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Review

District Heating Challenges for the UK

Michael-Allan Millar *, **Neil M. Burnside** and **Zhibin Yu**

College of Science and Engineering, University of Glasgow, Glasgow G12 8QQ, UK; Neil.Burnside@glasgow.ac.uk (N.M.B.); Zhibin.Yu@glasgow.ac.uk (Z.Y.)

* Correspondence: m.millar.1@research.gla.ac.uk

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Abstract: District heating uptake has grown with the increasing need for cleaner and more efficient energy supply. This has resulted in a rising number of new developments signing up to a district heating scheme, typically powered by Combined Heat and Power (CHP) boilers or biomass boilers with supplemental electrical or gas grid connections. These schemes have advanced rapidly in recent years, with much of the research focus targeting lower carbon technologies, improved load prediction and peak demand management. We assess the current status of District Heating Networks (DHNs) in the United Kingdom using published case studies and suggest next steps to improvement. Our findings show that the United Kingdom has good potential for uptake of district energy given the current political climate and government incentives, however significant improvements must be made to further penetrate the heating market.

Keywords: district heating; energy; low carbon; network

1. Introduction

The Paris Agreement sparked a global rush to de-carbonize and keep the increase of global average temperatures below 2 °C beyond pre-industrial (1990) levels, continuing and improving the commitments laid out by the 1997 Kyoto Protocol. While the resultant political and research climate has strongly focused on the de-carbonization of electricity production, thermal energy production accounts for around 50% of energy consumption in Europe, and therefore a significant contribution to carbon emissions [1]. In December 2018 at the 24th Conference to the Parties of the United Nations Framework Convention on Climate Change (COP24), guidelines were laid out to finalize agreements on how to implement the Paris Agreement [2]. In 2017, the UK produced 50.1% of electricity from low carbon sources—leaving another 50% produced primarily from natural gas [3]. These centralized natural gas power plants can be more efficient than traditional coal fired power plants, but do not come close to the possible efficiency and carbon reduction of a well-planned and operated, de-centralized district heating and energy network.

District heating is not a new technology—it has large potential and is fairly well documented—yet it only has an average market share of 10% throughout Europe and is primarily restricted to northern and central nations [1]. This can be related to the 1970s energy crisis, which encouraged many countries to seek and adopt strategies that would make them energy independent, such as significant investment in solar power and energy networks in places like Denmark and the Netherlands. This was not the case in the UK, where a focus on utilization of large coal and natural gas reserves led to an overlooking of alternative low-carbon energy sources, and a comparatively minor transition from oil boilers to readily available, and low cost, coal and natural gas [4].

While it is a centuries-old technology, district heating is only now emerging as a critical player in the challenges of reducing carbon emissions and improving the efficiency of energy use [5]. District heating has been recorded as far back as the 14th century in France, but not recorded until much later in the United States, around the late 19th century. District Heating Network (DHN) classification is commonly based on heat transfer fluid, energy source, energy supply, or time period of installation [6,7]; however, the definitions laid out within these categories are often inconsistent across published examples. To gain any appreciation, the individual scheme should always be considered and not a vague description of "generation". Figure 1 summarizes district heating and energy development. It shows how DHNs have evolved from a very high enthalpy, low technology (1st Generation district heating) into a much lower enthalpy and technologically diverse heat and energy supply (3rd and 4th Generation district heating).

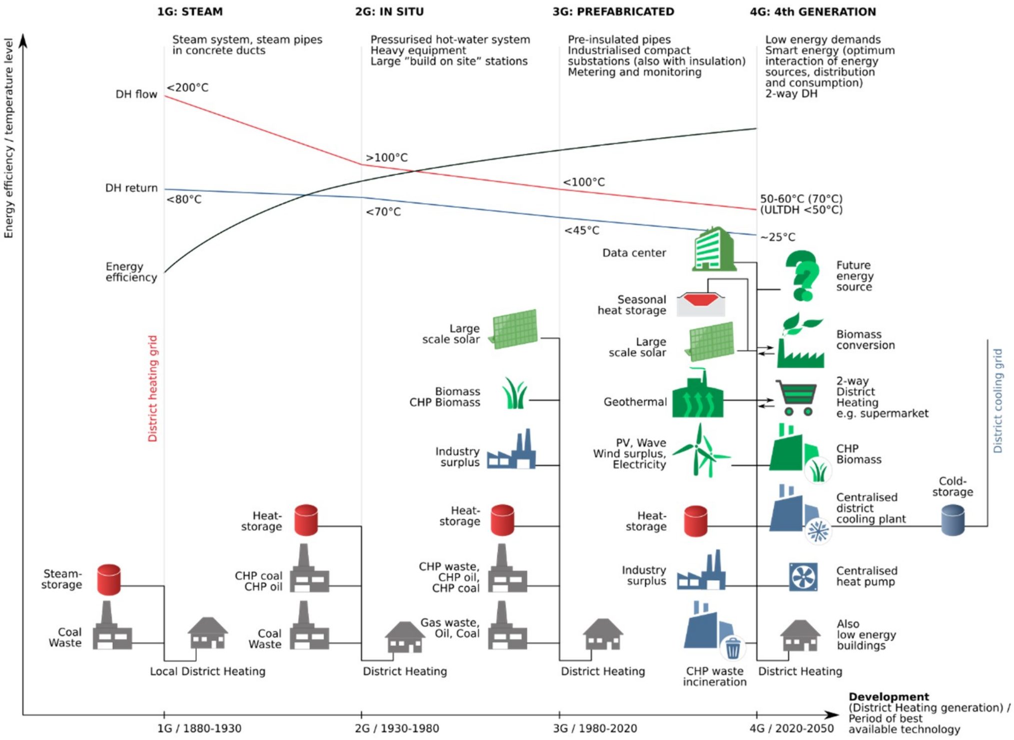


Figure 1. Summary of district heating and energy evolution, from 1st to 4th generation [8].

1.1. First Generation (1G) District Heating

The first generation of district heating was primarily high temperature and pressure steam, delivered through concrete ducts. Note that this is slightly different from the very early transport of hot water from geothermal sources, found in early Roman cities, and different from early steam transport for electricity production.

At the time, steam was a good choice—an extensive water network was not yet developed, steam was readily available from early power plants and could meet the demands from single large users (e.g., hospitals, industrial processes). These schemes could operate at conditions around 300 °C and 20 bar, creating a host of feasibility issues. At such harsh conditions, cast iron piping rapidly corrodes, and without significant insulation, any water coming into contact with the outer surface would vaporize. Any steam condensation on the inner pipe would result in high pressure water within the distribution system, damaging pipework through cavitation and higher corrosion rate. In addition, such high temperature fluid has a significant energy loss in the distribution system, lowering the efficiency of any such scheme. In modern day district heating, these schemes have high operating and maintenance costs, are difficult to connect to end users (high/low pressure interface) and have high thermal losses.

Few 1st generation schemes still exist, however one of the largest can still be found in Paris. This scheme is operated by the Parisian Urban Heating Company, and delivers steam (predominantly sourced from waste incineration) along 480 km and cooling along 71 km of pipeline. This is a good example of the fluid definitions often associated with district energy—this delivers steam similar to a

1G scheme, but combines heating, cooling and power with thermal storage like a 4G system, with low temperature loops, like a 3G system (described in Sections 1.3 and 1.4).

1.2. Second Generation (2G) District Heating

Second generation (2G) district heating began to emerge in the early 20th century. The opportunity to improve district heating schemes came to much of Europe as a result of re-construction work post World War 2, explaining why cities like Berlin and Bucharest have extensive networks [4]. The newer schemes operated at higher temperatures (>100 °C) and higher pressures than before, transporting super-heated water [9]. These systems primarily worked on two pipe closed loop systems (one supply pipe and one return pipe, similar to 1G, shown in Figure 2), meaning the returning condensate could be re-used or matched with a lower grade heat demand. The fluid was easier to manage, as significant improvements in hydraulic pumps had been made, allowing pumping stations to transport fluid across much further distances than before in 1G systems, with the entire pressure head met by one pump at the source. This, combined with improved piping and insulation, meant that the overall efficiency improved dramatically, encouraging many European cities to adopt district heating schemes as modes of primary heating and not just in the areas of highest population density.

At this time, Combined Heat and Power (CHP) was also growing in popularity, creating the possibility to tie exhaust gas heat with the district heating schemes. So while direct fossil fuel burners (coal and oil) were still the leading source of energy to the schemes, CHP was now being used to produce local electricity as well, reducing the cost of electricity and pollution in cities [6].

The improvements made have been suggested to increase efficiency from 1G to 2G by around 50%, however there was still much to be desired from 2G systems [10,11]. These systems often had painfully high capital costs, requiring thermal storage tanks and shell and tube heat exchangers at many end users, which, in conjunction with the high thermal loss and lack of system control, necessitated the development of 3rd generation district heating schemes.

1.3. Third Generation (3G) District Heating

Third generation (3G) district heating is currently the most popular version, and most new schemes follow this template, with 3G district heating becoming popular in the 1970s and 80s [4,6,9] alongside significant improvements to manufacturing processes. This newer form of district heating was brought on by increasing oil prices, generating incentive to produce more efficient and lower cost energy systems. These systems use high pressure water (similar to 2G), but at temperatures below 100 °C. A typical 3G transmission and distribution network will consist of much more compact materials. Pipes are thinner than 2G and pre-fabricated, usually with significant thermal insulation and placed in the ground. Shell and tube heat exchangers were replaced by plate heat exchangers, offering a more compact footprint and the ability to extend networks by the addition of plates to the heat exchanger. The change in heat exchanger also lowered maintenance and down-time due to the ease of cleaning and maintenance [12]. These changes lowered the cost of new systems, allowing many developments in countries that had previously been resistant (such as the United Kingdom). In this time, natural gas prices were low, encouraging larger CHP to dominate district heating supplies. Heat Interface Units (HIUs) started to appear in a more developed way in 3G district heating, allowing individual temperature control, rather than merely a pressure/temperature interface from the network to the end user.

There are many examples of 3G district heating, such as the Athletes Village in Glasgow. This district heating scheme was designed for the 2014 Commonwealth Games athletes' accommodation, and post-event, redevelopment into residential housing, and includes a 28 km network, providing heat to over 700 homes, large sports facilities, a care home and community buildings. The network is fed by a 1.68 MW CHP engine, operated at 85 °C and return at 60 °C. Each user as an HIU, essentially two plate heat exchangers (one for space heating, one for domestic hot water) with pressure control valves and auxiliary equipment. This allows the network to operate at any chosen temperature and pressure, without major concern for end user systems.

1.4. Fourth Generation (4G) District Heating

In all previous generations, there has been a lack of focus, incentive, technical ability or manufacturing capability to improve heating systems past basic and fairly rudimental enhancements. These factors can now be significantly improved and have a strong potential to produce well integrated heat and energy systems—smart fourth generation district heating, cooling and power. Lund, Werner, Wiltshire, Svendsen, Thorsen, Hvelplund and Mathiesen [10] identify key issues surrounding 4G district heating including integration with the transport sector, incompatibility with current infrastructure, space heating requirements and low heat demand density. However, 4G DHNs attempt to solve these problems by better sourcing and matching energy sources with user demand. This includes operating at lower temperatures than 3G (e.g., 60/40 °C), incorporating a larger share of low carbon energy sources and supply/demand management.

One of the largest efficiency losses from district heating is from secondary factors associated with end users. This is a difficult issue to address because it is caused by low quality buildings, high network supply temperatures and poor end user management. The current building stock is built to comply with current legislation (Buildings (Scotland) Act 2003 and Climate Change (Scotland) Act 2009), which does not plan for a sustainable future or any future district energy integration [13,14]. Figure 2 shows the number of demolished properties in Scotland compared with the number of completed new build homes and the total number of homes [15–17]. This shows that, while a significant number of new properties are entering the market, very few are being removed. This means that older properties will have a significant impact on future energy efficiency and must be considered now, not in the distant future when political concern is more likely to be directed at the heating sector.

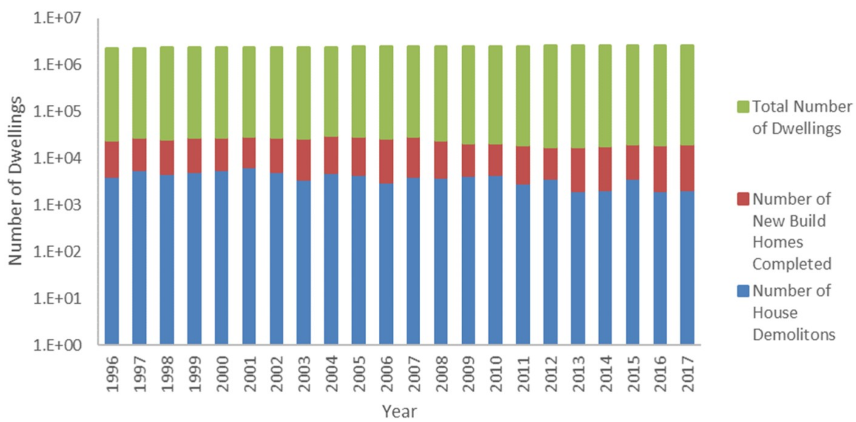


Figure 2. Chart of Scottish dwellings built, demolished and total for Scotland between 1996 and 2017 [15–17].

A number of studies have demonstrated that older building stock can be upgraded and integrated with lower temperature district heating networks to allow for operation at supply temperature of 45 °C for space heating [10,18–21]. It has been shown that reducing the operating temperature of DHNs from 80/40 °C (typical of 3G DHN) to 60/30 °C can provide over 30% saving of heat losses from the network [18]. It has been proposed that to operate at lower supply/return temperatures will require upgraded infrastructure, including improved radiators with return temperature thermostats and control, improved control systems and significant energy renovations, such as wall insulation and double glazing [22].

A critical part of 4G DHNs is the integration of low enthalpy heat sources, such as excess industrial heat. It has been estimated that the EU has over 300 TWh/year of waste heat potential, with almost 30 TWh/year from the United Kingdom alone [23]. This should be seriously considered as a heat source when planning a new DHN, however it is likely to be difficult in the UK due to the necessary and complicated balance between the agreement with the industry source, the DHN operator and maintaining a competitive cost to the end user.

2. Energy Supply

There are several thermal resources commonly utilized for district heating systems. The following sections discuss each of these individually in detail, but it should be noted that DHNs are often fed by multiple sources in an integrated fashion. Examples of this could be a CHP system, with a heat pump to upgrade heat captured by a cooling jacket and thermal storage, or a geothermal borehole, with heat pump for heat abstraction and storage combined with a solar collector. The energy source will primarily depend on the end use and requirements. End use typically falls into one—or a combination—of the following:

- Space heating
- Domestic Hot Water (DHW)
- Industrial process

The energy supply can range from a few kW to large MW scales, and not all sources are suited or scalable across the entirety of this range.

2.1. Combined Heating and Power (CHP)

CHP (a form of co-generation) is an electrical power producing engine, usually a gas turbine or micro gas turbine, which produces power locally to the user, and can therefore capture the high grade heat from combustion-produced flue gases. CHP schemes have been installed in hundreds of district heating schemes around the world due to their profitability [24–27]. Heat is recovered from the highest temperature source, the exhaust gases (circa 400–500 °C), but can also be recovered from lower grade heat from the cooling jacket or lubricating oils (<100 °C). CHP can range from a few hundred kW_e to several MW_e.

Early publications on CHP date from the 1970 and 1980s and primarily focus on proving a case for CHP installation [28–33] in order to offer an early strategic, operational and economic basis to develop co-generation systems. In the 1980s, significant investment and changes in policy allowed for further development, particularly in Denmark and Holland [34,35]. Some of this work began to computationally investigate thermal losses from the network [36] and assess the commercial viability of CHP DHN schemes in the United Kingdom [37]. By the 1990s, published works had a far greater technical focus, including one of the first linear optimizations of DH [38], which considered the costs of electricity and heating at different times across the year and suggested an operating schedule to minimize the operating costs. This method is still used today and features in many recent publications [39–41]; however, it is almost exclusively focused on a cost optimization and has little consideration for operational constraints or targets, such as carbon emissions. By the 1990s, carbon emissions were being acknowledged as a significant concern, and yet even now, CHP operating strategies rarely target carbon footprint minimization, so continued use of this methodology demonstrates a persistent disconnect between political and environmental motivations and technical advancements. This may be because with much lower penetration of renewables into the national grid at the time, CHP could offer a significant carbon reduction at the time and was one of the few commercially viable systems. That is no longer the case in the United Kingdom, and as the share of renewables increases, the viability of fossil fuel CHP dwindles. For CHP to have a sustainable outlook, it must adopt routes to reduce carbon emissions—potentially through biogas combustion or waste incineration.

Biogas combustion for co-generation has been considered in the past [25,42–45], but availability, transportation and mechanical constraints have prevented it replacing natural gas CHP. Biogas is a strong solution to a critical problem for CHP, as it incorporates a renewable fuel source into co-generation and reduces waste [46,47]. Most CHP schemes will have a finance plan across 20–30 years, meaning this “dirty” energy production is unlikely to shift without incentive. Although biogas conversion is not a perfect solution and cannot be applied to all engine types, it does offer some promise as a long term, low-carbon CHP fuel source.

2.2. Heat Pumps

Heat pump technology can be applied to a huge range of heat sources. They are commonly found in conjunction with CHP technology and ground source heat extraction. We primarily discuss heat pumps as a stand-alone technology in the present study, where heat can be readily and easily extracted. However, for optimal DHN utilization, we would typically recommend this technology as part of a wider integrated network.

Heat pumps take a low grade, low value heat source, and with a small amount of work energy, convert it to a higher grade, higher value heat source. The technical details of this process are not discussed here, but are well documented elsewhere [48–50]. There are two heat sources which are widely used and well suited to heat pump technology—air source and surface water source heat pumps. Air (e.g., data centers [51–54] and ambient air) and water (e.g., river water, sewage water [55–59] or sea water [60–64]) are largely available and a free resource, making good candidates for heat pump applications. Data centers can also be used as a heat source. Water is the preferred choice for a few reasons

- Water has a larger density than air, and therefore greater volumetric energy density
- Water temperatures are relatively constant and predictable across the year, where air can vary drastically diurnally
- Air source heat pumps require loud blowers and create more noise

River water is a huge thermal reservoir of un-tapped potential. There are very few river source heat pumps in operation, which could be due to the difficulty in matching thermal demand and network infrastructure or the necessity to take potentially variable natural parameters into consideration. Further problems can be caused due to the harsh conditions found in river water. Qin, et al. [65] show that fouling of the heat exchangers caused by river bacteria and algae can reduce the Coefficient of Performance (COP) by 3.73%, and suggests that a maximum performance is when the sediment concentration is below 100 $g \cdot m^{-3}$ and turbidity below 50 NTU [66]. However, this paper did not consider direct heat transfer from the river to the heat pump, only experimental simulation of river conditions. No discussion is given around heat exchanger choice or pre-treatment to minimize the fouling effect, leaving much work needed before practical and reliable guidelines can be suggested. However, this work is significant, as it is among the first research to begin questioning the operability of river source heat pumps.

Drammen, in Norway, is home to a significant DHN dating back to 2002, including 13 MW_T of sea-source heat pumps. These heat pumps operate at a COP of around 3 year-round, using ammonia as a refrigerant. The network has a summer mode and a winter mode. In the summer, the heating load is significantly reduced from 45 MW_T peak to less than 2 MW_T. In this case, the operating temperature is around 75 °C compared to 120 °C in the winter. This is a mix of both 2G and 3G operating strategies. The system has been shown to save over £1 million and 12,733 t CO_{2e} per year [67]. Although this type of heat pump has been shown to have great potential, it can only be deployed under specific conditions and areas close to suitable bodies of water, so is therefore not suitable for many users.

2.3. Geothermal and Ground-Source Energy

The types of heat extraction from the earth are not well defined. For the purpose of this section, we describe ground-source heat as any heat being taken from the ground, subsurface as shallow heat abstraction (typically from horizontal loop heat exchangers) and geothermal from deeper heat abstraction (typically borehole or aquifer).

Ground-source heat abstraction is growing in popularity, and since 2010, the number of geothermal and subsurface installations have increased by approximately 20–30% [68,69]. Geothermal and subsurface heat abstraction involves taking heat from the ground, either directly or (usually) in combination with a heat pump. Subsurface energy extraction is predominantly from horizontal loop soil systems at around 1–2 m depth, while geothermal can be from tens of meters to several kilometers, but is usually 40–150 m [70,71]. These systems both extract heat from the ground but with different approaches and prospects. Taking heat from the ground can be traced back to early roman times, however did not begin to become commercially available until the early 1900s [70,72]. Ground source heat is a reliable source of energy, as due to the low thermal conductivity of sediments and rocks, the ground temperature is almost constant throughout the year [73,74].

Geothermal heat comes primarily from radioactive decay in the ground and heat transfer from the hot inner core, either to rock or underground water [70,72]. The core is estimated at 3000–5000 °C at about 6000 km depth, however extraction usually occurs at less than a hundred meters and far below 50 °C [75,76]. The arrangement of geothermal heat abstraction can be open loop but is most commonly a double closed loop system, where the heat pump refrigerant and the ground do not come into direct contact. Instead, heat is exchanged via an intermediate heat exchanger [76]. The various configurations are discussed extensively elsewhere [68,69,77–82]. The most common type of extraction is borehole extraction, where a polyethylene U-tube is placed into the ground and used to pass heat between the ground and a heat transfer fluid. The heat is then upgraded using a heat pump and transferred into the network.

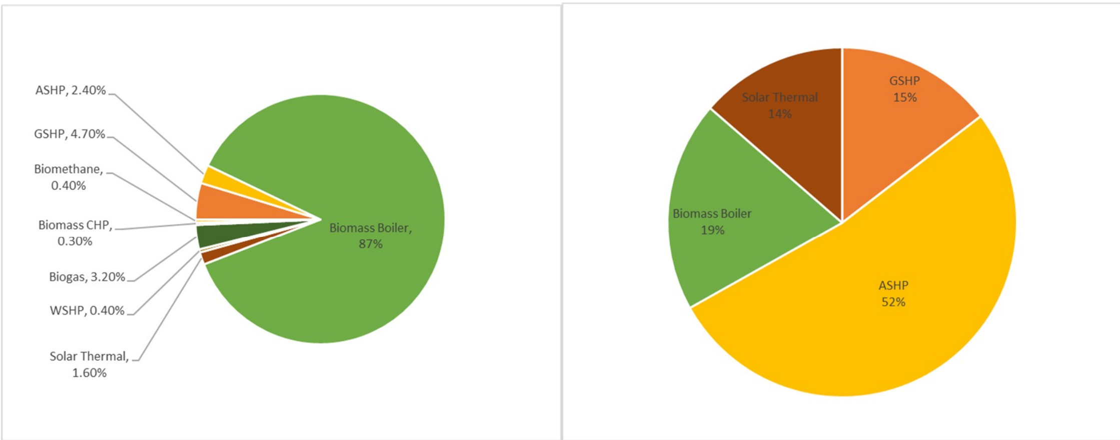
Geothermal heat has been estimated to yield between 50–100 W/m borehole depth of heat pump heating capacity, dependent on ground conditions [70,83]. Anything other than small district heating systems require heat on a MW scale, which would not be economical to extract from a single borehole. For larger heating demands, multiple boreholes are drilled and can have several thousand boreholes, with a capacity of several GW (e.g., Ball State University) [74,84,85].

2.4. Biomass and Biogas

Biomass exploitation uses biological solid (e.g., crops, wood and animal manure), liquid (e.g., oils and fats) and gas (e.g., anaerobic digestion or pyrolysis) byproducts. These materials can be burned to produce either heat or electricity. Bioenergy and waste usage has increased in recent years, from 4.1% of UK primary energy consumption in 2012, to 8.3% in 2017 [86]. This increase can be partially attributed to the Renewable Heat Incentive (RHI), which launched in the United Kingdom in 2014, offering subsidy for biomass usage. Figure 3 shows the domestic and non-domestic split of renewable energy sources, which are signed to an RHI agreement at the end of October 2018. There is a significant difference in RHI uptake of solid biomass for domestic (19% or 64,642) and non-domestic (87% or >18,200), including DHS systems [87,88]. This is likely because of the significant cost to individual users, the need to source biomass, a flue exhaust, storage space of fuel (typically 20 m^3 for an average dwelling), additional delivery and unloading time, low market choice of fuel supplier and high comparable operating costs to alternatives [89]. District heating offers the benefits of biomass combustion to a wider range of customers, without the end user having to deal with the management of the boiler.

Figure 4 shows the split of biofuels in the United Kingdom between bioliquids (primarily fats and oils), gas (from pyrolysis or anaerobic digestion) or solid biomass (crops, wood chips, wood pellets, etc.). This shows a signifcant solid biomass dominated biofuel usage, which can be accredited to the large usage shown in Figure 3.

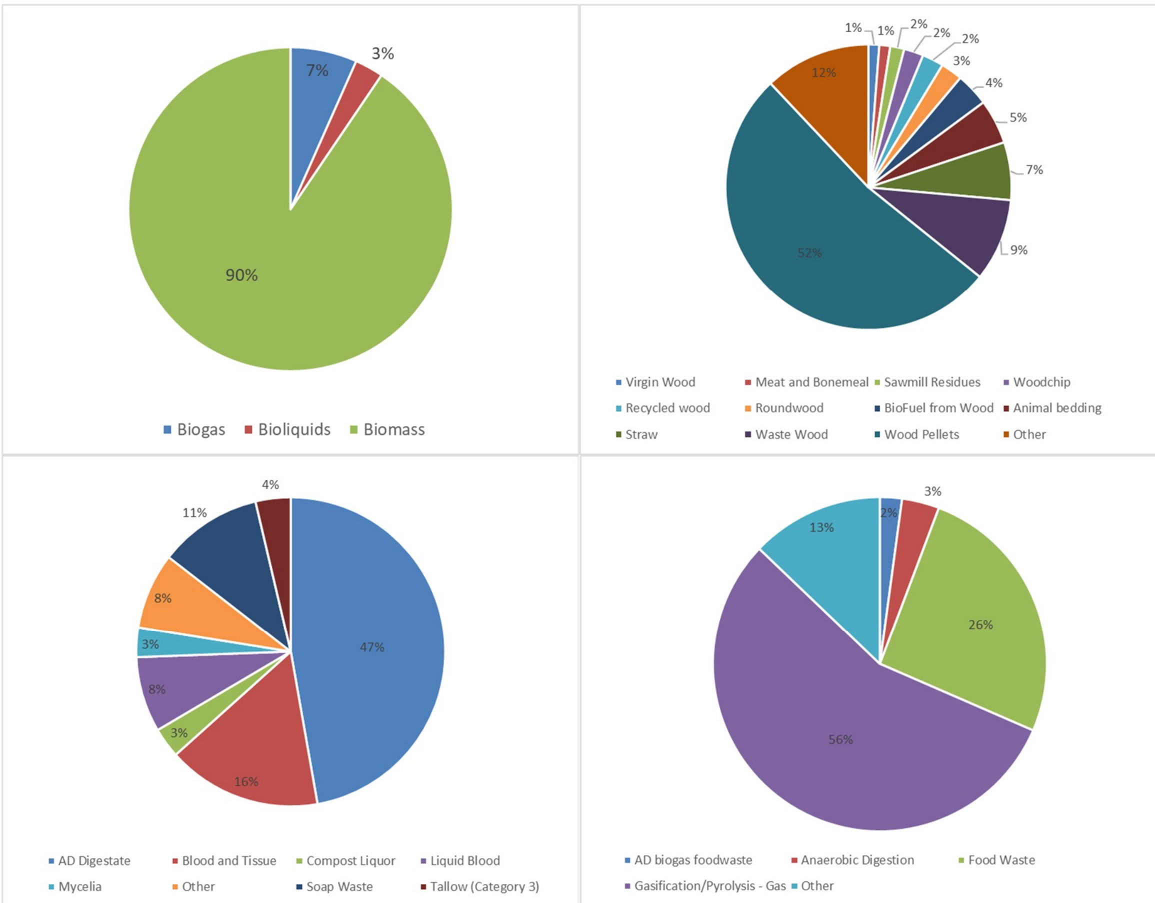
Biomass combustion is often considered a greener alternative to fossil fuels (wood chip—0.015 kg CO_{2e}/kWh compared to 0.204 kg CO_{2e}/kWh natural gas), however many papers have commented on the increase in particulate matter (PM) around biomass burners [90–92]. Although biomass combustion may have a local increase in PM pollution, this is unlikely to significantly contribute to pollution in the United Kingdom.



(a) (b)

Figure 3. Comparison of Renewable Heat Incentive installations by technology type as of October 2018. (**a**) Non-Domestic RHI and (**b**) Domestic RHI [87,88].

(a) (b)



(c) (d)

Figure 4. UK biofuel usage split for 2016 and 2017. (**a**) Total split of biofuel usage, (**b**) split of biomass fuel usage, (**c**) split of bioliquids fuel usage and (**d**) split of biogas fuel usage [93].

A biomass DHN operates much the same as any other DHN, with the exception of the need to transport solid fuel from storage to the boiler, known as the feeding and handling system, described in Table 1.

Table 1. Description of Different Biomass Feeding Systems [94–97].

Type of Feeder	Suited Biomass	Space Utilized vs size of biomass (%)	Advantages	Disadvantages
Belt	• Pellets • Woodchips	20–25	• Reliable • Simple • Low cost • Good over large distance	• Large footprint required
Screw	• Pellets • Wood chips • Sawdust	45%	• No dust emissions • Low cost	• Easily jammed • High power draw
Hydraulic Walking Floor	• Straw • Cereals	90%	• Can deal with non-homogeneous particle sizes	• Large footprint
Pneumatic	• Pellets • Wood chips	N/A	• Long distance transport	• Low capacity • High maintenance • Dust leakage

The first community owned biomass district heating scheme in Scotland is the St Bride's Community Centre (55.942645, −3.220485). This is a small scheme, providing 150 kW of biomass heat to the community centre, local church and bowling club from a 50 kW and a 100 kW wood chip boiler. This is fed from a 4-meter agitator and screw feeder and coupled with a 5000-liter thermal store. The feeder can be adjusted to operate from 30% to 100% maximum output, allowing the system to modulate during demand fluctuations. This system replaces oil burners and is expected to save 4849 tons of CO_{2e} per year. The system cost £161,170 and was funded mostly from local grants. It is expected to return around £16, 500 pa from the RHI, and the return on investment is expected to be around 5–7 years [98,99]. This is a small system, operating on a non-profit basis, similar to many schemes in Europe. This allows the system to remain competitive to alternative heating sources and encourages local ownership, improving local opinions and perceptions [98].

3. Thermal Storage

Thermal energy supply and demand will suffer from large losses in efficiency when the method of heat production must be either quickly increased or decreased. This can occur when a component in the system fails, or more likely, when there is a significant deviation in thermal demand from the anticipated thermal demand. When this happens, the control system can either increase the supply quickly, switch on supplemental gas boilers or use heat from a thermal store. Thermal energy storage (TES) provides a way to shift heat production away from peak demand times and higher cost periods, leading to reduced peak loading, lower heating costs and less mechanical wear on equipment [100].

TES is typically sensible or latent (also called phase change). Sensible TES is by far the most common. Sensible heat storage stores heat in a material by raising the materials temperature, without a phase change. The amount of heat that can be stored per kg depends on the heat capacity of the material and the phase change temperature (either melting or boiling). Latent heat storage forces a material to undergo a phase change, either by adding or removing heat. This will either store or release latent heat. A summary of properties is given in Table 2.

Table 2. Properties of Different Thermal Energy Storages (TES).

TES Type	Sub-type	Heat Capacity [70,101]	Energy Capacity [102,103]	Cost (£) [104,105]	Advantages [70,100–102]	Disadvantages [24,70,100,102,103,106]
Sensible	Water Tank	4.18 $MJ \cdot m^{-3} \cdot K^{-1}$	60–80 kWh/m^3	£26–183/kWh	• Easy installation • Well understood technology • Can be single user or district scale	• Expensive for small users • Only diurnal storage feasible
	Borehole Aquifer	1–4 $MJ \cdot m^{-3} \cdot K^{-1}$ 4.18 $MJ \cdot m^{-3} \cdot K^{-1}$	15–30 kWh/m^3 30–40 kWh/m^3	~£0.3–3/kWh £600–800/kW	• BTES—Efficiency increases over time • Seasonal storage	• High capital • Low energy density • Site specific geological conditions • BTES—Low thermal efficiency
Latent	Organic Inorganic Salts Metal Alloys		40–140 kWh/m^3 70–330 kWh/m^3 80–195 kWh/m^3	£40–350/kWh	• High volumetric energy density	• Low thermal conductivity • Low commercial availability • Can be incredibly expensive compared to other TES

TES has been shown to reduce overall primary energy usage by as much as 10% [107]. This is due to heat load variation which can be minimized by the use of TES, shown in Figure 5.

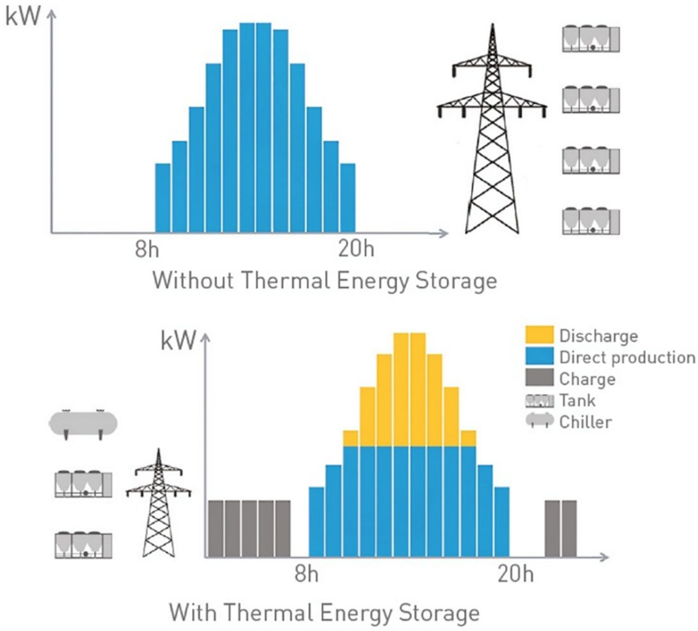


Figure 5. Diagrammatic example of thermal dispatch with thermal storage, reproduced with permission of The Carbon Trust [108].

District heating schemes have inherent thermal storage in the network pipes, however this is rarely enough to shave the peak demand [109,110]. This can be utilized by slightly increasing the supply temperature in the network prior to expected peaks, providing a few hours of storage [111]. Large tanks and pit storage can provide daily or weekly storage, while borehole and aquifer storage can provide seasonal storage. The aim of seasonal storage is to provide enough energy to allow the energy supplies to operate at a lower capacity through the heating season, rather than reducing diurnal peaks.

Current research has focused on optimizing supply and demand in networks. Schmidt, et al. [112] describes the design considerations for large scale aquifer and pit thermal storage. It is suggested that for aquifer storage, the heating and cooling load should exceed 250 kW, and the economy of scale in storage systems is shown.

While TES has been an integrated part of heating systems in many European countries for years, the uptake in the United Kingdom has been much slower. The current infrastructure in the United Kingdom has been built on a high carbon, chemical thermal storage in the form of natural gas, rather than sensible or latent storage. Currently, the only widely available TES is in the form of Economy 7 tariffs, tied with electrical storage heaters. This charges customers based on a day rate and night rate, charging the store during the night and discharging during the day. For TES to further penetrate the sector, it must support competitive pricing in renewable energy. This is difficult to achieve for small domestic users due to the high cost of small TES, low consumer uptake and consumer tariff control [113].

There are very few documented examples of TES in the United Kingdom. One example is Plockton High school. This is a high school on the North West coast of Scotland (57.334340, −5.666381), with boarding for students. It uses a 400 kW baseload biomass boiler, supplemental oil boiler and three 10 m^3 TES tanks. The capital cost of this project was £624,000 and is expected to save £64,000 per year on energy costs. The distribution network operates at 90 °C, typical for a 3G DHN. This is a fairly small scheme, with a peak load of 590 kW, designed for fuel security in an area of the United Kingdom not connected to the gas grid. The school is able to store around 3 weeks of biomass, providing fuel security the previous oil burner system could not. The thermal profile is given in Figure 6. This shows the biomass boiler running constantly at full capacity, loading the thermal store at low demand periods and discharging when needed [108].

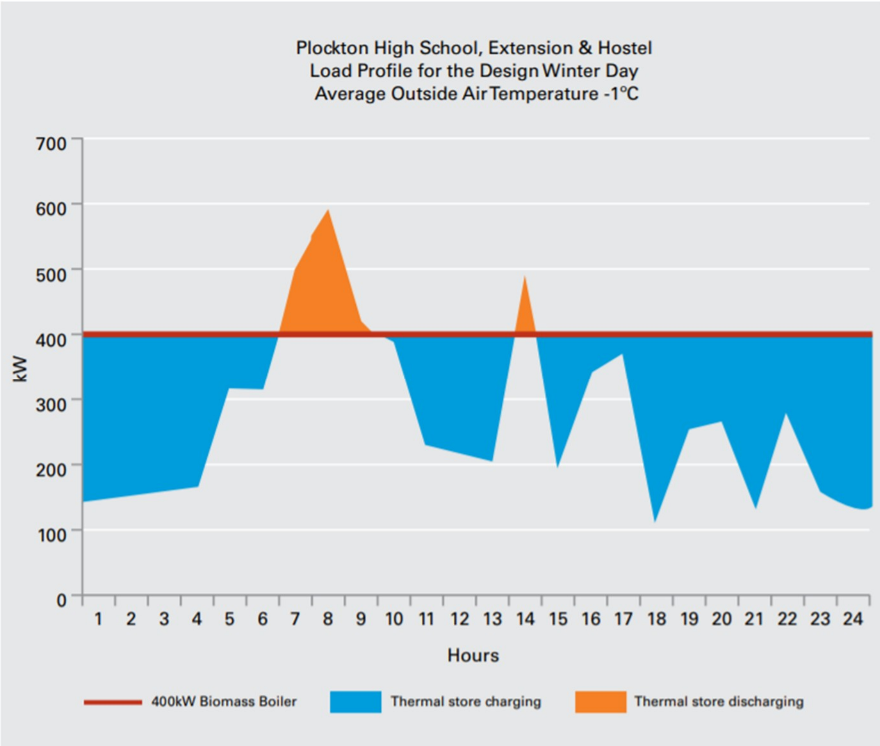


Figure 6. Load profile of Plockton High school, reproduced with permission of The Carbon Trust [108].

4. Load Prediction

District heating can only be deployed successfully when the consumer prices are competitive with alternative heating costs. To achieve this, DHN operators must keep distribution costs as low as possible, and it has been suggested that this will necessitate the use of co-generation, waste incineration, waste industrial heat, geothermal, biomass or a mix of these options [114]. Heating demand is controlled by the end user, while the energy supply center can be several miles away and must respond to demand very quickly. In a perfect case, the heating supply will perfectly match the heating demand. By closely matching supply and demand, the network will run at greater efficiency, leading to lower operating temperatures, lower distribution and transmission costs, which will in turn lead to lower end user costs, and therefore more users connecting to the network, further reducing costs [115–124]. To meet demand, DHN operators can control fluid flow in the network, differential pressure and supply temperature [118]. In many cases, the operator will slightly increase the supply temperature prior to an expected demand spike, slowly increasing heat and storing it for a few hours in the network. To reach any significant improvement in thermal dispatch, a smarter approach to demand management must be adopted.

Artificial Neural Network (ANN) models are a method of short term thermal load prediction, typically a few days or hours [118,125–128]. ANNs are an adaptive learning model capable of processing multiple streams of data in parallel and learning from a dynamic input-output response [129]. The model is presented with example data and known outputs. For a heating network, this could be example temperature or flow adjustments in a distribution system to match a known thermal demand. The model will then adjust the internal connection weights to reduce deviation from the simulated output and target output [130]. The initial learning can require a large amount of data, which isn't always available from DHSs, however the difficulty in gathering initial data is a worthwhile endeavor, as the ANN can be generalized and applied to other systems once learning has taken place [129,130]. ANN forecasting offers improvement on statistical methods (e.g., time series and regression), as ANNs can provide a non-linear response to a non-linear problem, while statistical modelling is typically linear [131].

Neto and Fiorelli [132] compare an EnergyPlus forecast and a feed-forward style neural network forecast. A feed-forward network has each neuron connected only to a neuron in the next or previous layer. EnergyPlus uses physical constants to model energy demand; further details can be found in the EnergyPlus Engineering Reference document [93]. EnergyPlus struggles to account for human variability. For example, it cannot account for a building occupant randomly opening a window. ANNs are trained from real data, including these random events, and can therefore produce a model capable of incorporating random variables. The results of this study showed EnergyPlus with an error of $\pm$13% for 80% of the tested data, while the ANN model showed 10% error when the forecast is split into working days and weekends [132]. Although the ANN results can be improved, serious improvement must be made before ANN becomes the next widely used energy forecasting tool. These improvements can be made through intensive focus on network training and data acquisition.

5. Economics and Regulation

It has already been described that DHNs have a low penetration in the U.K. heating market, with the Department of Energy and Climate Change (DECC, which was later replaced by the Department of Business, Energy and Industrial Strategy) estimating there are around 2000 schemes in the United Kingdom, with 55% of these in London [133]. Figure 7 shows the fuel type by size of DHN for available data (710 schemes), excluding any unknown fuel sources (1095 schemes). The DECC report defines users as [134]:

- Large—>500 residential properties or > 10 non-domestic users
- Medium—100–500 residential properties or 3–10 non-domestic users
- Small—<100 residential properties or < 3 non-domestic users

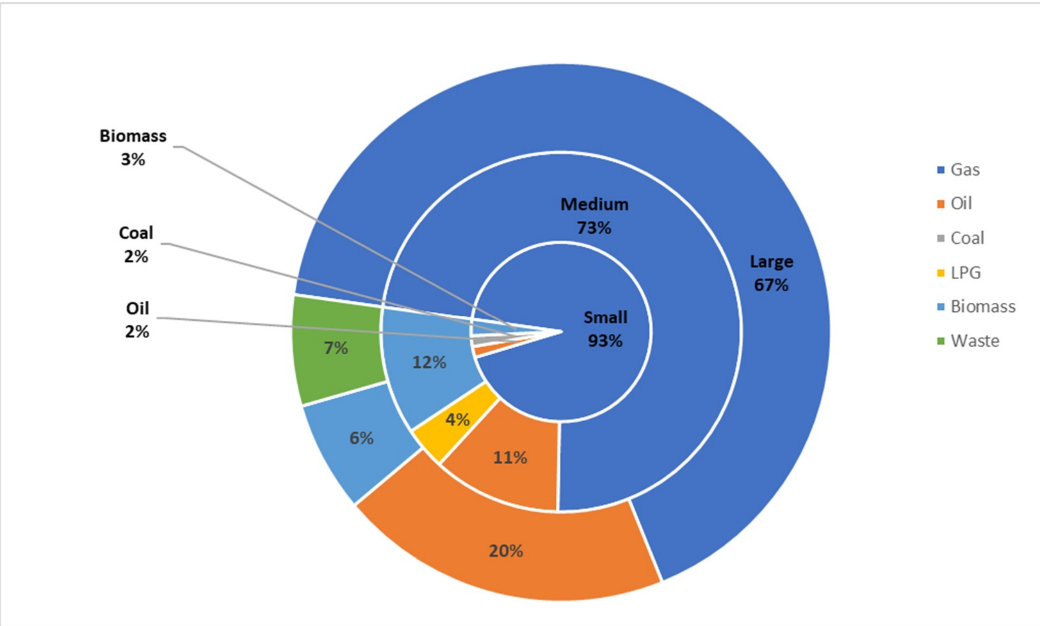


Figure 7. District Heating Fuel Type in the United Kingdom by Network Size.

It is no surprise that natural gas is the largest fuel source shown, with the UK gas network estimated to cover 85% of domestic heating [3]. This makes it difficult for new district energy suppliers to get a foothold in the existing gas and electricity monopoly, however it has been shown that once installed, DHNs have a tendency to grow and expand [135]. DHNs in the United Kingdom are typically led by the local authority or by the property developer (however, some community owned schemes are also present). In 2013, a UK government funded report identified the key issues to authority led DHN deployment as being financing, while for property developer led DHNs, the biggest roadblocks come from identifying suitably qualified consultants and agreeing financing terms with the service provider [135]. Costs can be significant and stretch beyond simply capital and operating costs—technical and financial viability studies (sometime £60,000), upskilling staff, legal advice and procurement, to name just a few. This creates a significant barrier, which many developers and local authorities would not be able to overcome without significant government help. Since this study was published, the Low Carbon Infrastructure Transition Programme (LCITP) has been launched in Scotland to support low-carbon projects across. Support available can include project development, expert advice and financial support to those able to provide at least 50% of the initial funding. Example projects supported include the Queens Quay and Clydebank district heating network (£6 million), the Dundee Low Carbon District Energy Hub (£2.9 million) and Callander Local Energy Opportunity (£100,000) [136,137]. This shows a significant government investment and a welcome focus, which has been echoed in Westminster by the launch of the Heat Network Investment Project (HNIP). The RHI is based on the volume of heat produced and the eligible technology. This can be used to support operational costs. For example, a 400 kW biomass boiler might expect an RHI, shown in Table 3.

Table 3. Example RHI calculation for Medium Biomass tariffs for systems installed after May 22, 2018. Note that in practice, operation would likely be far < 8760 h pa, and therefore so would the payment.

Heat Generation	Heat Generated per Tariff (kWh)	Tariff (p/kWh)	RHI/year (£)
Tier 1	3066 hours × capacity = 3066 × 400 kW = 1,226,400 kWh	3.05	37,405
Tier 2	Total capacity (400 kW × 8760 hours/year = 3,504,000) − Tier 1 heat (1,226,400) = 2,277,600 kWh	2.14	48,740
		Total	86,145

A significant hurdle to financial viability in domestic schemes is the consumer uptake. Energy Services Providers (ESPs) will have a minimum dwelling uptake to be able to consider a DHN, some will require as many as 500 dwellings to consider a CHP scheme economically viable [135].

As of December 2018, there is no regulator for heating networks, as there is for electric and gas networks (Ofgem), meaning consumers on DHNs have less security than traditional gas and electric consumers. This means there is no ombudsman to receive complaints, which can discourage consumers connecting to the heating network, making it even harder for network owners to make the necessary connections for an ESP to begin talks. The only current legislation specific to DHNs is the Heat Network (Metering and Billing) Regulations 2014, which describes the billing and metering for DHNs but does not legislate the quality of heat, market competition or DHN monopolies [138]. The Heat Trust is a voluntary standard launched by industry participants, while the Association for Decentralised Energy (ADE) and Chartered Institution of Building Services Engineers (CIBSE) have produced a heat network code of practice. Both of these are voluntary, and it is unclear how many DHNs in the United Kingdom meet these standards and practices. Therefore, it is clear that the UK must push legislation and regulation around heating networks in order to provide safe, secure and competitive heating network markets in order to facilitate the 17% predicted domestic heat supply by DHNs by 2050.

6. Conclusions

District heating networks have a long and proven track record in EU and the Nordic countries, but have struggled to make headway in the UK energy market. Past technology and political climates encouraged alternative heating, and it is only in recent years that the focus has returned to district heating schemes in the United Kingdom and become a part of the government's energy and environmental plans and legislation.

Although the UK share of district heating is increasing, it is clear that markets still cling to the security of the gas network, shown by the substantial share of CHP in district heating networks. This will ultimately limit the ability to de-carbonise the heating sector and limit uptake of government subsidy. There is some suggestion that converting a natural gas CHP to a biogas CHP is viable, however the biogas supply chain is unproven in a UK context, and long term, sustainable alternatives should be considered for all future district heating networks.

The choice of low carbon, renewable energy supply to a district heating network can only be made after careful consideration to site requirements—available space, funding, supply and fuel security must all be considered for each new district heating network. That said, as a general rule of thumb, larger heating networks will opt for a co-generation system, while smaller schemes will opt for low-cost alternatives, such as ground source heat pump or air source heat pump. Scottish government incentives are now making the resources available for district heating to be further dispatched, however without encouragement to abandon the high carbon gas network, district heating will only primarily appear in new developments and likely with gas CHP.

Thermal management has taken a back seat to electrical demand prediction and dispatch, but is slowly increasing in research focus. This is necessary to improve the efficiency, and therefore lower the cost of district heating networks in the United Kingdom. This can range from simplistic tank storage to more complex phase change materials and load prediction. Future work must be able to address the challenges with energy planning of unpredictable human events and offer simple, easily applied techniques to thermal demand management.

District heating has been shown to prevail in countries with strong government support, not yet felt in the United Kingdom. In a time of political uncertainty, it is crucial for government backing to continue and expand. We recommend that this should focus on:

- Developing consumer awareness of DHNs
- Providing further incentive to low carbon projects (e.g., RHI)
- Develop necessary engineering skills and experience of DHNs
- Providing regulation and security for DHNs

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