5] show that since the 1990′s, energy consumption by domestic and industry equates to almost 50% of the overall energy used

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in the UK as shown in Fig. 1, derived from the 'UK Energy in Brief Report' [5]. Furthermore, Fig. 2 alarmingly, displays how the contribution of natural gas consumption to the total energy consumption between 1990 and 2020 has risen 17%, predominantly due to the transition from coal. Although the combustion of natural gas emissions is lower in comparison to coal, it shall be at the forefront of priorities to accelerate the development of renewable heating technologies and their implementation to ensure suitability, user satisfaction, financial viability and resilience.

### *1.2. UK's approach on heating homes and buildings*

Recently, an UK government document – Heat and Buildings Strategy – [6] states that it is necessary to phase out all natural gas fired appliances and change to low carbon technologies such as hydrogen, heat pumps and new heat networks. Another key document, which is the Building Regulations Part L, introduces a fabric-first approach and ensures buildings are being built to standards which limits the heat output requirements [7]. It is also crucial to achieve zero carbon on existing buildings [8,9], and the thermal transmittance values of older homes are proposed to be improved by retrofitting insulation via incentives such as green homes grant [6]. The GB (Great Britain) electricity system report [10] discusses the predicted increased demand for electrification of heat which linearly intensifies the risk of overwhelming the electrical infrastructures capacity, therefore requiring re-enforcements. This is also supported by the Heating and Buildings Strategy published in 2021 [6], which displays a biased approach on technologies proposed for heating homes with a substantial target of 600,000 heat pumps to be administered per year by 2028. It is therefore transparent that major electrical infrastructure enhancements are required to enable the widespread application of heat pumps and other electrification of heating methods.

UK heat networks, also known as district heating (DH), have been used for centuries. However, due to their small proportion in the UK, heat networks were unregulated and unrecorded until 2014 where the heat network (for metre and billing) regulations were enforced [11]. The aim of this policy is to improve energy efficiency, reduce carbon emissions, energy consumptions and costs. A strong focus within the heat networks regulation is the implementation of accurate metering for end users so that billing can be applied. Additional heat networks schemes within the UK include Heat Networks Delivery Unit (HNDU) and Heat Networks Investment Project (HNIP). The main aim for the HNDU is to provide support and guidance to local authorities to overcome challenges and provide clarity on the benefits of DH [11]. The HNIP provides financial support [12] which leads to 320 million capital investment to increase the volume of heat networks. The considerable capital budget from HNIP displays a significant role to push DH as a low carbon heating

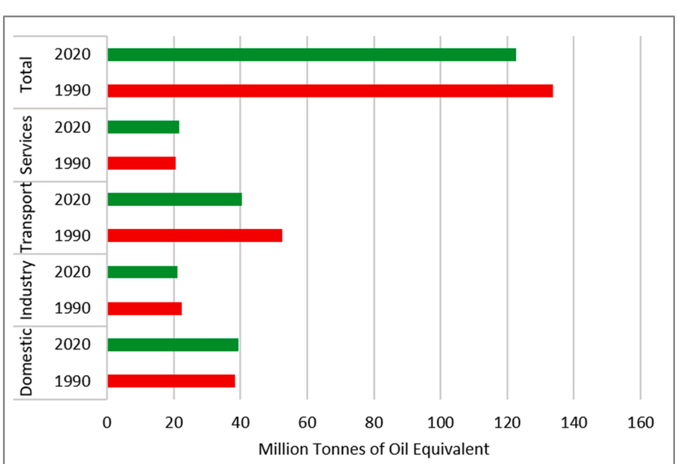


**Fig. 1.** Final energy consumption from 1990 to 2020 in the UK [5].


**Fig. 2.** UK's gross energy consumption from 1990 to 2020 derived from 'UK Energy in Brief Report' [5].

solution in the future. Echoing this, Mazhar et al. [13] expresses how it has been widely acknowledged that DH is considered a prime solution for revamping heating, particularly to urban areas. Furthermore, the UK government's report in 2021 predicts that 19% of total heat demand can be contributed by DH which further supports the significance of DH to the future of carbon neutral heating solutions in the UK [14]. Table 1 presents an overview of the current status of government strategies on sustainable home heating in the UK.

### 1.3. Importance and barriers in progression

The UK Department for Business, Energy & Industrial Strategy (BEIS) has recognised that DH systems could promote the necessary changes required within heating distribution to achieve zero carbon [14]. DH on a mass scale has already proven positive outcomes in other countries such as Denmark. Johansen and Werner [15] explains how the world energy council consider Denmark's energy security, equity and sustainability among the best in the word which has two thirds of private households served from DH. The large quantity of DH in Demark is due to the oil crisis in 1973 which triggered the nation to become one of the first to implement DH on a wide scale [16]. From that point onwards, Denmark has made a conscious effort to invest further into DH and renewable sources with the Danish District Heating Association [17] claiming that DH plays a vital role in Denmark becoming carbon neutral by 2050. For the UK to achieve zero carbon through DH, further testing is required into technologies and their applications to overcome the flaws and undesired traits of previous generations. It is also essential that existing DH networks must also undergo dramatic changes to ensure that efficiencies and emissions are improved without the expensive capital costs of replacing the entire system [18]. This could perhaps be the most challenging component, as the existing network's topology is designed on previous criteria which may not be easily adapted. Sorknæs et al. [19] simulated a DH Network in Aalborg Municipality in Demark where a third generation DH was upgraded to the features of a fourth generation, which, showed a decrease in primary energy consumption of the entire system by an estimated 4.5%. In larger DH systems this is a substantial saving; however, limitations need to be addressed to ensure that this can be achieved in reality.

It is of paramount importance that DH Networks are progressed urgently for the UK to reach the 2050 aim of net zero. DH Networks typically emit 15% less emission per MJ of heat compared to gas to heat combustion [20]. Unfortunately, research shows that there has been no improvement to emission rates from DH between 1990 and 2015 [20].

**Table 1**
Summary of the UK government's statistics, barriers, and current actions on sustainably heating homes.

| Focus | Concrete action | References |
|---|---|---|
| Statistical greenhouse gas emissions | Heating and hot water within domestic and commercial settings contribute to 98% of greenhouse gases | [4] |
| Key aims | Provide support and guidance to local authorities to overcome challenges and provide clarity on the benefits of DH | [11] |
| Financial aims | Delivers 320 million capital investment support to increase the volume of heat networks being built | [12] |
| Future electrical infrastructure | Future re-enforcements are required due to the intensified electrification of heat intensifying the risk of overwhelming the electrical infrastructure | [10] |
| Strategy to achieving zero carbon | Phasing out of natural gas fired appliances and promoting hydrogen, heat pumps, and developing new heat networks Target of 600,000 heat pumps to be administered per year by 2028 | [6] |
| Future heat networks potential in the UK | 19% of total heat demand can be contributed by District Heating Networks | [14] |

This reflects a lack of development over decades which could cause DH Networks to be over-looked as a vital solution to sustainable heating. This paper therefore investigates the implementation of key technologies including controls and design philosophies which are required to mitigate DH networks contribution to climate change.

### 1.4. Objectives

This review paper aims to find the answers to the questions of:

- What technologies and design philosophies are required to ensure that a low-impact district heating network concept is achieved in reality?
- How do new District Heating networks complying with the UK Government's guideline compare to the concept of a low-impact network?

## 2. Technology review

DH Networks provide flexibility by using the thermal capacity of water that is contained in the district heating network pipes to store energy and shift the heat load in time [21]. They are predicted to provide a substantial contribution towards future carbon neutral heating in the UK, particularly to urban areas [22]. History shows slow progression throughout the generations of Heat Networks; however, it is now urgently important for further research to be sought into the fourth and fifth generations to discover the solutions for achieving carbon neutrality [18]. Heat Networks Code of Practice in the UK [23] displays a lack of clarity and detail with regards to the fourth (4G) and fifth generations (5G). Although this publication entails a brief description of the network's characteristics, it does not specify exact requirements needed for fourth and fifth generation networks, which somehow prohibits further progression in the UK. Ergo, this section provides a critical evaluation of current publications with regards to the technologies, controls and design philosophies, which shall be applied to ensure that future DH generations are carbon neutral.

### 2.1. Heat production technologies

At the end of year of 2021, 90% of global DH Networks still relied on fossil fuels [24]. The majority of these systems rely on traditional gas fired appliances as their main source of energy due to their cost effectiveness, robust design and simplified implementation to meet DH network demands [25]. Moving forward, there are compelling references to a variety of renewable and highly efficient technologies such as heat pumps, hydrogen, geothermal, solar thermal, waste incineration, combined heat and power (CHP), and industrial surplus heat. Following sections of the review discuss three heat production technologies which are widely accepted to make a large impact on future DH becoming carbon neutral.

### 2.2. Combined heat and power

It is widely accepted that CHP can make up a large contribution of heat production within near future DH systems, which is acknowledged by Lund et al. [26] who states that 'district heating in future sustainable cities allows for the wide use of CHP'. CHP is considered to be a technology which can save energy around 30% and also similar reductions in $CO_2$ emissions in comparison to conventional methods [27]. Jimenez-Navarro et al. [28] reports how CHP could be a viable substitute for thermal power plants. The work was carried out in this study suggests that the conversion of thermal power plants to CHP and utilising the excess heat for DH could increase the energy systems efficiency from 63% to 80%. This demonstrates particularly how CHP application in power plants can improve efficiencies, reduce waste and lower carbon emissions on a mass scale.

Traditionally, CHPs are fuelled from natural gas. However, most recent versions can be fuel neutral, meaning that they can be fuelled from fossil fuels as well as renewable sources [29]. Due to the decarbonisation aims of the UK and the heightened stringency of emissions policies, it is crucial for CHP technologies to diverge from natural gas. Hedman et al. [30] explains how the role of CHP is changing to adapt to industry net zero objectives. Short term, CHP can provide resilience, flexibility and be the most efficient way of generating power and thermal energy. Long term, fuels such as hydrogen and renewable natural gas are possible alternative sources. It is further explained how renewable CHPs could offer carbon zero solutions to provide power and thermal energy to infrastructure and operations where resilience is critically required. At present, these types of fuels are limited and are high in cost, meaning that natural gas is highly relied upon short term. Formela et al. [31] describes how natural gas CHP's $CO_2$ emissions can be mitigated by the introduction of an absorption column. This process entails the exhaust gasses to be washed with solvent such as methanol to mitigate $CO_2$ being emitted to the atmosphere. These attributes show positive progression in increasing the viability of CHPs implemented into near future networks.

CHP also provides the benefit of relieving the electrical infrastructure which is predicted to be under extreme strain due to the increased electrification of heat proposed [32]. The deployment of electrical heat is expected to have challenges on both the transmission system operator (TSO) and on the distribution network operator (DNO) [10]. Rezaie and Rosen [33] described how in winter, heat produced from the CHP is considered the primary product while the electricity produced can be fed back into the grid or used on site. This in essence creates a "synergy" between networks and assists in achieving future electrical demands. A drawback to CHP is that it cannot efficiently accommodate for the peak heating demand of a network alone; therefore, often requiring back-ups from gas fired boilers. An extreme example of this was demonstrated in a case study of Østergaard and Lund [34], which showed technologies such as CHP units and heat pumps being unable to cover the demand most of the year. Consequently, boilers were used extensively and only inactive during the summer months. This results in greater carbon emission production as well as a substantial increase in capital expenditure are highly undesirable for a low-impact DH Network. Table 2 summarises the key points of CHP applied in the DH networks.

### 2.3. Heat pumps

Heat pumps are an example of electrification heat which absorbs and disperses heat from surroundings such as air, ground or water [35]. Most studies refer to heat pumps as being one of the primary technologies to be used in future DH networks. Whereas Lake et al. [36] states that there are better incentives for CHP and waste incineration DH systems, and the use of ground source heat pumps will likely decrease in both short and long term applications. However, the attributes of heat pumps such as the low operating temperatures would complement the proposal for low temperature DH networks and also provide flexibility on where they can be situated. As mentioned earlier, a major concern with electrification for heat is the increased demand on the electrical infrastructure. Siddiqui et al. [37] discusses how this could be prevented by using thermal energy storage, allowing for flexibility to avoid peak demands, which also providing cost benefits such as generating the heat between hours of a lower tariff. Werner [20] describes how the heated return waters in district cooling systems are used as a heat source in large heat pumps supplying heat into DH systems, known as heat recovery. As seen with CHP facilitating a synergy between electric and heating networks, similarly, heat pumps can improve cooling and heating networks efficiencies by working collaboratively with the likes of absorption chillers. Further, Bryne and Ghoubali [38] discussed how heat pumps have the ability to produce simultaneous heating and cooling synergies which benefits from reduced energy consumption. This method would also improve capital expenditure and increase the internal rate of return, making it a more attractive option for network owners. The type of refrigerant used in heat pumps shall also be considered moving forward, as some refrigerants have high global warming potential and Ozone depletion potential. The Fluorinated Greenhouse Gases Regulation [39] aims to cut down hydrofluorocarbons (HFCs) that can be sold in the EU by 79% by 2030. Recently, Slorach and Stamford [40] discussed how a pure propane refrigerant (R-290) is a viable alternative, when swapped for R-134a, the overall climate change impact for generating 1 kWh of heat becomes negative at -0.009 $kgCO_2eq/kWh$ in comparison to 0.008 $kgCO_2eq/kWh$ for R-134a in a 2050 scenario.

Finally, an additional benefit of heat pumps is their ability to recover heat from various sources. A survey by David et al. [41] shows current DH Networks within Europe which operate heat pumps using a variety of sources such as sewage water, industrial waste heat, geothermal water, flue gas and solar heat storage as a source of heat, which demonstrated the flexibility for heat pump integration. Werner [20] explains how natural resources such as lakes and deep seas in countries with cold winters can also utilise the stored cold waters for district cooling within summer months. This would relieve the cooling equipment's working load by narrowing the temperature differential between the source and supply temperatures. Thus, decreasing the amount of energy and costs required to effectively supply cooling to buildings. Table 3 presents the key points of heat pumps applied in the DH networks.

### 2.4. Waste heat recovery

An increasingly popular trend within recent studies shows that heat recovery from waste is considered a way of utilising heat which would traditionally dissipate into the environment as a bi-product. Cioccolanti et al. [42] acknowledge how waste heat recovery from energy intensive

**Table 2**
Summary of the key points of CHP in DH networks.

| CHP key points and characteristics | References |
|---|---|
| CHP is typically 30% more efficient and also has the similar reductions in $CO_2$ emissions in comparison to conventional methods | [27] |
| Absorption column to be introduced for the exhaust gasses to be washed with solvents to mitigate $CO_2$ emissions | [31] |
| Particular case study shows gas fired boilers being used extensively except in the summer due to heat pumps and CHP unable to cover the demand for the majority of the year | [34] |
| In short-term, CHP can provide resilience, flexibility and being the most efficient way of generating power and thermal energy; while in long-term, fuels such as hydrogen and renewable natural gas are possible alternative sources for CHP | [30] |
| Study proposes how CHP could be a viable substitute for thermal power plants with efficiency improvements from 63–80% | [28] |

**Table 3**
Summary of key points for heat pumps being implemented into DH.

| Heat pumps key points and characteristics | References |
|---|---|
| Predicted decrease in heat pump application due to larger incentives for CHP and waste incineration | [36] |
| Utilising thermal energy storage, allowing for flexibility to avoid peak demands, reducing the likelihood of overwhelming the electrical infrastructure and improving energy costs | [37] |
| Utilising heated return waters in district cooling systems to be used as a heat source in large heat pumps supplying heat into DH systems | [20] |
| Simultaneous heating and cooling synergies which benefits from reduced energy consumption | [38] |
| Propane refrigerant (R-290) is a viable alternative, when swapped for R-134a, the overall climate change impact for generating 1 kWh of heat becomes negative at -0.009 $kgCO_2eq/kWh$ in comparison to 0.008 $kgCO_2eq/kWh$ for R-134a in a 2050 scenario | [40] |
| Europe case study presents heat pump integration flexibility by recovering heat from sources such as sewage water, industrial waste heat, geothermal water, flue gas and solar heat storage | [41] |

industries has a great potential in curbing $CO_2$ emissions. This is supported by Arnaudo et al. [43] who state that waste heat recovery at 10% of the peak load can reduce fossil fuels by 40%. A study in the UK shows that if the re-used waste heat from its buildings and industrial processers, this could be used to supply 14% of the hot water and heating demand in UK homes [44]; when directly comparing this to the results of Arnaudo et al. [43], this would indicate that a possible over 40% fossil fuel reduction could be achieved. Most recently, Hancox et al. [45] revealed the viability of harnessing waste heat from the hot smoke through a cold abatement smoke extract system over the course of industrial manufacturing in the UK.

As the new form of DH is considered to operate at lower supply temperatures, Rezaie et al. [33] explained that heat recovery from industrial surplus, incineration plants and energy plants could solely supply low energy buildings if stability was maintained. Many other forms of waste can also be utilised, a case study conducted by Sun et al. [46] reported that using a steam generator's exhaust gas increased the heating capacity of the system by 41%. This was achieved by heat transfer through an ejector heat exchanger based on the ejector refrigeration cycle, transforming the way in which the whole network performed. The results particularly show lower return temperatures and an improved heat transmission by 66.7% without changing any flow rates. This study demonstrates not only the benefits of using waste heat, but also the improvement of heat transfer by using an ejector heat exchanger transfer method.

Lund et al. [26] acknowledge how heat resources from waste is limited and therefore should be used in an optimal way. There is widespread agreement that waste heat should be used optimally, however, more recent studies suggest that heat resources from waste are not as scarce as initially suggested. Wheatcroft et al. [47] provides examples such as data centres, metro systems, public sector buildings and waste water treatment plants. A common source of heat is the use of sewage water, which can be connected to a DH Network in multiple different ways including heat exchangers, or connected to the evaporator side of a heat pump [48]. Averfalk et al. [49] report that some of the world's largest DH networks which utilise heat pumps often rely on the likes of sewage water, ambient water and industrial heat as a main resource. Their findings show that sewage water was more resilient in a long-term in comparison to the other resources used.

Another form of heat recovery is heat transfer between various prosumers connected to the DH Network. Lake et al. [36] discussed how integrated thermal networks could allow multiple producers of thermal energy to supply the network. Examples of this include customers who have heat generation capacity that could sell excess heat via supplying it to the DH network, for example a customer's solar collector. Although prosumers seem a simple approach with many benefits, it is important that the extent of controls and design philosophies are understood. Studies from Brange et al. [50] and Brand et al. [51] investigated the impact of prosumers on a network show similar findings. Their discoveries reveal that often there are adverse effects caused by lower temperatures being supplied into the network, causing an overall decrease in the network's operating temperature. Furthermore, it is seen that an imbalance of velocities results in the system's flow rates and pressure differentials to become obscure. In addition, the change in the DH's thermal and dynamic profiles causes dissatisfaction for customers due to the lower supply temperatures their properties receive. Table 4 summarise the key points of waste heat recovery implementation in the DH networks.

**Table 4**
Summary of waste heat recovery implementation into DH.

| Waste heat recovery key points and characteristics | References |
|---|---|
| Waste heat recovery at 10% of the peak load can reduce fossil fuels by 40% | [43] |
| It is viable to harness waste heat from the hot smoke through a cold abatement smoke extract system over the course of industrial manufacturing in the UK | [45] |
| Heat recovery from industrial surplus, incineration plants and energy plants could solely supply low energy buildings if stability was maintained | [33] |
| Case study showed a steam generator's exhaust gas increased the heating capacity of the system by 41%; this was achieved by heat transfer through an ejector heat exchanger based on the ejector refrigeration cycle | [46] |
| Case study presents some of the world's largest DH networks which utilise heat pumps often rely on the likes of sewage water, ambient water and industrial heat as a main resource, while sewage water was revealed the most resilient source | [49] |
| Case studies show adverse effects caused by prosumers' lower temperatures being supplied into the network, causing an overall decrease in the network's operating temperature | [50,51] |

*2.5. Design temperatures*

The progression of DH throughout the generations exhibits a common trend of reduced ambient water temperatures within the network. Low temperature district heating provides lower heat losses in the DH networks [52]. Studies have shown a substantial variation in what current temperatures are in existing networks compared to what they are proposed to be in a future 5G networks. Millar et al. [53] report that it is generally accepted that 5G ambient networks is in the region of 10–40 °C. However, Averfalk and Werner [54] argues that the existing documentation of low temperature systems displays no average system return temperature below 30 °C. This suggests that existing low temperature networks in operation are not designed to temperatures as low as stated by Millar et al. [53] or that the heat source is not operating reciprocally to the dynamic heat loads within the network. There are many articles supporting the idea of low temperature distributions, such as Lund et al. [26], who acknowledged that lower temperatures, combined with small pipes, reduce distribution heat losses to existing networks by roughly 75%. The heat loss throughout distribution is directly related to the networks operating temperature, resulting in a negative impact on the efficiency of the network when at higher temperatures.

The fabric first approach can ensure that buildings which are yet to be built can be designed to accommodate the low supply temperatures for heating purposes [55]. It is becoming more common that buildings and homes are equipped with underfloor heating which provide good flexibility potential due to the inertia of this type of emitter [56]. This system is also complimentary to the lower supply temperatures, therefore can be categorised as 'future-proofed'. A study by Li et al. [57] however, suggest that underfloor heating would not correspond to a DH Network's design temperature differential. To ensure that the floor is heated evenly, it is important that the temperature does not drop excessively, otherwise this would cause cold spots. It is expected that at a 30 °C flow, the return temperature would be near 27 °C. The 3 °C temperature differential would be a slight compromise, notwithstanding, the return temperatures are still low with Lund et al. [58] discussing a typical return temperature of 20 °C, therefore in comparison, only a 7 °C variation.

Averfalk and Werner [54] suggest that supplying radiators with supply and return temperatures of 45–25 °C for an ambient air temperature of 20 °C. This unusually high temperature differential is double the current UK standard of 75–65 °C with an ambient air temperature of 20 °C [59], which will also result in larger radiator sizes. A solution to achieving a desired higher "delta T" (that is, the temperature differential) would be the implementation of pre-settable thermostatic radiator valves (TRVs) that set radiator flows low enough to achieve the desired return temperature as seen in some Scandinavian systems [60]. Although these implications could be accounted for at the design stage of new developments, further challenges arise when considering low temperature DH for existing buildings and homes. Using an Analytic Hierarchy Process (AHP) method, Pellegrini et al. [61] distinguished an order of importance regarding the key barriers when upgrading from an existing DH to low temperatures within Italy. The results show that the highest importance (32.3%) was given to the impact on customers. This was due to the large quantity of low energy efficient buildings, which had a higher risk of dissatisfactory thermal comfort due to the lower supply temperatures. This is directly relatable to the UK, which is estimated to have 80% of buildings already built in 2050 [8]. It implies that existing DH networks need more focus and attention than new ones. Currently, there is funding available to improve building's thermal transmittance and air tightness as previously discussed, however, there are limitations to how well this can be practically applied. It therefore be reasonable to suggest that 4G and future networks (such as 5GDH) may range in temperature depending upon the circumstances of customers' buildings. With continuous improvement to existing buildings fabrics, the DH temperature can gradually decrease as newer renewable technologies are applied, however, not with immediate effect or consequence to customers.

An alarming concern commonly discussed is the inadequate supply temperatures for domestic hot water (DHW) production. The operating temperatures which are expected from a 5GDH network will not provide the hot water requirements laid out by the Approved Code of Practice L8 [62]. It is transparent that even a supply temperature of 45–50 °C is not always adequate to deliver the hot water requirements. A promising method to overcome this, explained by von Rhein et al. [63], is that utilising an instantaneous heat exchanger and a micro-tank with immersion heater on the consumer side for DHW preparation. A similar but alternative option would be to introduce the boosting element on the DH networks supply which is typically at a lower flow rate. The boosting element could elevate the network supply temperature and be controlled from the consumers heat interface unit via a micro-switch or hall sensor to only energise the element when DHW is flowing. This type of system allows for control integration between the consumer and the network which will benefit from lower return temperatures, ensuring efficiencies are maintained. Yang and Svendsen [64] report a comparison of the above methods which showed that the most efficient method was when introducing the micro-tank on the consumer sides hot water flow which lowered the return temperature the most. For instance, where a building has a high hot water demand, there will often be a necessity for a hot water storage tank within the building. In fact, there are multiple ways to increase the supply temperature, such as immersion heaters. Lund et al. [26] discussed how micro CHP may be required within the consumers' building and substations to boost the water to the necessary temperature. Although this results in a higher return temperature in comparison to an instantaneous heat exchanger, the design approach will ensure that the return temperature remains minimal. The requirement for an extra heat source within the consumers' building or at a local substation would increase the capital costs significantly. This also raises concerns to whether the DH network is a feasible option altogether. The key points of design temperatures for 5GDH are concluded inTable 5.

**Table 5**
Summary of design temperatures key points for 5GDH.

| Design temperature key points | References |
|---|---|
| 5G ambient networks to be in the region of 10–40 °C | [53] |
| Future buildings are equipped with underfloor heating which provides good flexibility potential due to the inertia of this type of emitter | [56] |
| Typical 5GDH return temperature is 20 °C | [58] |
| Desired higher delta T to be achieved via pre-settable TRVs that set radiator flows low enough to achieve the desired low return temperatures | [60] |
| Italian case study reports that dissatisfied customer is the most important barrier which is mainly due to inefficient existing buildings and low supply temperatures causing thermal discomfort | [61] |
| Instantaneous heat exchanger and a micro-tank with immersion heater on the consumer side for DHW preparation with low supply temperatures | [63] |
| Temperature elevation via micro-CHP situated in customers building or substations | [26] |

## 2.6. Design considerations

For DH networks to be most effective, it is important that the consumers' dynamic loads are estimated to a reasonable degree of accuracy. Guelpa and Verda [65] point out that demand side management in an electricity grid is a well-known concept; however, it is significantly less widespread in district heating system's thermal demands. This is a crucial element to consider enabling heat sources within a network to be sized and designed to respond in cohesion with the consumers load demands. It is therefore important that available data from metering devices should be analysed to create algorithmic modelling for accurate dynamic heat load predictions, which is currently being widely researched. For example, Song et al. [66] show an estimation model based on spatiotemporal hybrid convolution neural network long-short term memory (CNN-LSTM) displayed accuracy advantages of predicting performance in comparison to support vector machine (SVM) and other ensemble algorithms. Similarly, Lumbreras et al. [67] presented a 'Q Algorithm' which was fed data from heat meters. The heat load profiles were then analysed, and a model based on multiple variable regression and supervised clustering methods were used to predict loads. Specifically, variables including external weather conditions were taken into account and the results indicated a good performance for yearly prediction with a maximum deviation of 15% in the worst fitted building. These studies demonstrate the importance of utilising mass data from monitoring devices within networks to promote continuous development and model calibration. This brings benefit to future network's load predictions as well as provides engineers with the information required to carry out continuous calibration to replicate the dynamic load profiling within existing networks.

Unlike previous networks, which typically have one main heat source, it is proposed in future that multiple technologies will make up a DH Network. It is stated by Averfalk and Werner [54] that a single-technology perspective does not suffice, in order to ensure 100% renewable energy a more integrated approach is required. This is echoed by Werner [20] who also points out that a combination of heat recycling and renewable heat is the current focus for district heating systems. Thus, it is crucial that local resources are utilised such as lakes, ground and waste heat from industrial processes depending on a network's location. Upon selection, renewable energy supplies and waste heat requires resource assessments, appropriate technologies, and systems that can properly integrate the renewable energy sources by meeting demands with the right temporal profile [68]. It is therefore necessary to determine what typical temperatures are likely to be supplied by various sources and how resilient they are. This will then facilitate the decision-making process in terms of what type and size of heat sources are required.

It is claimed by Lake et al. [36] that waste incineration has less of effects on ground source heat pumps compared to biofuel CHPs. This is mostly due to increased temperatures causing heat pumps to work less effectively compared to a mean temperature of 40 °C. This can be overcame with the application of various controls such as a three-port actuator valve positioned on the return pipework before the heat pump. It allows for higher temperatures to bypass the heat pump and be reutilised within the flow pipework. This configuration is described in the Heat Networks Code of Practice [23], while the purpose of the aforementioned scenarios is to maintain a heat pump manufacturers' appropriate temperature differential. When considering how networks are going to utilise these resources, it is important that a hierarchy approach is used. Priority should be given to heat recycling initially to create a base load followed by renewable technologies before the consideration of any fossil fuels, as discussed in the study of Lund et al. [26].

Many studies recognise that CHPs are to play a pivotal role in future DH networks. Kelly and Pollitt [69] report how CHP is a proven technology that can significantly contribute to increasing energy efficiency and the mitigation of carbon emissions, while CHP's high operating temperature characteristics however would seem contradictory to the low operating temperatures of a 5GDH network. Dwyer [70] stated that how CHP applications are designed to operate at a large delta T similar to other technologies, with a return temperature of typically 45–40 °C. Due to this higher temperature differential, a smaller pipe will be applicable which reduces heat losses by 43%. It is therefore shown that the key aims for a 5GDH network including reasonably low return temperatures and high delta T is still achieved. As a result of this, it is suggested that CHP could be a steppingstone solution to improve emissions for existing networks which may require higher temperatures due to low energy building limitations.

To maximise the efficiency of the CHP, it is important that the loading profile is accurately predicted. The variability of operating conditions can often render the application of CHP ineffectively [71]. Fig. 3 shows an example of a load profile for a CHP and a thermal store over a 24-h period, which has been modelled to display an effective implementation of a CHP and a thermal store [23]. It is evidenced that the CHP and the thermal store would meet the peak demands by operating simultaneously, however, the CHP is also able to meet the average site heat demand as a priority whilst excess heat is provided to the thermal store for future use. This allows the CHP to generate a constant supply of about 2300 kW. This model displays how the low carbon technology, being CHP, is prioritised over the top-up boiler and how the thermal store has smoothed out variable heat demands; and therefore, enabled the CHP to operate at maximum efficiency by eliminating the requirement to satisfy instant heat demands.

In the past, bypasses were deemed necessary within DH to maintain pump's minimum flow rates. However, recent studies show that bypasses yield high return temperatures roughly similar to the supply temperatures [72]. Crane [60] demonstrates the impact of small and fixed flow bypasses which at low flow rates displayed over 50% of the return water at 80 °C, therefore, doubling the return temperature. This instance identifies the inability to achieve minimum flow rates without sacrificing the return temperature. Averfalk and Werner [54] also express the impacts of bypasses, stating that approximately 10–20% of annual DH flows are wasted to bypasses. The study suggests that networks should exclude bypasses and integrate a third pipe of a smaller size to re-circulate the supply water when required. The use of a smaller third pipe ensures heat losses are minimal within the flow while the return water is not contaminated. Similarly, Crane [60] also expresses future networks should not include bypasses, while an alternative method would be to ensure that the pumping arrangements have a large turn down to operate effectively at minimum system flow. However, this is not always achievable, and therefore it is suggested to use multiple smaller or jockey pumps to run alongside the large peak flow pumps.

However, the common issue with variable flow systems is the lack of hydraulic balance, specifically the systems which compromise multiple variable flow circulation pumps. This type of configuration can often cause hydraulic oscillation which leads to sever water hammers causing damage to the pipes and pumps [73]. For this type of system, the extensive use of differential pressure controllers and flow limiters can ensure a constant pressure is maintained throughout sections of the network and excess flow kept minimal. According to the report of Boysen and Thorsen [74], this method ensures a fair distribution of water flow rate as well as delimits the quantity of re-circulated water, therefore reducing the return temperature in the network. Alternatively, Schmidt et al. [52] discussed how controllers and valves can be designed out by implementing a 'ring network topology'. This design method ensures balanced pressures and flow rates across the whole network by having equal pipe-lengths similar to the traditional 'reverse return' concept. However, in reality, for a network which consists of multiple heat sources and substations, the implementation of a loop topology may prove difficult to configure. Table 6 outlines the design considerations of the future DH network progression.

### 2.7. Controls and communications

As evidenced above, there are numerous challenges and limitations associated with the various technologies proposed to be implemented into future DH. Thus, it is crucial that these components are monitored and operated via intelligent controls to ensure the network's performance and efficiency are optimised. It is thought that the intelligent controls strategy begins at the consumers' building. These controls will assist in delivering variable temperatures throughout the secondary circuit, dependent upon external weather conditions, which is commonly known as "weather compensation" [75]. An example of this

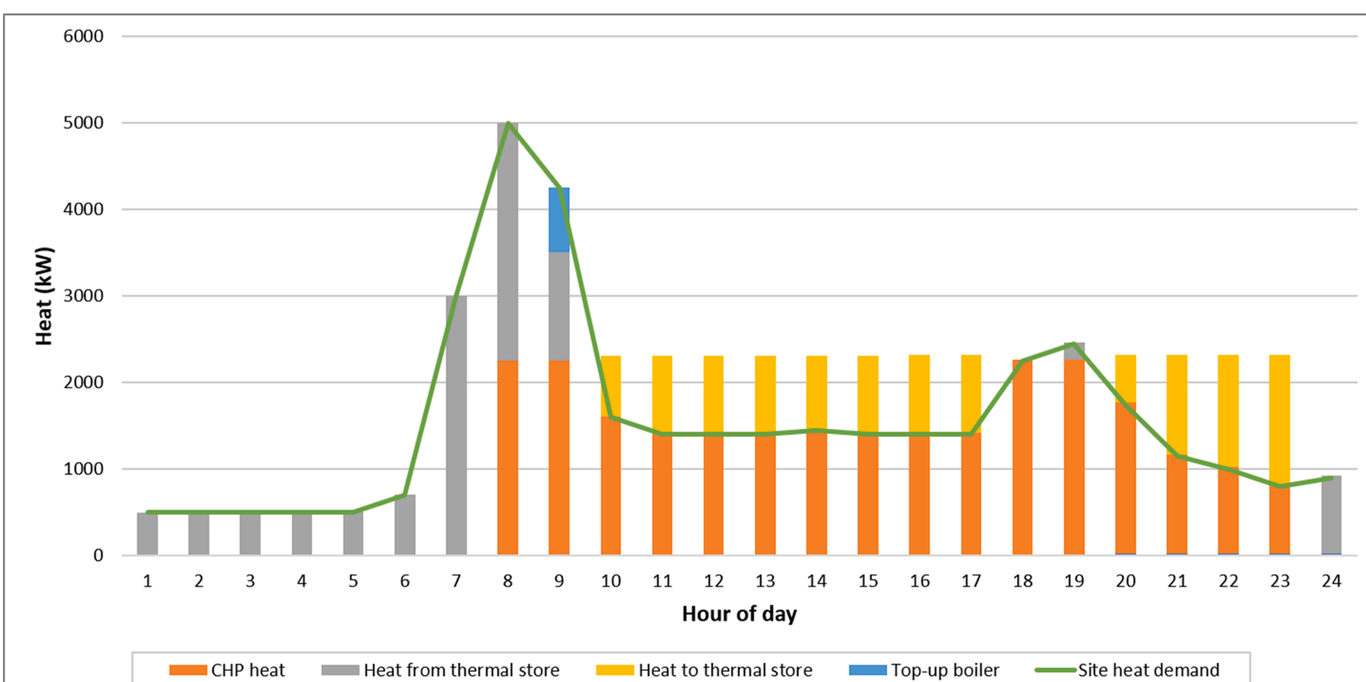


**Fig. 3.** CHP and thermal store heat demand modelling over a 24-h period [23].

**Table 6**
Overview of design considerations with regards to future heat network progression.

| Design considerations focal points | References |
|---|---|
| Utilisation and analysis of metering devices to create algorithmic modelling for accurate dynamic heat load predictions | [66,67] |
| - To ensure 100% renewable energy, an integrated approach is required which involves multiple technologies within a single network<br>- Predictions of 10–20% of annual DH flows are wasted to bypasses, and networks should exclude bypasses and integrate a third pipe of a smaller size to re-circulate the supply water when required | [54] |
| When selecting renewable energy supplies and waste heat recovery methods, resource assessment should be carried out; furthermore, multiple technologies being implemented need to share the right temporal profile for efficient operation | [68] |
| CHP applications should be designed to operate at a large delta T with a return temperature of typically 45–40 °C; due to this higher temperature differential, a smaller pipe will be applicable which can reduce heat losses by 43% | [70] |
| The variability of operating conditions can often render the application of CHP ineffective therefore needs to be suitably sized through maintaining the systems base load | [23,71] |
| - The impact of small and fixed flow bypasses which at low flow rates showed over 50% of the return water to be at 80 °C, therefore, doubling the return temperature<br>- Future networks to disregard bypasses and ensure that circulation pumps have a large turn down to maintain minimum system flow efficiently | [60] |
| Mitigating extensive use of controllers and valves to accurately control variable flow systems by implementing a 'ring network topology', which ensures balanced pressures and flow rates across the whole network by having equal pipe lengths | [52] |

was explained by Lund et al. [26], in a scenario of an underfloor heating system which was weather compensated, allowing for the concrete deck to discharge before the occurrence of excess solar gains. This was achieved by taking into consideration future external conditions, therefore, lowering the heat output to the building accordingly. In turn, this created a more comfortable environment as well as improved efficiencies.

Recent studies also exchange views on a weather compensated primary network which controls the heat production plant directly as seen in a simulation model presented by Østergaard and Svendsen [76]. This would provide key benefits including lower supply and return temperatures, lower heat losses and increased responsiveness. A major, yet rarely discussed limitation is that the minimum flow temperature in the primary network will be governed by the secondary requirements for DHW [77]. As stated earlier, the idea of a Low Temperature District Heating network (LTDHN) may be inadequate to provide the DHW requirements at maximum operating temperature, thus an even lower supply temperature would seemingly be unsuitable. A possible solution voiced more commonly is to weather compensate the substations that supplying the properties, which is discussed in a more recent study of Østergaard et al. [72]. It is demonstrated a substation compromising of a controller enabling weather compensation, external weather sensor, flow pipework sensor, actuating valve and differential pressure controller to ensure appropriate operating conditions for the control valve; while the control valve is located in close proximity to the heat exchanger to ensure that heat delivery is achieved in an appropriate time-scale especially when considering DHW production.

Gao et al. [78] characterised 5GDH controls as computational intelligence which was close to the human brain with the ability to optimise the DH network's performance. This was comprised of several control methods including fuzzy control, neural network control, expert control, human-simulated intelligent control and hybrid control. The control system itself was split into three parts: dispatching and management system, on-line energy consumption analysis system, and accident alarm system. It was designed to provide real time performance, fault alerts and the ability to regulate large amounts of data to automatically adjust the network's dynamic profile, and as a result became more efficient. Moreover, the data can then be stored on a cloud platform to access, share and store diversified energy information. A case study by Grosswindhager et al. [79] presented a DH network in Tannheim using a fuzzy direct matrix control (DMC) to handle the inherent nonlinearity characteristics of DHN by considering the volume flow rate at the plant as fuzzy variable. The results show that the fuzzy DMC identified that the DH network was trading off between pumping and heat losses. This significantly impacted the operational costs and ultimately the overall efficiency of the network. It is apparent that the implementation of fuzzy controls in a DH network could meet the demanding complexity of the network's characteristics which require controlling, as well as the ability to improve the effectiveness of the automated control systems.

In addition, meters with pulsed outputs to the heating network's energy management system is assumed to provide many benefits. Averfalk and Werner [54] explained how the increased implementation of information and communication technology would alleviate the work to counteract temperature errors in substations and customer heat systems. The output received from the meters can actively monitor the use of heating, cooling and DHW usage from individual buildings and substations. In essence, this would assist in continuous calibration of the heat network as the system's profile is built up based upon patterns of customers' usage. The data collected can be stored and processed to establish any anomalies caused by faults within the substation, which if left unnoticed, could ultimately lead to decreased efficiencies and waste. It is also believed that the Internet of Things (IoT) platform could assist with this type of data collection and provide various other benefits to DH Networks. Brundu et al. [80] report how this technology can collect, process, and analyse energy consumption data. An example of this is explained as a temperature sensor installed in a heat exchanger which can exploit the data to determine a building's energy profile. While the accurateness of the heat loads prediction is crucial to an efficient system as well as being able to continuously calibrate current systems. Echoing this, Liu et al. [81] discussed how the implementation of a IoT wireless connection system enabled large amount of high quality data to be collected from the heat network and buildings to establish heating characteristics. This was then utilised to predict building loads which could then be used to determine what heating mode was most efficient. IoT technologies can therefore act as a catalyst to improve the quality of mass data being collected from DH networks. This data can then be used advantageously to produce algorithms and predictions to ensure that heat loads between the network production and consumption are reciprocal leading to a highly efficient network.

A common concern regarding DH networks is that the customers' feel locked into DH networks with apprehensiveness of poor system performance and billing. Despite this, it is clear that the extensive use of metering and IoT could play a vital role in engaging customers and the network. Coates-Smith [82] explains how the users will also be able to monitor and control their properties remotely by the use of smartphone apps, which is now becoming increasingly popular in homes utilising gas fired boilers. Similarly, Novitsky et al. [83] summarises that transparency and easy access to the DH information space for all customers, dynamic pricing and ability of the users to adopt to their desired habits or schedules are among objectives to be accomplished. The increased flexibility in controls combined with easy monitoring of the network, which may ease customers' tensions on DH as well as improve the property's thermal comfort, energy costs and performance. A summary of the measures of controls and communications for 5GDH is presented in Table 7.

## 3. Current state and outlook of UK district heating

Research carried out within the literature review basically shows research gaps in regard to the current situation of DH in the UK. It was found that most studies are commonly targeted around Northern

**Table 7**
Summary of 5GDH controls and communications.

| Controls and communications focal points | References |
|---|---|
| User controls integrating weather compensation for improved efficiencies and thermal comfort | [26] |
| Demonstrations of weather compensation of the whole heat network and more recent studies show that substation compensation which incorporates weather sensor, flow sensor, actuating valve, differential pressure controller to ensure appropriate operating conditions for the control valve | [72,76] |
| 5GDH controls to be provided with computational intelligence which is close to the human brain with the ability to optimise the DH network's performance; while the control system itself is split into three parts: dispatching and management, online energy consumption analysis, and accident alarm systems | [78] |
| DH networks in Tannheim using a fuzzy direct matrix control (DMC) to handle the inherent nonlinearity characteristics of DH by considering the volume flow rate at the plant as fuzzy variable; while the fuzzy DMC identified that the DH network was trading off between pumping and heat losses significantly impacting on the operational costs, and ultimately the overall efficiency of the network | [79] |
| IoT technology such as a temperature sensor installed in a heat exchanger, which can exploit the data to determine a buildings energy profile | [80] |
| Implementation of a IoT wireless connection system enables large amount of high-quality data to be collected from the heat network and buildings to establish heating characteristics to accurately predict building thermal loads | [81] |
| Easy access for customers to the DHS information, dynamic pricing and ability of the users to adopt to their desired habits/schedules are among objectives to be accomplished. | [83] |

European countries such as Denmark and Sweden, for instance, research by Østergaard et al. [34,68,72,76], Averfalk et al. [49,54] and Lund et al. [26,58]. These countries are often studied because of their larger deployment of heat networks and their continuous progression on achieving sustainability, as discussed most recently in the paper titled 'Something is sustainable in the state of Denmark: A review of the Danish district heating sector' by Johansen and Werner [15]. For the UK to improve and become comparable to the networks discussed in other European countries, it is crucial to firstly determine the current stance of DH network developments within the UK.

Therefore, this section summarises and analyses the mass information present in the UK government's quarterly reports of 'Heat Network Project Pipeline (HNPP)' during the year of 2020–2021 [84–87]. These reports provide summarised information about all DH projects supported from the development stages to construction by the Heat Networks Delivery Unit (HNDU) and projects seeking capital support from the Heat Networks Investment Project (HNIP). The information collected from this set of documents was based on new networks between October 2020 and September 2021 with a total of 154 projects ongoing. The data was used as a statistical resource to allow for a quantitative analysis into three key areas – quantity of technologies, size of network, and cost of network – to identify any influential trends to the technologies being selected.

Fig. 4, according to the HNPP reports [84–87], shows that gas fired CHP is being implemented excessively into new networks with over double the amount (41%) compared to the next most popular (that is, water source heat pump). The combination of gas fired CHP, CHP energy from waste and biogas CHP contributes to a staggering 56% of heat networks as a primary heat source, which demonstrates these technologies' high level of dominance. The implementation of heat pumps is presented to be the second most common, having been applied to 32% of networks as a primary heat source; within the 32%, water source heat pumps are predominantly utilised, making up over half of the total amount of heat pumps being implemented. On the other hand, air source heat pump is the least popular type, which has only been applied as a primary source to 4% of total networks. Similarly, gas fired boilers, heat from waste plant and biomass are also examples of heat sources which have been neglected from the majority of networks in the UK.

The mean capital costs based on the HNPP reports [84–87] are shown in Fig. 5. Biogas CHP and ground source heat pumps are distinctively most expensive, being the only technologies over £3Million/MW. Water source heat pumps also shows a high capital cost of over £2Million/MW. This is narrowly followed by heat utilised from waste which could also obtain a heat pump as part of the heat transfer process. Inversely, the lowest capital cost heat source is from CHP energy from waste, which in proportion, is only a third of the cost of heat

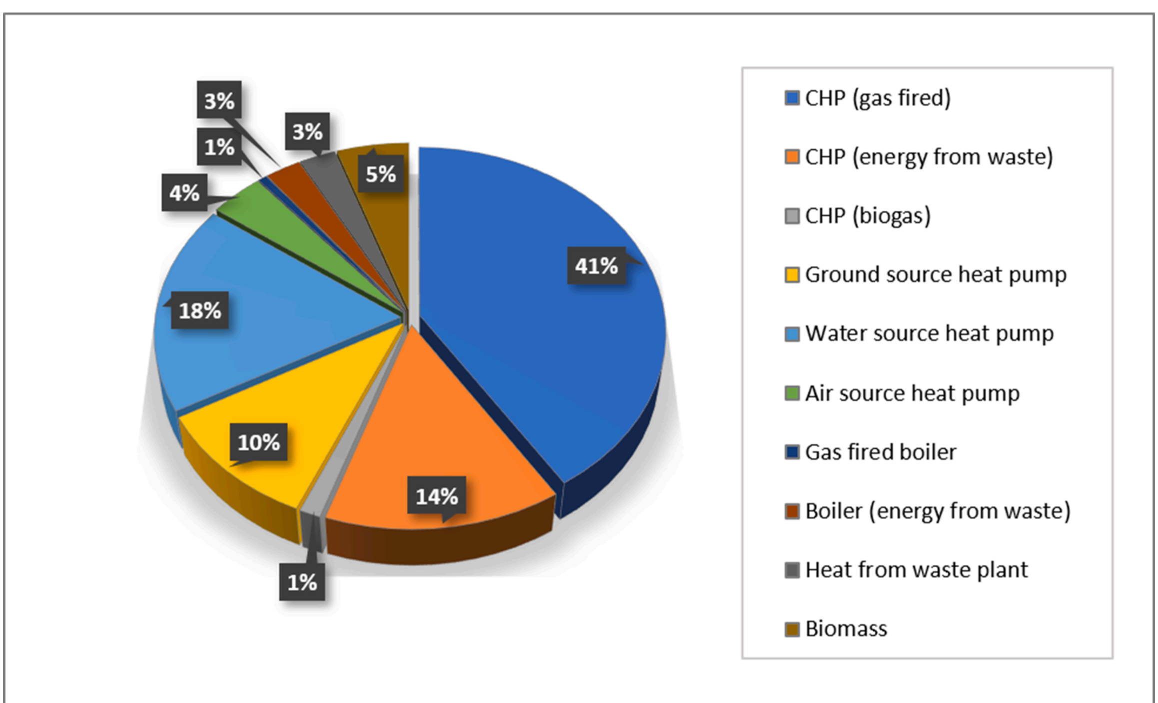


**Fig. 4.** Quantity of primary heat sources within new UK DH Networks [84–87].

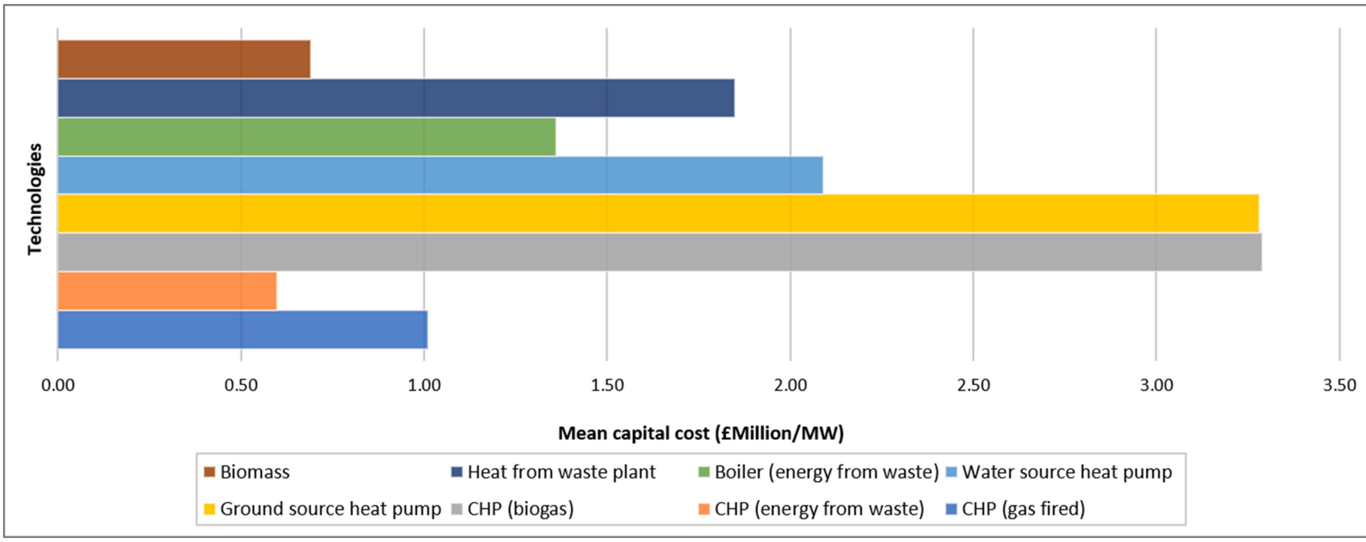


**Fig. 5.** Mean capital costs of primary heat sources within new UK DH Networks [84–87].

used directly from waste. Gas fired CHP is also at the lower end of the scale, which represents a linear relationship between cost and size with 1 MW costing near £1M. This equates to 69% cheaper than the biogas CHP. It is easily perceived when viewing Fig. 5 that there is a remarkable difference between the lowest and highest capital costings with a £2.68Million/MW differential, which corresponds to an 81% cost comparison.

Fig. 6 presents a high number of secondary heat sources required within the DH networks as stated in the HNPP reports [84–87]. The implementation of technologies such as ground source heat pumps, biomass, boiler (energy from waste), biogas CHP and heat energy from waste show 50% of their overall networks requiring back up sources from utilising fossil fuels. With the exemption of gas fired boilers which do not require any type of back up source, CHP (energy from waste) displays the lowest type of technology to rely upon back up heat with only 27% of the networks requiring secondary sources, but 100% of the back-ups within CHP (energy from waste) networks are reliant upon fossil fuels. This is also relatable to biomass, boiler (energy from waste), biogas CHP and heat directly from waste plant, which are all examples of networks with 100% of secondary sources burning fossil fuels. At the higher end of the scale, gas fired CHP is the most common type of technology that requires secondary back up heat sources with 68% of these networks obtaining additional technologies, of which 72% of them are considered non-renewables.

Based on the HNPP reports [84–87]. The quantity of networks that requiring secondary heat sources is summarised graphically in Fig. 7. It is apparent that over 50% of the overall networks are reliant on extra heat source technologies to meet the load demands, with 79% of these being non-renewables. Finally, only 31% of networks being implemented are carbon neutral with the remaining 69% utilising fossil fuelled appliances as either a primary or secondary source, as can be seen in Fig. 8. As 58% of primary heat sources are considered to be a carbon neutral technology, this would indicate that the secondary technologies are having a detrimental effect on the network's sustainability and carbon emissions.

## 4. Discussion

Currently in the UK, gas fired CHP as a primary heat source is present in over 40% of total networks and remarkably implemented into

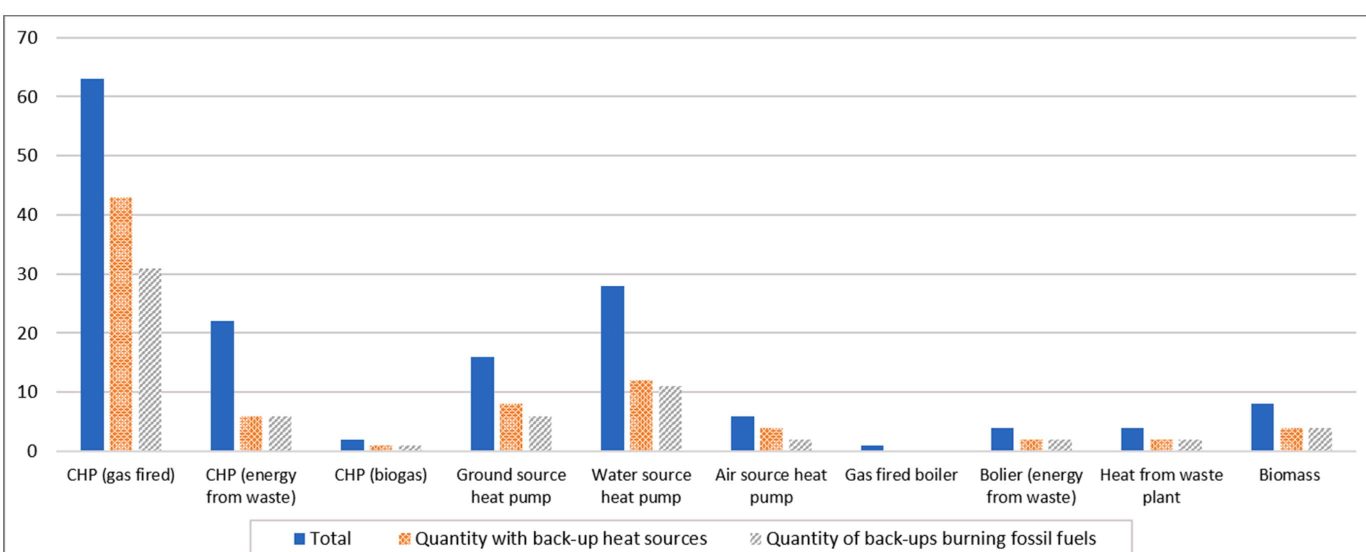


**Fig. 6.** Quantity of back-up heat sources utilising fossil fuels within new UK DH Networks [84–87].

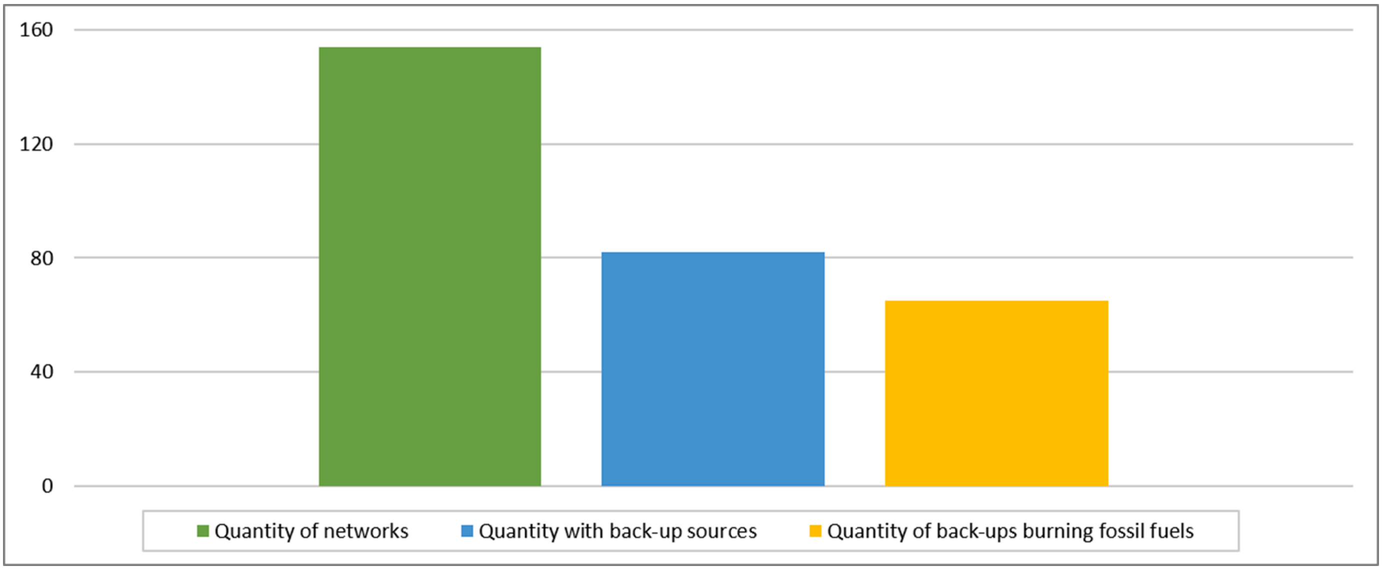


**Fig. 7.** Summary of networks with back-up heat sources utilising fossil fuels within new UK DH Networks [84–87].

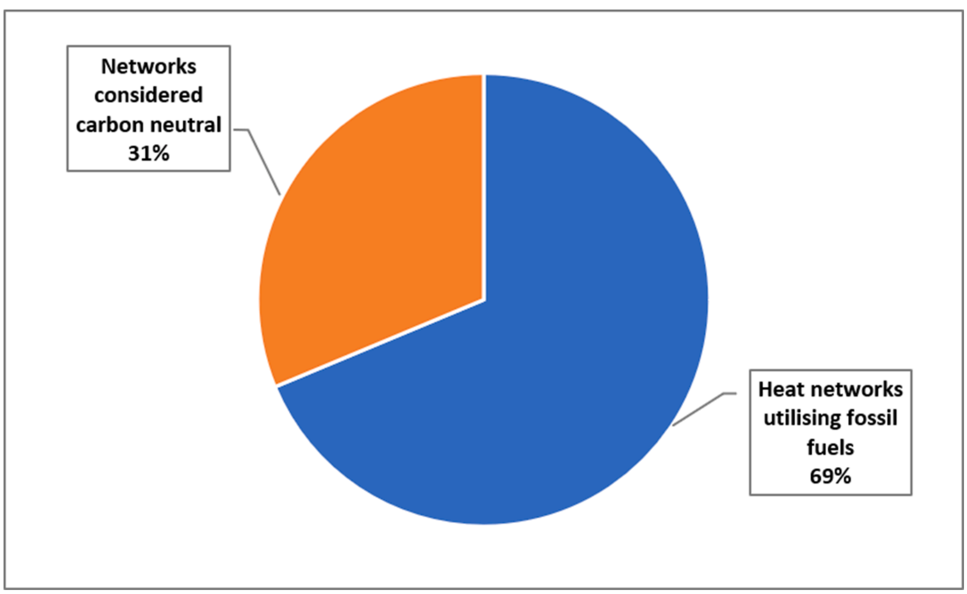


**Fig. 8.** Networks being implemented are considered carbon neutral within new UK DH Networks [84–87].

additional networks, which require secondary back-up for making up to nearly 50% of overall networks with gas fired CHP implemented. As evidenced, the total amount of networks considered to be carbon neutral is only about 31%, meaning that gas fired CHP is the largest contributor to networks being not considered as carbon neutral. The high implementation of gas fired CHP could be due to a number of reasons, one being the relief to the electrical infrastructure it provides, which is discussed by Millar et al. [53] as being a critical challenge as electrification of heat is becoming more popular. Another reason could be due to the cost effectiveness, as seen in Fig. 5 it is the third lowest cost per MW, with biomass and CHP (energy from waste) being the lowest. Unlike these two sources, gas fired CHP can be more flexibly implemented, whereas biomass and CHP (energy from waste) is only applicable to work effectively in particular locations due to their fuel requirements [88]. It is reasonable to suggest that gas fired CHP is being used predominantly as a lower carbon alternative to a gas fired boiler which share similar flow temperatures, indicating that high temperature networks, particularly serving existing buildings are still a high requirement. This could be due to buildings being served from the network, which is designed to operate at high operating temperatures. However, in an existing building, which could require major works to be converted to a low temperature system, resulting in undesired high capital expenditure causing user dissatisfaction. As it stands, it would seem unlikely that gas fired CHP is being used as an intermediary stage to be upgraded to the alternative biogas CHP in the future. This is mainly due to the lack of biogas CHP currently being implemented representing under 4% of the total networks and the extravagant costs associated, which is nearly 53% over the average network's capital expenditure [84–87].

When contrasting the quantity of ground source heat pumps to gas fired CHP, there is only a quarter of the amount currently being implemented. This corroborates the predication of Rezaie and Rosen [33] that ground source heat pump systems in DH will likely decrease due to the higher incentives for CHP. This could be due to the ground source heat pumps implementation being much more stringent than gas fired CHP, as well as the associated capital costs which is 2.25 Million

£/MW more expensive than the gas fired CHP [84–87]. Furthermore, most ground source heat pump networks require alternative heat sources which could be due to several reasons. The first reason is that ground source heat pumps require additional heat input to accommodate for peak demands, which is unlikely due to a correctly sized thermal store possibly being able to overcome this issue as shown in the CHP scenario in Fig. 3. Secondly, additional sources may be required to improve a heat networks resilience; however, this can be drastically improved by reducing heat load variations in the system such as utilising dynamic thermal storage and building demand side controls as explained by Li et al. [57]. Lastly, the most likely reason is that the temperature from a ground source heat pump is too low to effectively serve buildings.

Water source heat pumps are proving to be a popular option having been implemented into 18% of total networks as a primary heat source. A benefit of water source heat pumps compared to ground source is noticeably the capital costs, this will most likely be due to the extra labour and pipework infrastructure required for ground source. This also suggests that there is a focus on utilising local resources, which in these cases are predominantly rivers. Werner [20] explained how the challenges of DH networks are often associated to local heat and cold resources. This has seemingly been overcome to a certain extent, however, 43% of networks utilising water source heat pumps require back up from mostly non-renewable technologies. This would suggest that there is a lack in capacity or resilience with water source heat pumps as a stand-alone heat source, which could be a major hurdle in the future when aiming to be a fully sustainable and carbon neutral network.

The results in Fig. 6 also show how gas fired CHP has the highest amount of secondary heat sources implemented with over 68% of all gas fired CHP networks. This is as expected due to CHP's efficiencies being at the highest when in a peak load, therefore this would indicate that most of these networks have been sized to maintain the base load with surplus heat for thermal storage with additional back-up sources at peak times [89]. The large quantity of secondary sources being implemented is complimentary to the study by Østergaard and Lund [34], who claimed that a single technology perspective would not suffice when aiming for a 100% renewable energy system. On the contrary, it is also evident that the majority of networks implementing additional sources are having the opposite effect which is due to the high concentration of gas fired appliances, particularly CHP. The reasons for this may be that gas fired appliances are well tested, which are considered resilient and easily implemented, while the undesirable high capital costs associated with renewable technologies can meet the full demand. According to Fig. 5, the mean average capital cost for the heat pumps (both ground and water sources) is about 62% more expensive than that of gas fired CHP. Another possible reason could be due to the low operating temperatures of some popular renewable technologies such as heat pumps, therefore are being primarily utilised as a pre-heat for the network which is designed for higher operating temperatures. It is most likely due to the buildings limitations to be served at lower temperatures.

Moreover, Fig. 6 distinctively shows that gas fired boilers are the lowest primary heat source being implemented. It is encouraging that UK's DH networks are shifting priorities away from gas fired boilers, as Lund et al. [58] report that the majority of the first three generations were solely reliable upon burning fossil fuels. Although the amount of fossil fuel appliances still being implemented are noticeably high as seen in Fig. 8, there has been a deliberate approach in implementing renewable technologies. It is reasonable to suggest that most networks are replacing gas fired boilers for a more efficient and lower carbon alternative technology such as gas fired CHP technology. This does not necessarily fit in with the scope of a low temperature 5GDH network due to the higher operating temperature of around 70–80 °C and still utilising fossil fuels as a primary energy source. As expressed in the literature review in this paper, it is expected that new developments and existing homes would undergo extensive fabric improvements to allow for lower supply temperatures, which in reality is possibly being neglected due to the quantity of high temperature networks being implemented currently in the UK. It is therefore apparent that most UK networks are not considered to be low temperature networks, which also results in higher heat losses throughout transmission leading to inefficiencies; these have been undesired characteristics of previous DH generations. Another disadvantage to this approach would be that any networks which are connected to buildings at a high supply temperature would prove more difficult to adapt to lower temperatures in the future without customer dissatisfaction, as discussed by Pellegrini et al. [61]. Furthermore, the requirement of re-sizing emitters and possible implementation of domestic hot water temperature boosts in the future would prove to be a high expense and would require major works and an extensive amount of time to implement.

## 5. Conclusions

The review carried out in this paper identified common trends between various resources relating to the characteristics and desirable traits within the district heating network toward to sustainability. Specifically, the review was to answer the following two questions:

1. What technologies and design philosophies are required to ensure that a low-impact district heating network concept is achieved in reality?
2. How do new District Heating networks complying with the UK Government's guideline compare to the concept of a low-impact network?

In response to the first question, we reviewed a wide range of scientific literatures, commercial reports and government documents on different aspects that might be considered in the design and uptake of district heating towards low environmental impact. Technologies selection for a low-impact DH network is dependent upon local resources within the area. The main type of technologies being implemented are renewables, predominantly are heat pumps as well as heat recovery methods from industrial processes which shall be prioritised. Some studies also refer to photovoltaic systems, which could be utilised on the consumer's side to provide extra heat for domestic hot water temperature elevation. The design philosophy for a low-impact DH network is also aimed towards low temperatures, including very low return temperatures which could be varied between 20–40 °C depending on the type of heat source technology. This can be achieved by sophisticated controls, effective pipework insulation, and accurate demand profiling of the network. However, it is found that stand-alone renewable technologies and waste heat are not effective enough to provide the full network demands. It is therefore determined that the low-impact networks (such as 5GDH) should incorporate a variety of technologies working in conjunction, unlike large central plants which are typically seen in prior generations. Currently, gas fired CHP plays a major role in leading the way to more efficient networks by being a direct low carbon alternative to gas fired boilers. CHPs' emissions have been improved further due to carbon capture methods. However, for future networks to be fully sustainable and carbon neutral, it is required that gas fired CHPs are phased out for alternative renewable technologies which operate at lower temperatures; this could be a major hurdle in the future for heat networks to decarbonise the way homes and buildings are heated.

For the second question, we did a retrospective analysis by reviewing the mass information present in the UK Government's quarterly reports of 'Heat Network Project Pipeline (HNPP)' during the year of 2020–2021. These documents are considered fundamental to building a profile with regards to the various types of heat source technologies being implemented into new UK District Heating networks. Basically, there is a large variety of renewable technologies being implemented into UK heat networks, which is a positive sign that UK Networks are moving in the right direction. We found that many networks still rely on natural gas appliances such as boilers and gas fired CHP. Although gas fired CHP provides a more efficient and carbon friendly solution in comparison with gas fired boilers, there is a future requirement for these to be exchanged for an alternative renewable source to ensure sustainability. It is therefore assumed that gas fired CHP could be used as a bridge gap until renewable technologies are further developed. That being said, it would seem that most networks are not being designed to lower operating temperatures, instead it is anticipated that these networks typically operate around a flow temperature of 70–80 °C. This will result in networks to be susceptible to high heat losses throughout transmission which may also prove difficult and costly to reduce to low operating temperatures in the future. The results derived from the 'Heat Network Project Pipeline (HNPP)' document displays that there is only a minority of new networks which are fully sustainable and considered carbon neutral. On the other hand, the UK are prioritising gas fired CHP technology in networks as a low carbon alternative to the predecessor gas fired boilers. In the short term, the reduction in carbon emissions will likely to be drastically reduced however, unless the rest of the network's infrastructure has been implemented through future proofing methods; otherwise, the likelihood of these new networks to transition to a low temperature network in the future are unlikely. It seems a short-term approach has been taken by implementing gas fired CHP, as in theory technologies such as heat pumps would be most suitable to match the characteristics of a low temperature network yet only a minority of networks have heat pumps as a primary source. A major issue to reduce flow temperatures and system temperature differentials in the future is the changes to the systems dynamics including flow rates and pressures throughout, which means the entire infrastructure will likely require renewing. Thus, the possibility for low temperature renewable technologies, such as heat pumps, to be used as a primary technology in the future is low, which means technologies require further development for a network to be fully sustainable and carbon neutral. Overall, the majority of networks which are currently being designed and implemented may not meet the characteristic of a low impact network such as a 5GDH network and will also unlikely meet these characteristics in the future due to the reasons discussed previously. A further challenge which will likely to prohibit low temperature networks is that the existing buildings were not designed to operate at low temperatures, while the building fabrics were not suitable for this. Therefore, it should be at the forefront of priorities that new buildings are built to much higher standards than what is stipulated in the related legislations, for instance Building Regulations Part L, to ensure suitability for low temperature networks as per the UK aims to be carbon neutral by 2050.

## Limitations to the paper and future research directions

There are noticeable limitations in conducting this review, which form the basis of research to pursue in the future, identified and summarised as follows:

- The information available from the HNPP were limited to dates between 2020 and 2021. Thus, there is a possibility that some networks recorded within the dataset have since changed in costs or technologies, ultimately affecting the accuracy of the results.
- As the HNPP is being continuously updated, not all project information was available. For example, the costs of air source heat pumps or gas fired boilers networks were unavailable, which, therefore, were excluded from the capital cost datasets and results. Therefore, the mean average calculated costs only represent a minority within certain type networks.
- Due to multiple technologies being implemented, the capital costs could only be based upon the primary source alone, therefore there may be discrepancies due to the additional technologies not being considered. Other unknown variables such as project specific complexities may also influence projects cost. Furthermore, some technologies had more available data than others, therefore the mean average for technologies like gas fired CHP is much more widespread than it is with the likes of ground source heat pumps.
- The networks considered to be carbon neutral were assumed on the basis that no information was present which would suggest otherwise. There is a possibility that these networks may have additional non-renewable energy resources which were withheld from the HNPP information. As a result, the calculated 31% of renewable DH networks being implemented in the UK could be lower in reality.
- Absent from the literature review was the use of hydrogen fuelled appliances which is a relatively sparse topic within District Heating literature. Due to many technologies currently being implemented in the UK are still gas fired, future research shall be sought into how hydrogen conversion of the natural gas grid could perhaps benefit future networks.
- Due to the limited information available within the HNPP document, it is proposed that a more qualitative analysis into particular networks would identify some of the key design philosophies being implemented such as controls, temperatures differentials and the consumers' systems, which were not able to be achieved within this paper. From this, more in-depth knowledge can be gained into what future-proofing qualities are being implemented into current networks and how they compare to the concept of a low-impact network.
- Further research needs to be sought into the most suitable solutions for evolving existing heat networks into carbon neutral, low temperature networks and possible future-proofing methods for new networks which cannot rely solely on renewable technologies at this time.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## References

[1] R.B. Jackson, et al., Global fossil carbon emissions rebound near pre-COVID-19 levels, Environ. Res. Lett. 17 (3) (2022), 031001.
[2] A. Guterres, Carbon Neutrality by 2050: the World's Most Urgent Mission, Le Monde, 2020.
[3] UNFCCC, The Paris Agreement, United Nations Climate Change, 2021 [cited 2022 17 January]; Available from, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
[4] The Parliamentary Office of Science and Technology, Carbon Footprint of Heat Generation, London, 2016.
[5] BEIS, UK energy in brief, Department for Business, Energy, and Industrial Strategy, Editors, National Statistics, 2021.
[6] BEIS, Heat and Buildings strategy, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2021.
[7] Building Regulations, Approved Document L: Conservation of Fuel and Power, HM Goverenment, 2010.
[8] UKGBC. *Climate Change: UKGBC's vision for a sustainable built environment is one that mitigates and adapts to climate change*. 2022 [cited 2022 18 June]; Available from: https://www.ukgbc.org/climate-change-2/.
[9] UKGBC. *Climate Change*. 2022 [cited 2022 5 June]; Available from: https://www.ukgbc.org/climate-change-2/.
[10] Vivid Economics, Accelerated Electrification and the GB Electricity System, Committee on Climate Change, 2019.
[11] Department for Business, Energy, and Industrial Strategy, Heat Networks Delivery Unit, 2017 [cited 2022 9 March]; Available from, https://www.gov.uk/guidance/heat-networks-delivery-unit.
[12] BEIS, Delivering Financial Support For Heat Networks, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2018.
[13] A.R. Mazhar, S. Liu, A. Shukla, A state of art review on the district heating systems, Renew. Sustain. Energy Rev. 96 (2018) 420–439.
[14] BEIS, Opportunity Areas for District Heating Networks in the UK: Second National Comprehensive Assessment, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2021.

[15] K. Johansen, S. Werner, Something is sustainable in the state of Denmark: a review of the Danish district heating sector, Renew. Sustain. Energy Rev. 158 (2022), 112117.
[16] MIBEC. *History of District Heating*. 2020 [cited 2022 23 January]; Available from: http://mibec.co.uk/history-of-district-heating/.
[17] D. Fjernvarme. *Danish District Heating Association*. 2021 [cited 2022 28 February]; Available from: https://www.danskfjernvarme.dk/sitetools/english/about-us.
[18] M.-A. Millar, N. Burnside, Z. Yu, District heating challenges for the UK, Energies 12 (2) (2019).
[19] P. Sorknæs, et al., The benefits of 4th generation district heating in a 100% renewable energy system, Energy 213 (2020), 119030.
[20] S. Werner, International review of district heating and cooling, Energy 137 (2017) 617–631.
[21] A. Vandermeulen, et al., Analysis of building parameter uncertainty in district heating for optimal control of network flexibility, Energies 13 (23) (2020), 6220.
[22] D.J.C. Hawkey, District heating in the UK: A Technological Innovation Systems analysis, Environ. Innovat. Soc. Trans. 5 (2012) 19–32.
[23] Association for Decentralised Energy, CP1 Heat networks: Code of Practice for the UK, Chartered Institution of Building Services Engineers (CIBSE), London, 2020.
[24] IEA. *District Heating*. 2021 [cited 2022 25 March]; Available from: https://www.iea.org/reports/district-heating.
[25] Y. Li, Y. Rezgui, H. Zhu, District heating and cooling optimization and enhancement – Towards integration of renewables, storage and smart grid, Renew. Sustain. Energy Rev. 72 (2017) 281–294.
[26] H. Lund, et al., 4th Generation District Heating (4GDH), Energy 68 (2014) 1–11.
[27] U. Çakir, K. Çomakli, F. Yüksel, The role of cogeneration systems in sustainability of energy, Energy Convers. Manag. 63 (2012) 196–202.
[28] J.-P. Jimenez-Navarro, et al., Coupling the heating and power sectors: the role of centralised combined heat and power plants and district heat in a European decarbonised power system, Appl. Energy 270 (2020) 115134.
[29] I. Pakere, et al., Climate index for district heating system, Rigas Tehniskas Universitates Zinatniskie Raksti 24 (1) (2020) 406–418.
[30] B. Hedman, D. Jones, V. Tutterow, Beneficial CHP–Is That a Thing? Considering CHP in the Context of Beneficial Electrification, in Energy Technologies Area, Lawrence Berkeley National Laboratory, 2021.
[31] K. Formela, et al., Reactive extrusion of bio-based polymer blends and composites-current trends and future developments, Express Polym. Lett. 12 (1) (2018) 24–57.
[32] A. Kalam, et al., Combined heat and power systems: economic and policy barriers to growth, Chem. Central J. 6 (1) (2012) 1–13.
[33] B. Rezaie, M.A. Rosen, District heating and cooling: review of technology and potential enhancements, Appl. Energy 93 (2012) 2–10.
[34] P.A. Østergaard, H. Lund, A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating, Appl. Energy 88 (2) (2011) 479–487.
[35] P. Carroll, M. Chesser, P. Lyons, Air Source Heat Pumps field studies: A systematic literature review, Renew. Sustain. Energy Rev. 134 (2020), 110275.
[36] A. Lake, B. Rezaie, S. Beyerlein, Review of district heating and cooling systems for a sustainable future, Renew. Sustain. Energy Rev. 67 (2017) 417–425.
[37] S. Siddiqui, J. Macadam, M. Barrett, The operation of district heating with heat pumps and thermal energy storage in a zero-emission scenario, Energy Rep. 7 (2021) 176–183.
[38] P. Byrne, R. Ghoubali, Exergy analysis of heat pumps for simultaneous heating and cooling, Appl. Thermal Eng. 149 (2019) 414–424.
[39] EEA, Fluorinated Greenhouse Gases 2021, European Environment Agency, 2021.
[40] P.C. Slorach, L. Stamford, Net zero in the heating sector: Technological options and environmental sustainability from now to 2050, Energy Convers. Manag. 230 (2021).
[41] A. David, et al., Heat roadmap Europe: large-scale electric heat pumps in district heating systems, Energies 10 (4) (2017) 578.
[42] L. Cioccolanti, et al., District heating potential in the case of low-grade waste heat recovery from energy intensive industries, Appl. Thermal Eng. 191 (2021), 116851.
[43] M. Arnaudo, et al., Waste heat recovery in low temperature networks versus domestic heat pumps - A techno-economic and environmental analysis, Energy 219 (2021), 119675.
[44] Aglén, L. *Wasted opportunity: using UK waste heat in district heating*. 2020 [cited 2022 15 January]; Available from: https://www.cibsejournal.com/technical/wasted-opportunity-using-uk-waste-heat-in-district-heating/.
[45] L. Hancox, et al., An assessment for the viability of recovering heat from a smoke extract system, Energy Built Environ. (2022), https://doi.org/10.1016/j.enbenv.2022.03.003.
[46] F. Sun, et al., A new waste heat district heating system with combined heat and power (CHP) based on ejector heat exchangers and absorption heat pumps, Energy 69 (2014) 516–524.
[47] E. Wheatcroft, et al., The role of low temperature waste heat recovery in achieving 2050 goals: a policy positioning paper, Energies 13 (8) (2020) 2107.
[48] Celsius. *Don't waste the waste water: clean energy from sewage*. 2020 [cited 2022 12 March]; Available from: https://celsiuscity.eu/clean-energy-from-sewage/.
[49] H. Averfalk, et al., Large heat pumps in Swedish district heating systems, Renew. Sustain. Energy Rev. 79 (2017) 1275–1284.
[50] L. Brange, J. Englund, P. Lauenburg, Prosumers in district heating networks – a Swedish case study, Appl. Energy 164 (2016) 492–500.
[51] L. Brand, et al., Smart district heating networks – a simulation study of prosumers' impact on technical parameters in distribution networks, Appl. Energy 129 (2014) 39–48.
[52] D. Schmidt, et al., Low temperature district heating for future energy systems, Energy Proc. 116 (2017) 26–38.
[53] M.-A. Millar, et al., Roadblocks to low temperature district heating, Energies 13 (22) (2020), 5893.
[54] H. Averfalk, S. Werner, Essential improvements in future district heating systems, Energy Proc. 116 (2017) 217–225.
[55] L.J. Hurst, T.S. O'Donovan, A review of the limitations of life cycle energy analysis for the design of fabric first low-energy domestic retrofits, Energy Build. 203 (2019), 109447.
[56] J. Le Dréau, et al., Upscaling the flexibility potential of space heating in single-family houses, J. Phys.: Conf. Ser. (2019).
[57] H. Li, et al., Toward 4th generation district heating: Experience and potential of low-temperature district heating, in: 14th International Symposium on District Heating and Cooling, 2014.
[58] H. Lund, et al., Perspectives on fourth and fifth generation district heating, Energy 227 (2021), 120520.
[59] British Standards Institution, *BS EN 442-1: Radiators and convectors*, in *Technical specifications and requirements*. 2014, British Standards Institution.
[60] Crane, M. *The perfect return – heat network return temperatures*. 2016 [cited 2022 3 February]; Available from: https://www.cibsejournal.com/technical/the-perfect-return-heat-network-return-temperatures/.
[61] M. Pellegrini, et al., Classification through analytic hierarchy process of the barriers in the revamping of traditional district heating networks into low temperature district heating: an Italian case study, Int. J. Sustain. Energy Plann. Manag. 20 (2019) 51–66.
[62] Health and Safety Executive, *Legionnaires' disease: The control of legionella bacteria in water systems*. 2013, Approved Code of Practice L8.
[63] J. von Rhein, et al., Development of a topology analysis tool for fifth-generation district heating and cooling networks, Energy Convers. Manag. 196 (2019) 705–716.
[64] X. Yang, S. Svendsen, Achieving low return temperature for domestic hot water preparation by ultra-low-temperature district heating, Energy Proc. 116 (2017) 426–437.
[65] E. Guelpa, V. Verda, Demand response and other demand side management techniques for district heating: a review, Energy 219 (2021), 119440.
[66] J. Song, et al., Predicting hourly heating load in a district heating system based on a hybrid CNN-LSTM model, Energy Build. 243 (2021), 110998.
[67] M. Lumbreras, et al., Data driven model for heat load prediction in buildings connected to district heating by using smart heat meters, Energy 239 (2022), 122318.
[68] P.A. Østergaard, et al., Sustainable development using renewable energy technology, Renew. Energy 146 (2020) 2430–2437.
[69] S. Kelly, M. Pollitt, An assessment of the present and future opportunities for combined heat and power with district heating (CHP-DH) in the United Kingdom, Energy Policy 38 (11) (2010) 6936–6945.
[70] Dwyer, T. *Module 130: applying combined heat and power (CHP) in heat networks*. 2018 [cited 2022 12 February]; Available from: https://www.cibsejournal.com/cpd/modules/2018-08-chp/.
[71] A. Franco, F. Bellina, Methods for optimized design and management of CHP systems for district heating networks (DHN), Energy Convers. Manag. 172 (2018) 21–31.
[72] D.S. Østergaard, et al., Low-temperature operation of heating systems to enable 4th generation district heating: a review, Energy 248 (2022), 123529.
[73] H. Wang, H. Wang, T. Zhu, A new hydraulic regulation method on district heating system with distributed variable-speed pumps, Energy Convers. Manag. 147 (2017) 174–189.
[74] H. Boysen, J.E. Thorsen, Hydraulic balance in a district Heating System, Danfoss District Energy, 2007.
[75] J. Fong, et al., Application of a new dynamic heating system model using a range of common control strategies, Buildings 6 (2) (2016) 23.
[76] D. Østergaard, S. Svendsen, *Space heating with ultra-low-temperature district heating–a case study of four single-family houses from the* 1980s, Energy Proc. 116 (2017) 226–235.
[77] A. Rahmatmand, M. Vratonjic, P.E. Sullivan, Energy and thermal comfort performance evaluation of thermostatic and electronic mixing valves used to provide domestic hot water of buildings, Energy Build. 212 (2020), 109830.
[78] L. Gao, et al., Technologies in smart district heating system, Energy Proc. 142 (2017) 1829–1834.
[79] S. Grosswindhager, et al., Fuzzy predictive control of district heating network, Int. J. Model., Identif. Control 19 (2) (2013) 161–170.
[80] F.G. Brundu, et al., IoT software infrastructure for energy management and simulation in smart cities, IEEE Trans. Ind. Inform. 13 (2) (2017) 832–840.
[81] L. Liu, H. Zhang, Y. Liu, A smart and transparent district heating mode based on industrial Internet of things, Int. J. Energy Res. 45 (1) (2020) 824–840.
[82] Coates-Smith, A. *Digitisation of the heat network customer interface*. 2019 [cited 2022 27 January]; Available from: https://www.insite-energy.co.uk/blog/digitisation-heat-network-customer-interface?cont=true?cont=true.
[83] N.N. Novitsky, et al., Smarter smart district heating, Proc. IEEE 108 (9) (2020) 1596–1611.
[84] BEIS, Heat nextworks: 2020 Q4 pipeline, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2020.
[85] BEIS, Heat nextworks: 2021 Q1 pipeline, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2021.
[86] BEIS, Heat nextworks: 2021 Q2 pipeline, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2021.

[87] BEIS, Heat nextworks: 2021 Q3 pipeline, Department for Business, Energy, and Industrial Strategy, Editors, HM Government, 2021.
[88] K. Natarajan, et al., Optimal locations for methanol and CHP production in eastern Finland, BioEnergy Res. 5 (2) (2011) 412–423.
[89] H. Wang, et al., Analysis of the location for peak heating in CHP based combined district heating systems, Appl. Thermal Eng. 87 (2015) 402–411.

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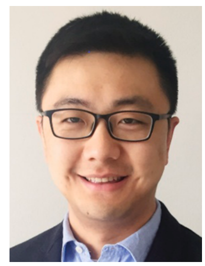

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