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The future role of energy geostructures in fifth generation district heating and cooling networks

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ABSTRACT

Energy geostructures are novel dual use engineering sub-structures that can be used for heat transfer and storage as well as original structural function. Their use is becoming increasingly popular in delivering cost-effective shallow geothermal energy. Currently, they are mostly used as a part of ground-source heat pump (GSHP) systems for supplying partial or full heating and cooling demands of different types of buildings. The recent introduction of fifth generation district heating and cooling (5GDHC) networks can pave the way for the exploitation of energy geostructures as ground-coupled low-temperature energy sources and stores for providing energy demands of a wider range of energy users in districts rather than single buildings. In this article, the capability and feasibility of the novel concept of integration of energy geostructures into the 5GDHC networks are evaluated through reviewing different aspects of thermal performance of operating energy geostructures and 5GDHC networks. The potential advantages and challenges along with the knowledge gaps in such integration are discussed, and some practical recommendations are provided concerning dealing with some implementation challenges. It is highlighted that the incorporation of energy geostructures in 5GDHC networks can enhance the sustainability, flexibility and resilience of the network. There is the potential to exploit a greater share of cost-effective geothermal energy, and the ability to act as both thermal energy sources and stores for efficiently supplying both heating and cooling demands. However, since the development of fifth generation thermal networks and energy geostructures, particularly energy walls and energy tunnels, are still in their infancy, further research is required to assess the magnitude of the opportunities and quantify the advantages of integrating energy geostructures into the 5GDHC networks.

1. Introduction

Heat is recognized as a significant contributor to greenhouse gases (GHG) emissions, accounting for over 50% of global energy consumption in 2015 [1]. Heating in buildings itself accounted for 40% of this heat consumed. Therefore, to reach the net-zero emissions goal, a critical transformation is required in providing low and zero carbon heat supply for buildings. Currently, heat supply for space heating or domestic hot water in buildings is mainly provided by individual heat sources (e.g. boilers) or by district heating networks (DHN). The key advantages of DHNs over individual heat sources includes delivering heat in a more efficient manner, more cheaply and with lower carbon emissions. These systems are currently used noticeably in counties with a cold climate such as Scandinavia, Eastern European countries and Russia [2]. For instance, 90% of the housing in Iceland is heated via district heating networks distributing hot water sourced from geothermal energy [3]. Despite the long and proven track record of DHNs in the EU and the Nordic countries, many countries still lag behind in their application. For example, it is only in recent years that DHN in the UK has become part of the national strategy [4] and DHNs still provide only about 2% of the overall heat demand, despite research showing that this could be increased to 43% by 2050 [5].

A key advantage of DHNs is their ability to facilitate the integration of low-temperature energy sources that otherwise cannot

Abbreviations: 3GDH, Third Generation District Heating; 4GDH, Fourth Generation District Heating; 5GDHC, Fifth Generation District Heating and Cooling; CHP, Combined Heat and Power; CoP, Coefficient of Performance; DHN, District Heating Network; DHW, Domestic Heat Water; GHE, Ground Heat Exchanger; GHG, Greenhouse Gases; GSHP, Ground Source Heat Pump; HP, Heat Pump; LTDH, Low Temperature District Heating; RES, Renewable Energy Sources; SH, Space Heating; SWOT, Strengths, Weaknesses, Opportunities, and Threats; ULTDH, Ultra-low Temperature District Heating; UTES, Underground Thermal Energy Storage; WSHP, Water-source Heat Pump.

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be utilised, e.g. low-temperature renewable energy and waste heat. This is particularly important since only a small amount of heating and cooling supply comes from renewable energy, despite their large contribution to GHG emissions. The share of renewable energy sources including heat energy captured by heat pumps in the supply of heating and cooling in EU countries, is shown in Fig. 1 [6]. While the EU average is 29%, there is a range from significant adopters like Sweden (66%), and places like the UK with only 8%.

There have been several reviews concerning utilising low-temperature energy sources in district heating networks. These reviews deal with different aspects such as the policy and legal frameworks [7], the expert assessment and regulatory frameworks [8], along with the key issues in the inclusion of more than one low-grade heat sources [9] and unconventional excess heat sources [10]. From these it can be concluded that to improve the efficiency and sustainability of DHNs, systems need to be integrated with more reliable and efficient thermal resources. In this article, the potential of energy geostructures as energy resources are investigated in the context of integration into the district heating networks. Energy geostructures are a specialist type of shallow geothermal energy, where in-ground civil engineering structures are equipped with heat transfer pipes allowing them to play the role of ground heat exchangers (GHE) transferring the heat from/to ground [11]. Energy geostructures have an advantage over traditional drilled borehole GHE. Since the heat transfer pipes are embedded in a ground contact structure, or in an excavation already taking place for their construction, this means that the capital cost for drilling special purpose GHE is reduced. This therefore offers lower investment costs than conventional GHEs. Energy geostructures constructed as a part of ground-source heat pumps (GSHP) systems have seen increased growth in markets and research in the last few years [12]. However, their wider potential to integrate to district heating networks has yet to be explored.

The main aim of this article is to evaluate the capability and feasibility of the integration of energy geostructures with district heating and cooling systems. The current review can make a step forward to better understand the potential role of energy geostructures linked with thermal networks, particularly fifth generation networks. This article is structured into four main sections. Section 2 briefly describes the history of thermal networks, with their recent developments. The challenges and opportunities that come with lower temperature distribution are discussed in Section 3. Section 4 reviews different types of energy geostructures focusing on energy walls and tunnels and gives examples of their current uses. Their potential to be integrated with district heating and cooling systems is then explored in Section 5. Limitations, knowledge gaps and recommendations for the deployment of the technology integrated with thermal networks are provided.

2. District heating networks

Traditionally, a district heating network comprises an underground piping (distribution) network that delivers the production of heat from energy source(s) to end-users. The complexity of the systems varies with the different parameters associated with these subsystems and should be thoroughly considered in analysis, design, and optimisation processes. These parameters can be mainly stated as: the type of heat source (e.g. geothermal energy, combined heat and power (CHP), etc.), the number and variety of the users connected to the system, temporal heat demand profile and spatial concerns (e.g. coordinates of all users) [13,14]. In the following sections, the history of DHN development and their capability to integrate geothermal energy are briefly described.

2.1. Early development

Since the 1880's, DHNs have been evolving from high temperature networks with low thermal efficiency to efficient low temperature networks with diverse heat sources. Given in terms of the different generations of technology, Table 1 summarises this development in terms of the heat transfer fluid, energy source(s), and network temperature. Both first and second generation DHNs have became outdated, due to the noticeable heat losses and low energy efficiency, with third, fourth and fifth generations currently in operation [15].

Third generation DHNs utilise pre-insulated pipelines connected to compact building substations, where a heat exchanger is installed to take heat from the network [15]. They use energy centres to replace oil with various fuels such as biomass, and waste energy and in a few cases renewable energy [18]. In addition,

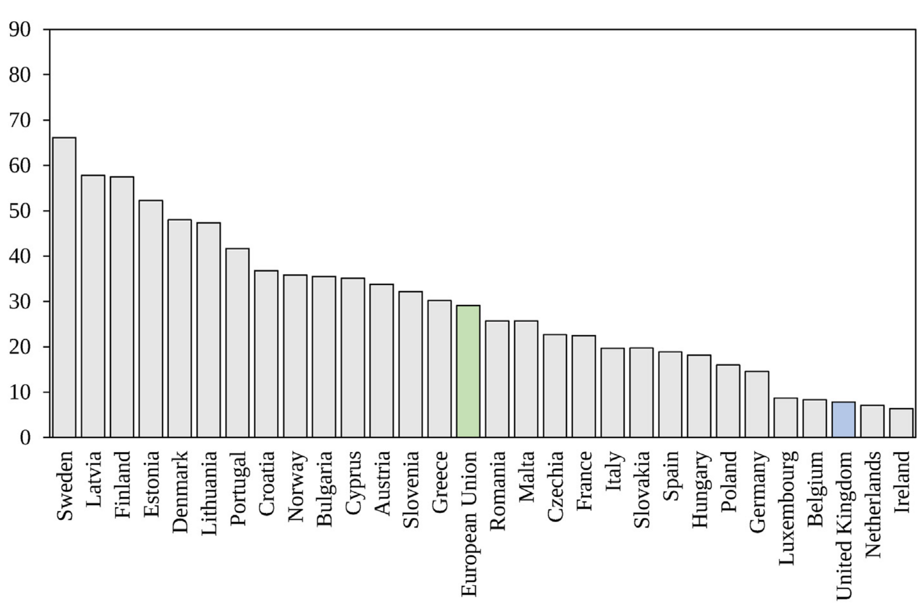

Fig. 1. Shares of renewable energy sources (RES) for heating and cooling in the EU, in 2019 [6].

Table 1
Summary of main characteristics of thermal energy networks from the first to fifth generation [15–17].

	First generation	Second generation	Third generation	Fourth generation	Fifth generation
Peak period of installation	1880–1930	1930–1980	1980–2021	2018–2050	2018–2050
Energy Production	Heating	Heating	Heating	Heating	Heating and cooling
Heat transfer fluid (distribution temperature)	steam (>150 °C)	Pressurized hot water (>100 °C)	Pressurized hot water (90-60 °C)	Hot water (45–55 °C)	Low temperature water (<45 °C)
Energy sources	Coal	Coal and oil	Biomass, waste, fossil fuels, direct use of geothermal energy	Heat recovery, Renewable energy sources (RES) including shallow geothermal energy incorporated with HPs	Low temperature heat recovery and low temperature RES including shallow geothermal energy
Pipeline material	In situ insulated steel pipelines \Concrete ducts	In situ insulated steel pipelines	Pre-insulated steel pipelines	Pre-insulated twin flexible plastic pipelines	Uninsulated plastic pipelines

combined heat and power (CHP) systems are typically integrated to balance the electricity and heat demand, as well as increasing the overall efficiency of the heating network. Although geothermal energy has been integrated with third generation district heating (3GDH) networks, the number of cases remains limited [19]. For instance, Unternahrer et al. [20] assessed the integration of geothermal energy into a DHN and found that network profitability is influenced by spatial density of the end-users. Some more examples cases are found in Turkey [21,22] and Germany [23], but geothermal 3GDH networks are not widespread since locations with the potential of providing sufficient supply temperature is confined to specific geological environments. However, in some cases, geothermal absorption heat pumps combined with CHPs has been used to enhance the efficiency and flexibility of the technology [24,25].

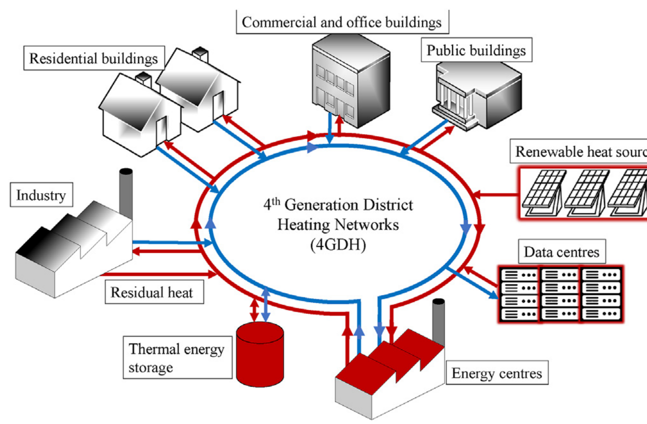

Fig. 2. A representation of a typical fourth generation district heating network.

2.2. Fourth generation district heating networks

Fourth generation district heating (4GDH) systems operate at lower temperatures (less than 55 °C), allowing extensive use of waste energy and renewable energy, and reducing heat losses from the distribution pipes [26,27]. The concept of 4GDH systems goes beyond the low loss heat network to include a coherent smart energy system integrated with electricity and gas grids supplying low-energy buildings [15]. Due to the low network operating temperature, these networks are also referred to low-temperature district heating (LTDH) networks in the literature [28,29].

Case studies show that transition from 3GDH to 4GDH is typically cost effective [26]. For example in the city of Aalborg a decrease in network losses from 21% to 15% gave a corresponding reduction in the annual energy system cost of 2.7% [30]. Averfalk et al. [31] also report higher profitability due to inclusion of waste and renewable heat sources. It is this decarbonisation potential where 4GDH can bring real benefits [8]. This capacity for use of low temperature sources, like shallow geothermal, is significant [32]. Consequently, the important role of geothermal energy systems in the fourth generation district heating networks have been considered in a number of studies [33,34] including the Heat Roadmap Europe (HRE) [35], where their potential is determined to be considerable. For instance, Kljajic et al. [36] evaluated the potential of shallow geothermal energy as an energy source for heat pump systems connected to a 4DHN in Serbia. It was found that integration can reduce the network input primary energy at least 30% compared with the current use of natural gas boilers, with a payback period of less than five years.

Despite the improvement of 4GDH networks compared with 3GDH in terms of energy efficiency, energy sources and integration with the electricity grid, the topology and structure of 4GDH networks are almost the same as 3GDH networks: the network of supply and return pre-insulated pipelines deliver heat production from centralized energy centre(s) to a wide range of consumers. This typical structure of a 4GDH network connecting a variety type of buildings, and heat sources incorporating thermal energy storage units is illustrated in Fig. 2.

However, this traditional DHN structure does retain some disadvantages. Even though the distribution temperature in 4GDH is relatively low, traditional networks still suffer from some heat losses from the distribution system. In particular, this can happen in summer, when the networks generally only supplies domestic hot water (DHW), and thus the retention time of hot water in the networks is higher leading to more network heat losses [37]. 4GDH is also only suitable to provide heating and cooling via two separate supply and return pipe networks, at associated high capital costs. Since many individual users and networked districts actually require simultaneous heating and cooling, this has driven development of fifth generation systems [37,38]. Lund et al. [39] discusses the differences and similarities between fourth and fifth generation DHNs. The implementation and operational aspects of fifth generation networks are described in the following section.

3. Fifth generation district heating and cooling networks

The most recent thermal energy networks development is fifth generation district and cooling (5GDHC) networks [38]. The concept is to provide simultaneously both heating and cooling demands, via an ultra-low temperature distribution network (less than 45 °C). Hybrid substations are equipped with water source heat pumps which can lift (or reduce) temperatures to those required by users, and also enhance the integration of the thermal and electricity grids (decentralized smart energy systems [40]) contributing to decarbonisation of heating. Unlike the traditional DHNs, fifth generation networks consist of single cold and warm pipelines circulating heat transfer fluid in a direction depending on whether more heating or cooling demand is needed in the network. This allows the network to take advantage of the direct use of waste heating or cooling of one user to match the cooling or heating demand of other users. This allows broader integration of low temperature heat sources, including shallow geothermal energy, without any need to boost their temperatures before feeding the network. This approach is also referred to in the literature as bidirectional low temperature networks [41–43], neutral networks [44] and ambient loop networks [45,46]. However, the concept is the same in all these cases.

End-users' substations are essential components of all thermal networks due to the their significant role in satisfying the thermal energy demands of buildings. However, their roles in fifth generation networks are even more critical, as each substation connected to the fifth generation networks operates both as a consumer and producer, i.e. so-called prosumers, of thermal energy. This prosumer concept has already been used in the power sector [47], where end-user electricity consumption can come from the power grid, while still being able to sell back electricity from rooftop PV panels during times of low usage. Similarly, in 5GDHC networks, while end-users take thermal energy from the network, excess thermal energy, e.g. waste heat from chiller condensers in supermarkets, can also be fed into the network to provide balance. The main concept of the 5GDHC network is depicted in Fig. 3.

In spite of the recent introduction of 5GDHC networks, only a small number of networks are currently in operation, and they are often mainly seen as pilot or demonstrator projects [37,48]. Buffa et al. [37] assessed the benefits of 5GDHC networks by reviewing 40 cases in Europe. It was highlighted that technical and non-technical knowledge about 5GDHC is limited, particularly for integration with shallow geothermal energy. In another study, Boesten et al. [48] demonstrated how a local district heating and cooling network (the Mijnwater system in Heerlen, the Netherlands) has been converted into a 5GDHC network. The original network comprised a triple pipeline network (cold and warm supply along with return) using a flooded coal mine as a low temperature geothermal source. This was converted into a 5GDHC network with the inclusion of several local low temperature heat sources, e.g. supermarket refrigerators, using bidirectional warm and cold pipelines. It was concluded the 5GDHC principles could be adopted and applied for even large scale thermal energy networks.

A review of 5GDHC networks based on their main benefits and integration challenges is presented in the next section, with a summary from technological, economic, environmental and social perspectives presented in Table 2. In the following sections, consideration is given to the leading network energy sources, typologies and energy demand prediction and management issues.

3.1. Advantages

Lower temperature operation of 5GDHC networks, i.e. close to the ground temperature, offers the advantage of minimum heat losses (close to zero) in the distribution networks compared with previous generations. Therefore wider use can be made of local low-grade energy sources, which otherwise could not be directly integrated, either into 4GDH or at an individual user level. This includes shallow geothermal energy from a number of sources, including energy geostructures. This particular benefit is more significant in the urban area where often many low-grade heat sources are available close to heat users. For instance, in London, the waste heat from industrial and commercial activities along with the heat which can be extracted from the air, water and ground are estimated to offer around 71 TWh/yr, approximately 10% higher than the estimated London's heat demand [49].

Another advantage of 5GDHC networks is the higher level of flexibility that is a consequence of the integration of heating, cooling and electricity grids as well as thermal energy storage technology, thus providing thermal energy at various level of temperatures and time scales [48]. This technology leads to a smart coupling of the electricity and thermal grids by using decentralized heat pumps or chillers in the hybrid substations and paves the way for electrification of the heating sector in buildings [50].

Equipping each individual building with heat pumps additionally benefits the end-users, allowing them to adjust their own comfort temperature independently based on the types of buildings, and including both new and existing buildings with variety of comfort temperature requirements. Therefore, there is no limitation for integration of any type of buildings, in contrast to the previous network generations in which old buildings could be

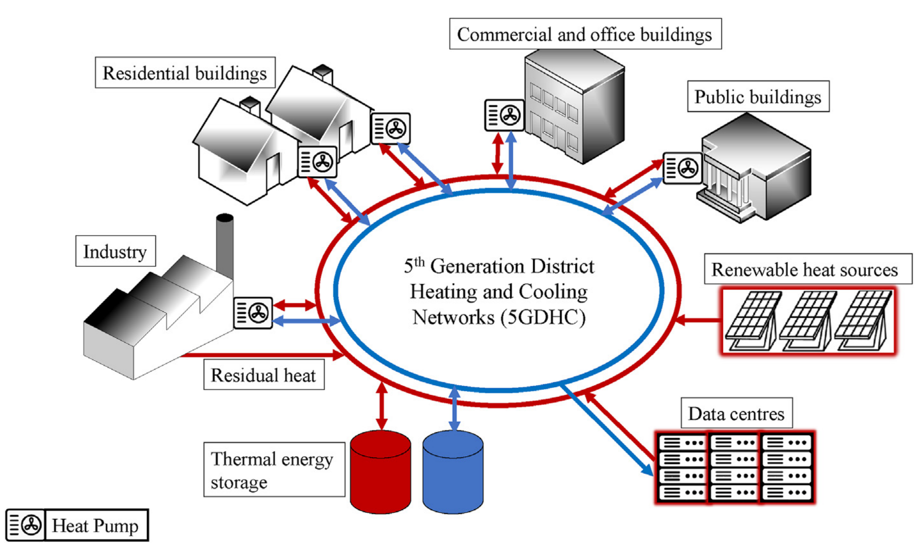

Fig. 3. A representation of a typical fifth generation district heating and cooling network.

Table 2
The main advantages and challenges of the implementation of fifth generation district heating and cooling networks in terms of technological, economic, environmental and social aspects [17,37].

	Advantages	Challenges
Technological aspects	• Integration of extensive local low-temperature heat sources such as shallow geothermal energy. • Covering both heating and cooling demands of the networks, simultaneously. • Higher network flexibility and modularity can be achieved. • Network resilience to buildings efficiency levels and consumers demands at different temperature levels. • The network and the ground can play the role of thermal energy storage. • Sustainable electrification of thermal sector through smart coupling of electricity and thermal grids via the use of decentralized heat pumps.	• Absent of guidelines and standards for designers and planners for development of such networks. • Requiring relatively large thermal energy storage and/or electricity storage technology. • Dependence on the thermal characteristics and performance of heat sources which may have fluctuating and intermittent nature. • Higher level of complexity in terms of planning, designing and controlling.
Economic aspects	• Cost effective uninsulated polymeric materials can be used for network pipes. • No centralized energy centre needs to be constructed.	• End-users' substations are expensive. • Higher pipeline diameter and larger thermal energy storage are required due to lower temperature differences between supply and return pipelines. • Higher pumping cost in the networks due to the higher fluid viscosity because of the lower operating temperature.
Environmental aspects	• Higher system efficiencies when simultaneous heating and cooling. • Integration of local low-temperature waste and renewable energies. • Reduce GHG emissions	• Electricity consumption for decentralized heat pumps and circulation pumps, as well as higher temperature lifts for some consumers can effect overall efficiency.
Social aspects	• End-users' energy costs reduce through the wider use of waste and renewable energies.	• Lack of culture for thermal energy networks, particularly at ultra-low temperatures, in some countries, e.g. the UK. • User acceptance required for switch from individual heat source approaches (e.g. boilers).

integrated only if the heating infrastructure, e.g. radiators, thermostat, and control systems, are significantly upgraded [51]. In some buildings with poor thermal conditions, this integration to 4GDHN is therefore unlikely due to the significant renovation costs [52]. This particular benefit of the fifth generation can be considered more critical where the number and density of older properties is relatively high. Millar et al. [4] indicated the significant role of older properties in the future energy efficiency of thermal networks in the UK and concluded they must be properly considered in the thermal network market.

The capability of integration of both heating and cooling sources in 5GDHC networks enables the network to operate at higher energy and cost efficiency, particularly when heating and cooling demands are present at the time. This suggests the significant potential opportunities for 5GDHC integrated with energy geostructures due to their capability of providing both heating and cooling demands and somewhat balancing the thermal loads. Wirtz et al. [43] introduce the Demand Overlap Coefficient (DOC), to evaluate the energy efficiency of a network compared with individual buildings. It was demonstrated for an operating case in Germany, that 25% of heating and cooling demands can be offset in individual buildings and 45% by connection to the 5GDHC networks. Furthermore, thanks to the self-balancing concept of 5GDHC networks, constructing centralised energy centres can be avoided. Without centralized energy centres and major temperature drops in distribution networks, the systems can be more conveniently expanded compared with previous generations [37,53]. This feature of 5GDHC networks leads to enhancing not only the resilience of the network in balancing heating and cooling by involving more buildings and energy sources, but also flexibility and suitability in terms of network expansion in both growing and built urban areas.

Due to the decentralized nature of low-grade energy sources in urban areas, construction of long pipeline networks for connecting energy sources to end-users is not required. In addition, operating at a low temperature close to the ground temperature allows the pipelines to be none-insulated and made of polymeric materials rather than insulated pipelines in the previous generations [37]. These two features of fifth generation distribution networks lead to considerably lower front-end investment costs of network construction.

3.2. Challenges

Despite the clear advantages of moving to 5GDHC networks, either by upgrading existing 4GDH or transitioning from individual heat sources (like boilers), there remain some challenges related to technical and economic development of such systems. For example, the thermal and economic benefits strongly depend on the thermal characteristics and performance of the energy sources integrated into the networks. Buffa et al. [37] indicated that although the main concept of 5GDHC networks is the same for all cases, utilization of local low-temperature energy sources is distinctive for each case, and appropriate local thermal and economic assessments are required. The main integration challenges of low-grade energy sources usually relate to their fluctuating and intermittent nature. However, with the recent increase of research interests in 5GDHC networks, the development of new dynamic models and tools, to address this challenge for designing and managing networks, has been growing [54]. For example, the dynamic thermal behavior of the distribution network can be taken into account to avoid any unexpected time lag and diffused thermal responses to energy users in delivering thermal energy [55,56].

Therefore, the integration of low-grade energy sources into the network needs to be carried out with different thermal and electricity storage technologies, and smart control mechanisms [17]. Storage is also highlighted by Mahmud et al. [57], who indicate that the temporal and spatial demand functions are the main technical issues which should be addressed with the implementation of energy storage systems (ESS) both at the network level, for seasonal thermal energy storage (TES) [58], and at building level for shorter term storage [59]. However, there also remain challenges in determining the demand of the different network users in combination, and in attempting to manage that demand to reduce the amount of storage required (refer to Section 3.4 and 3.5).

Wider integration of low-grade energy sources, energy stores and decentralized heat pumps through bidirectional networks also introduces a challenge in control to ensure optimal operation without failure in meeting the thermal energy requirements of end-users. Bunninga et al. [41] and Buffa et al. [60] developed two control strategies to deal with this challenge and highlighted the importance of the smart control of the multiple energy sources and prosumers in 5GDHC networks.

A potential challenge of 5GDHC networks can be legionella in the networks due to the low operating temperatures, between 25 and 45 °C, which may be suitable for the growth of legionella bacteria. However, since each end-users' substations in 5GDHC networks is equipped with heat pumps, by operating the heat pumps up to 55–60 °C, the legionella risks in networks are eliminated. Millar et al. [46] briefly reviewed Legionella prevention methods in low-temperature networks including 5GDHC networks, and concluded more efficient methods can be developed, such as effective use of copper and silver ions or Chlorine dioxide in the water system, rather than increasing of supply temperatures.

Together, these factors result in a higher level of complexity in 5GDHC networks, both in terms of design and importantly control systems. The flexibility of fifth generation networks to operate using different pipeline topologies can also influence this complexity. These aspects, in addition to equipping all substations with heat pumps and storage technologies, must be carefully assessed both from technical and economic viewpoints to enable the thermally-efficient and cost-effective integration of low-grade energy sources into fifth generation networks. In the following sections, these critical challenges are reviewed in more detail, starting with discussion of typical and potential low-temperature energy sources.

3.3. *Energy sources of 5GDHC networks*

Fifth generation district heating and cooling networks enable the integration of a wide range of low-grade waste and renewable energy sources that would be impossible to be exploited in the previous generations. The integration of energy sources can be varied based on the thermal load and heating/cooling requirements of energy users ranging from a few kW to the tens of MW. Buffa et al. [37] carried out a comprehensive survey on energy sources in operational fifth generation district heating and cooling networks in Europe (Fig. 4). It was shown that 42% of thermal energy comes from low-temperature water sources including seawater, lake water, river water and groundwater. These energy sources can be exploited either directly: similar to open-source ground source heat pump systems [61], or indirectly: as a closed-loop system, via installed heat exchangers [62]. Sources of water for thermal energy exploitation can also include more novel approaches. For example, groundwater draining from a mountain tunnel in Switzerland has been used as the sole heat source for a 5GDHC scheme [63]. Minewater, which is often warmer than natural groundwater, has also been used as a heat source in a number of locations, including at Heerlen in the Netherlands [64].

Waste heat is another important heat source for 5GDHC networks. Although Buffa et al. [37] identified relatively few waste heat sources in their review, for example a local dairy with the supply temperature of up to 25 °C [65], there remains considerable potential for other waste heat sources to be integrated into such networks [17]. Lagoeiro et al. [66] reviewed the opportunities for the exploitation of urban waste heat sources and novel heat recovery technologies with a focus on the underground railway in London. They showed the economical and environmental benefits of using a reversible fan with the ability to operate in both extraction and supply modes, in the existing ventilation shafts in the London underground combined with heat pumps as a heat source integrated into a thermal network [67]. The thermal

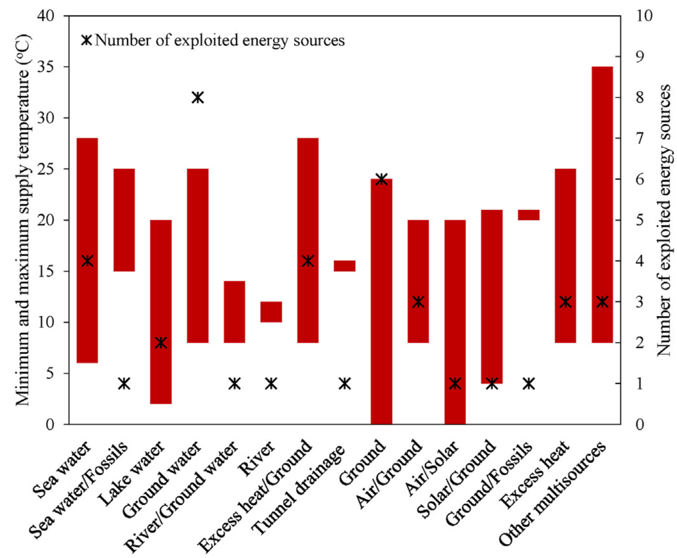

Fig. 4. Supply temperature variations (solid bars) and number of case study examples (double cross) for different energy sources in operational 5GDHC networks [37].

network utilising this energy source is not a fifth generation network. Therefore the 18–28 °C water that exits the ventilation shaft must have its temperature lifted by a two-stage heat pump to allow connection the network. Connection to a fifth generation network instead would remove this requirement.

There are several other waste heat sources with the significant potential to be integrated into fifth generation networks through the heat recovery process. The energy performance of a number of these sources, e.g. data centres [68,69], supermarkets' refrigeration systems [70,71] and sewage systems [72] has been studied and analysed in the literature. However, their integration has not been implemented yet in practice in the fifth generation networks. Fig. 5 illustrates some of the main waste heat sources available in urban environments. The gray strip in this figure shows the average range of supply temperature in operational fifth generation networks based on Fig. 4 [37]. The range of typical supply temperatures of the waste heat sources can be seen to be well matched with the

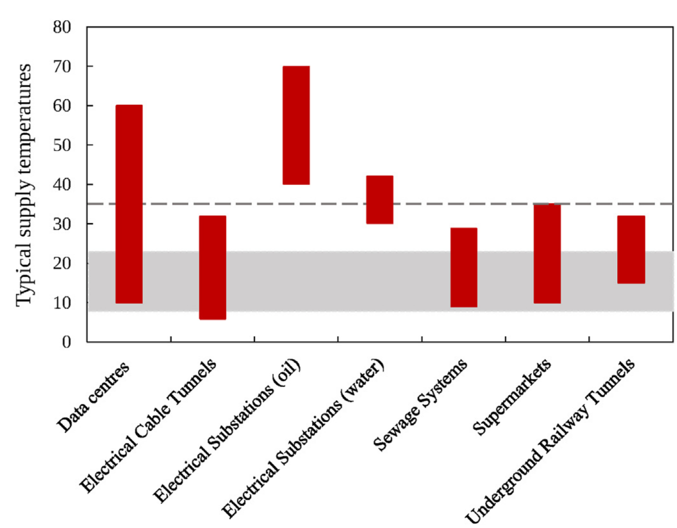

Fig. 5. The main urban waste heat sources and their typical temperatures along with the average range of supply temperature in 5GDHC networks (the gray strip) and maximum supply temperature in 5GDHC networks (dashed line) [17,37,66].

required operating temperature of fifth generation networks. A comprehensive review of waste heat sources in the thermal networks in terms of availability, advantages, and restrictions was carried out in two studies by Lagoeiro et al. [66], and Revesz et al. [17].

As well as heat sources, it is important to have thermal energy storage in 5GDHC networks. Borehole field thermal storage [73] is a highly suitable option for this task, but other underground thermal energy storage (UTES) systems, such as aquifer or mine water thermal energy storage are also suitable. It was found that in the 37.5% of operational networks, more than one energy sources was utilised mainly to boost the regeneration process of thermal energy from thermal energy storage [37]. For instance, in the fifth generation network in Nümbrecht, Germany, a 43 square meter solar systems with evacuated tube collectors have been connected to the distribution network to improve the heat quality through the system. This ultra-low temperature network with operating temperature ranging from −4 to 21 °C, also exploited rainwater tanks at a depth of 1.5–4 m as other heat sources [74]. Hybrid photovoltaic-thermal hybrid solar collectors were also utilised as the main heat supplier of a number of fifth networks incorporated with seasonal UTES systems [75,76]. In some other cases, ambient air energy from the outdoors has also been used as a thermal energy source, e.g. for dry coolers, to directly perform the heat supply or rejection processes in the network and regenerate the thermal energy stores [37].

3.4. Energy demand prediction for 5GDHC networks

The dynamic behaviour of energy demands, and the balance of heating and cooling required by the users in thermal energy networks plays a significant role in their thermal performance. If the dynamic energy demands of users is not properly considered there is a risk of failing to deliver sufficient thermal energy through the ultra-low temperature network to maintain the decentralized heat pumps at the optimal efficiency range. This can lead to higher electric consumption at the substations, hence reducing both energy and cost efficiency overall. Therefore, forecasting dynamic heating and cooling demands of energy users can be noticeably useful for the network designers to ensure efficient operation of networks. This aspect of the design is much more important for 5GDHC networks utilising low temperature sources, compared with previous generation networks [54].

Generally, network energy demand prediction approaches can be classified into top-down and bottom-up approaches [77]. In top-down approaches, forecasting energy consumption of a network is performed based on the historical time series data of the entire network loads, rather than individual buildings. On the other hand, bottom-up approaches are based on the analysis of energy consumption of individual buildings in networks using either physics-based or statistical methods [78]. Due to the novelty of the fifth generation thermal network and hence the absent of measured data of the energy users, top-down approaches cannot be considered a suitable method for the thermal load prediction of the network.

Statistical bottom-up approaches have been developed for modelling the energy use of a number of urban area such as the city of Aarhus, Denmark [79], Rotterdam city district, Netherlands [80] and New York, US [81]. However, similar to the top-down approaches, this requires historical data from the current situations and cannot deal with the impacts of future energy efficiency measures or include new buildings into the network which makes it less of interest for demand predictions for fifth generation networks.

In physical-based bottom-up approaches, the thermodynamic principles of heat and mass flows across the buildings fabrics, heating/cooling systems and the networks are used for the calculation of the dynamic thermal energy behavior of the buildings. Due to the simulation of physical phenomena in buildings, the dynamic thermal energy behavior of the buildings in the network is typically more accurate compared with the statistical approaches [82]. Although, some levels of uncertainty are generally introduced due to simplifications, or not having a sufficient amount or quality of input data, including climate data, building geometry, network topology, construction standards and usage schedules [83]. In addition, depending on the volume and details of the input data, the computational cost of energy demand calculation can be higher than other approaches. However, there are a number of studies proposing models to predict network energy demand with reasonable computational cost and acceptable accuracy level [54,82,84].

There are also several simulation tools introduced in the literature which can be used for bottom-up physical-based demand analysis of fifth generation thermal energy network [85]. One of the most prominent tools is EnergyPlus which was implemented for load prediction of a district in Cambridge, US [86], and Boston, US [87]. Physical-based simulation tools for district level energy demand prediction were comprehensively reviewed by Abbasabadi et al. [88] and Ma et al. [89].

3.5. Demand-side management

Demand-side management (DSM) can refer to planning, implementing and monitoring the energy consumption of end-users and controlling their energy use to reduce thermal peak demands [50]. Through demand-side management the heating and cooling demands of the networks can also be reshaped to better match the network production and the network availability. This is relevant for 5GDHC networks since any reduction in the peak demands, or synchronisation between supply and demand, will assist with the efficiency of the network, and also reduce its complexity. There are many studies in the literature dealing with demand-side management including reducing the peak demand or moving the demand from peak time to off-peak time. For example, Guelpa et al. [90] illustrated how demand-side management in thermal networks could shave the energy peak demand of the networks. They indicated by optimal time rescheduling of building heating systems, more than 5% peak reduction can be achieved. Brennenstuhl et al. [91] applied novel demand-side management on the fifth generation networks connected to 23 buildings with agrothermal collectors, decentralized heat pumps and PV systems. They showed this network could operate at competitive heat cost, and under ideal conditions with the optimisation of the self-consumption of PV electricity, up to 50% cost savings can be achieved on the building level. In another study, Buffa et al. [60] presented new demand-side management strategies implemented on substations of 5GDHC networks using an Artificial Neural Network-based model predictive controller. They demonstrated that using this method can shift the electricity consumption up to 14% from peak time to off-peak time in the network.

3.6. Pipeline configuration and topology

Two main pipeline configurations can be possible for 5GDHC: single-pipeline networks, also referred to as so-called reservoir networks [92], and double-pipeline fifth generation networks. A four-pipeline fifth generation network has been also proposed by Millar et al. [46]. However, multiple initial investments required for piping as well as high operational cost due to the involvement of more hydraulic pumps make this latter option a less attractive configuration for the fifth generation network.

In the single-pipeline fifth generation networks, both heating and cooling demands of energy users are provided from a single pipeline network by means of using water source heat pumps (WSHP) that draws/discharge heat transfer fluid directly from/to the same pipeline. In such networks, each substation's heat pump operates in series with different inlet fluid temperature to the main pipeline. This results in the heat pumps located farther from the energy sources receive less thermal energy and hence higher heat pump energy consumption is required leading to lower efficiency of the heat pumps [93]. Sommer et al. [92] compared single-pipeline and double-pipeline fifth generation cases for four consumers and a connected borehole field. It was shown although the single-pipe network requires only half the pipe length of a double-pipe, the diameter of the single pipeline should increase up to 95%, leading to higher hydraulic pump consumption. It was also demonstrated that the annual difference between electric energy consumption (both heat pumps and hydraulic pumps) for single and double-pipeline networks is less than 2%. It was therefore concluded a single pipeline fifth generation network can be efficient only for a small networks with a small amount of flow, as in larger single pipeline networks, higher heat and hydraulic losses occur in the main pipeline leading to greater consumption at both heat pumps and circulation pumps for the losses compensation [94].

Given the advantages of double-pipeline fifth generation networks compared with the single-pipeline network, this configuration is found to be the most prevalent [37]. In such networks, the cold and warm heat transfer fluid (typically water) are bidirectionally circulated through the distribution network (depending on the network dominant heating or cooling demand), and plays the role of heat source/sink for the HPs installed in the network's substations.

Double-pipelines can be laid out in three primary network topologies to connect the energy users of the network to the energy sources, including: radial or tree network [95], ring network and meshed network [96,97]. These main fifth generation network structures along with their potential capital investment costs are depicted in Fig. 6 and briefly described below.

Due to the connection of numerous prosumers to the heating and cooling sources in the fifth generation networks, the meshed network can be considered as the best solution for multiple low temperature heat sources to the network, particularly with high demand diversity where the heating or cooling demand and supply can be mostly balanced during a year [97]. However, the piping and trenching is the highest in this case compared with other two topologies. Therefore, this raises a potential trade-off between the energy performance and investment costs that should be properly evaluated in the early design stage [98]. Rhein et al. [97] developed an analysis software tool to evaluate different fifth generation network topologies based on the life cycle cost analysis including both investment and operational costs. They showed for a small and low load diversity fifth generation network, a radial grid with a minimal spanning tree topology is the most economical effective solution. However, they indicated further research is needed to investigate the effects of energy demand diversity on the fifth generations network topology.

4. Energy geostructures

Despite a number of proven advantages of energy geostructures in providing both heating and cooling loads to buildings, their feasibility and potential for connection to 5GDHC networks have not yet been established. Traditionally energy geostructures have been coupled to ground source heat pump systems and been used as either a source or store of thermal energy. Their potential to perform both these roles in fifth generation networks is therefore also large. In this section, the various types of energy geostructures and their thermal characteristics will be discussed. The main advantages as well as barriers will be introduced, with a focus on the integration into the thermal energy networks.

The first energy geostructures were piled foundations. Plastic heat transfer pipes were first cast into deep foundations in Austria and Switzerland in the 1980's [99]. These so called energy piles or thermal piles were then able to act as ground heat exchangers and supply heat and/or cool to the overlying building via a ground source heat pump system. Successful examples of this approach include Zurich Airport [100], Old Oak Common Depot [101] and the Crystal Building [102]. Recent studies show that these novel ground heat exchangers can provide comparable system performance to traditional ground source heat pump systems connected to

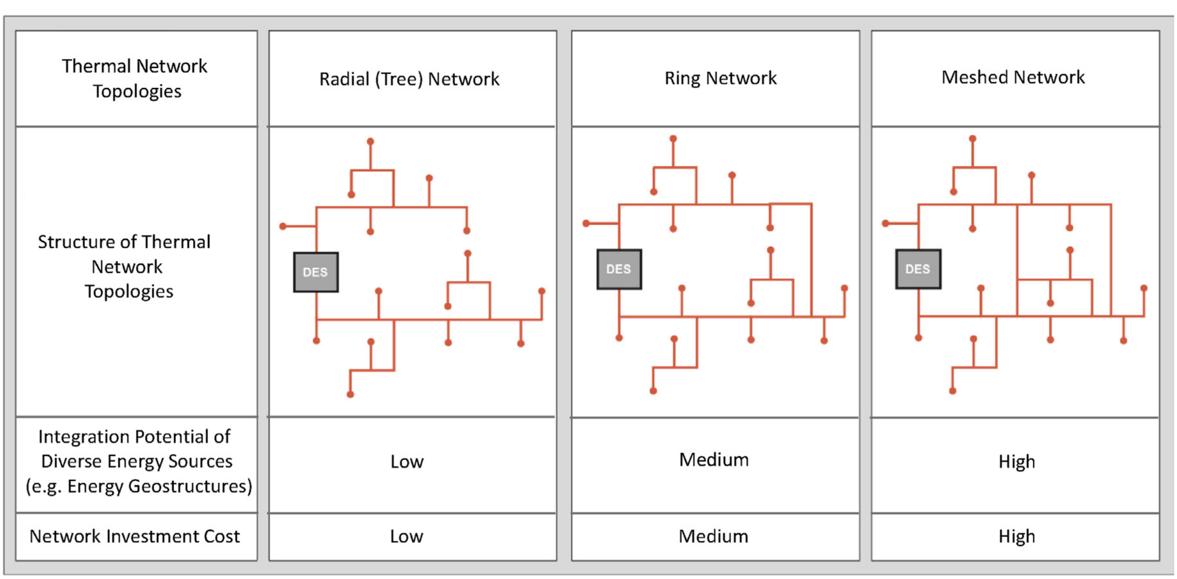

Fig. 6. Main thermal energy network topologies and their potential in integrating diverse energy sources, e.g. energy geostructures, as well as the network investment cost (reproduced from Ref. [97]).

borehole heat exchangers [103].

In the last two decades the energy geostructure concept has been extended to include many other forms of underground construction, some of them shown in Fig. 7. Operational or trial energy geostructures have now been developed with heat transfer pipes installed in embedded retaining walls, basement slabs, tunnels, sewerage pipes and ground anchors [104]. Of these energy walls and tunnels are the most common after energy piles [105]. However, depending on the situation, these structures do not necessarily have a dedicated overlying building for which to supply heat. Where embedded retaining walls are part of a building basement construction they can function in a very similar way to energy piles in terms of heat supply, e.g. at Keble College in Oxford [106]. However, deep retaining walls used for metro station construction, e.g. Crossrail in London [107] or the Grand Paris [108] developments, do not have the same obvious heat user. Hence the issues of coordination between heat supply and the demand of local users can become a barrier to implementation of some energy geostructures. Therefore, the potential to connect to thermal energy networks acts to break down this barrier and encourage wider uptake of other energy geostructures.

The following sections 4.1 and 4.2 give further details of energy walls and tunnels along with Section 4.3 explaining their design methods, before Section 5 explore how these structures can be integrated into 5GDHC networks.

4.1. Energy walls

The first energy walls were constructed in the 1990's, with the first well documented case being in Switzerland [109]. Notable cases followed in Austria, including the diaphragm walls supporting the high rise Uniqa Tower in Vienna, and the bored piled retaining walls supporting the LT24 Lainzer cut and cover railway tunnel [104]. The first energy wall in the UK was constructed of bored piles and installed at Keble College [106] and achieved a coefficient of performance (CoP) of 5.8 in heating and 3.9 in cooling. Like the Uniqa tower heat was supplied to the overlying building. A recent well documented case study pertains to a building basement in northern Italy support by anchored diaphragm walls [110]. Over four months of operation the walls provided up to 850 kWhr/day heating to the overlying building, operating at a coefficient of performance of between 4.2 and 5.0. Further details of these schemes is given in Table 3. It can be seen that meaningful rates of energy exchange are achievable (up to 54 W/m^2 of wall area), with schemes providing hundreds of megawatt hours of useable energy. The precise amount of energy obtainable will depend on a number of factors, including the construction details. However, the two most important factors will be the ratio of heat exchange versus storage that can be achieved, i.e. the balancing of thermal demand, and the use of the excavation space supported by the wall. For building basements the space may be relatively cool, but for cut and cover railway tunnels or metro stations with train breaking there will be an additional source of heat which can be utilised.

Most of the case studies in Table 3 use basement energy walls and provide energy to the overlying building. The exception is the Lainzer cut and cover railway tunnel which does not have an overlying heat user, and in this case exported the available heat to a nearby school, where up to 194 MWhr/year was utilised [104]. Other urban metros and light rail have also proved popular for energy wall applications. Energy walls have also been installed as part of the U2 metro line construction in Vienna [104], at shafts and station constructions for Crossrail in London [107] and at the new stations for the Grand Paris outer rail link developments [108]. It is not always known in these cases where the heat will be utilised when the schemes are constructed which provides a significant barrier to the success of such projects. A leap of faith is required by the infrastructure client, to pursue the additional works for construction of the geostructure without a confirmed heat user in mind. Planned applications via thermal energy networks therefore offers many advantages for fuller exploitation of these energy sources.

While most energy walls built to date have involved new construction in terms of the structure or infrastructure that includes the wall, recent developments have considered the topic of

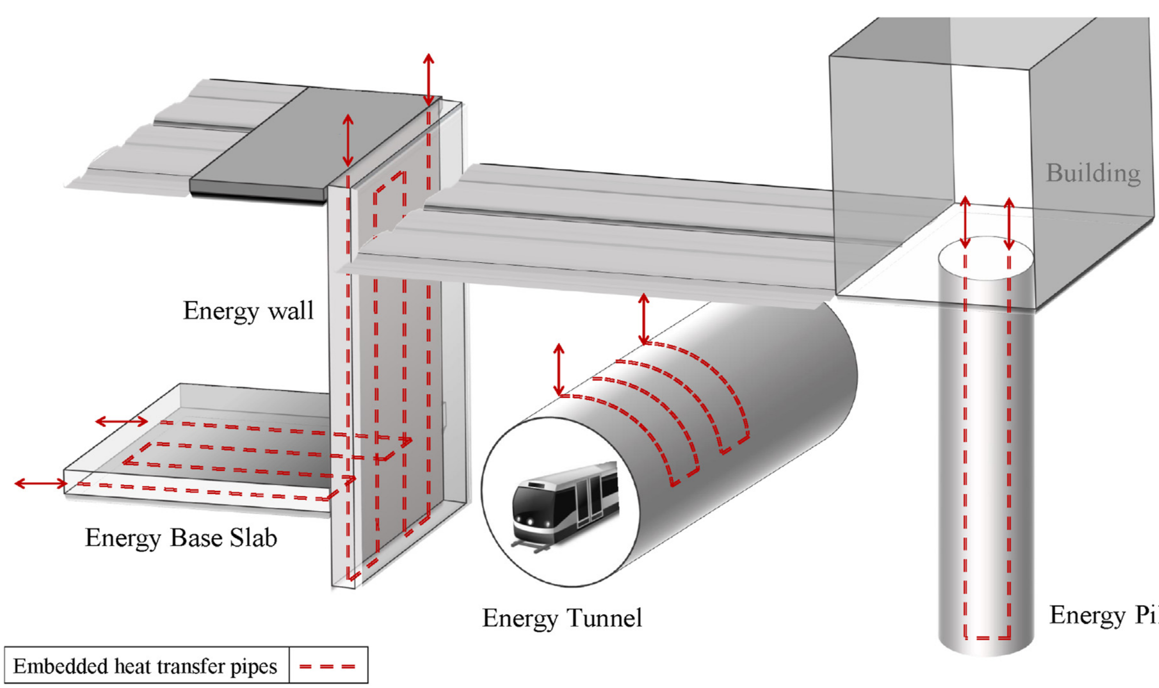

Fig. 7. Schematic of energy geostructures including: the energy wall, energy tunnel, energy based slab and energy pile.

Table 3
Energy wall case studies and their performance.

Case	Wall Type	Maximum Power		Energy Exchanged		Coefficient of Performance	References
		kW	kW/m^2	MWhr/year	MWhr/year/m^2		
Uniqa Tower, Austria	Diaphragm Wall, 7800 m^2	420 heating 240 cooling	54 heating 31 cooling	818 heating 646 cooling	105 heating 83 cooling	NR	Ref. [104]
Lainzer Tunnel (LT24), Austria	59 piles, 1.2 m diameter, 17.1 m deep	NR	NR	194 heating	51 heating	NR	Ref. [104]
Keble College, Oxford, the UK	61 piles, 450 mm diameter, approximately 12 m deep	45 (design)	44 (approximate)	74 heating 91 cooling	71 heating 88 cooling	5.8 heating 3.9 cooling	Ref. [106,112,113]
Basement northern Italy	Diaphragm wall, 2378m^2	36	12–15 heating	Up to 0.85 MWhr/day during heating	NR	4.2–5.0 (four months of heating)	Ref. [110]

N.R. = Not reported.

retrofitting existing retaining walls for heat exchange and storage. Baralis and Barla [111] have trialled techniques to retrofit heat transfer pipes to the outside of walls based on local excavations. This opens up the possibility of much greater reach and uptake for energy walls.

4.2. Energy tunnels

Energy tunnels are less developed than energy walls in terms of practical application. At least seven notable trial sites have now been developed [114,115], mostly for rail tunnels, but there is little operational data available. The details of the best documented examples are given in Table 4. The nature of the construction of the ground heat exchanger component of energy tunnels varies according to the tunnelling construction method. Where the tunnel lining is made of precast segments then these can be equipped with heat transfer pipes within a factory setting [115,116]. Installation is then straightforward on site, however, many pipe joints must be made along at the segment boundaries and this task can be time consuming. It is also possible to construct the heat exchanger in situ, either between the primary and secondary tunnels linings, e.g. Ref. [117], or retrofit on site if there is space, e.g. Lee et al. [118].

Of the case studies summarized in Table 4, only the Jenbach tunnel is connected to an adjacent building where it supplies heating. The system provides parts of the building energy demand, with 15 kW coming from the tunnel, 28 kW from a heat pump and the remainder from an auxiliary system. None the less the other trials have demonstrated that the technology does work, with heat exchange rates between 5 and 66 kW/m^2 recorded (Table 4). Additional heat transfer could be available for “hot tunnels” where there is an internal source of heat such as in a sewerage network, or train braking in metro tunnels [11]. The fact that fewer energy tunnels are connected to nearby buildings compared with energy walls is an indicator of the greater barriers involved with connecting heat suppliers and users within the infrastructure environment rather than a building environment. Again, this barrier could be reduced with greater connection to and application of thermal energy networks.

4.3. Design methods

Methods for estimating the heat potential of geostructures are in variable states of development. Given their earlier development and implementation, the availability of practical methods and tools is much more advanced for energy piles than for other types of geostructures. Here there are a number of analytical solutions available to describe the thermal behaviour of the foundation (e.g. Man et al. [120], Li and Lai [121], Loveridge and Powrie [122], Maragna and Loveridge [123]) in response to the type of time varying thermal demands that could result from either a single ground source heat pump user, or multiple heat users in a network. There are also analytical methods for dealing with multiple interacting piles (e.g. Loveridge and Powrie [124], Alberdi-Pagola et al. [125]). Some of these approaches are also suitable for integration into tools like TRNSYS and EnergyPlus and are therefore accessible for designers of district heating and cooling networks. For example, the Duct Storage model [126] is validated for use with energy piles [100], exists as a component in TRNSYS and can also be accessed as a standalone TRNSYS based software package for design of energy piles [127]. Other software for the design of borehole heat exchangers, or EnergyPlus components for the same, can also be adapted for application to energy piles as long as the limitations of such approaches are understood.

For energy walls and energy tunnels, however, the availability of standard design approaches is limited. Work has been carried out to develop design charts for assessing thermal capacity based on

Table 4
Energy tunnel case studies and their performance.

Case	Tunnel type and internal diameter	Thermally Activated Area (m^2)	Ground Heat Exchanger Type	Maximum Power		References
				kW	kW/m^2	
Linchang, Mongolia	7.7 m	70	Placed in situ between linings	NR	50–55	Ref. [117]
Stuttgart-Fasanenhof Tunnel, Germany	Railway tunnel, 9.6 m	360	Cast in situ, fixed to the outer lining	NR	5–30	Ref. [114]
Jenbach Tunnel, Austria	Metro tunnel, 13 m	2200	Segmental lining	15	15	Ref. [114,116]
Seocheon, South Korea	Adandonned road tunnel	90	Fixed to inner lining	NR	4–37	Ref. [118]
Torino, Italy	Metro tunnel, 6.9 m	60	Segmental lining	NR	40–66	Ref. [115,119]

N.R. = Not reported.

ground conditions [128,129]. However, these do not allow consideration of different types of thermal demand that would need to be accounted for in most realistic detailed design scenarios for both standalone systems and heating and cooling network applications. Instead, most detailed analysis to date has been carried out by numerical simulation (e.g. Bidarmaghz et al. [130], Rammel et al. [131], Sterpi et al. [132]) which can be computationally expensive. Such approaches are useful for research applications, and can be acceptable for individual large construction projects. However, the absence of fast run time analytical approaches, capable of being implemented with realistic time varying thermal loads, remains a current knowledge gap.

Some initial work on development of analytical design approaches for walls has been carried out in the last few years. One method applies the distributed thermal network approach and has been testing successfully against specific field data [133]. However, the method requires the use of weighting factors which need to be numerically (or experimentally) derived and hence without development of a large library of cases is not practical for routine application. Additionally, recent work has begun testing the validity of simpler analytical solutions for energy walls [134], but is yet to be completed. For energy tunnels, analytical approaches for routine use are more limited still. An analytical model has been proposed by Zhang et al. [135] based on radial coordinates, but only tested over a limited timeframe. There has also been an empirical model, used by Tinti et al. [136] for estimations of thermal capacity for a mountain tunnel in Italy and Austria. Nonetheless a universally applicable method for assessment of thermal capacity remains to be developed.

5. Integration of energy geostructures into 5GDHC networks

Recent work, using the UK as a case study, has determined the potential from energy geostructures. Considering piles, wall and tunnels in future transport infrastructure, drainage construction, and retrofitting energy geostructures to the sewerage network, Loveridge et al. [137] determined that at least 50 TWh/year of thermal energy could be made available, or almost two thirds or urban domestic heating demand. However, not all this potential can be delivered without use of thermal networks to reach users, given the disconnect between heat owners and demand. To tap this potential using 4GDH networks, large scale heat pumps would be required to upgrade the low temperature thermal energy from geostructures making this type of integration technically and economically quite challenging. This is due to the fact that the large scale heat pumps would be first required to lift the temperature to the level sufficient for the supply to the 4GDH network, and then the temperature would drop through the distribution network due to the heat losses. This would significantly reduce the thermal efficiency and cost-effectiveness of such integration. Detailed case by case evaluation of factors such as network size and thermal demands, which can affect the integration performance, would also be required. However, now, with the development of 5GDHC networks, the potential for low temperature geothermal energy provided by energy geostructures to be exploited and fed into the ultra-low distribution network integration can be realised. In this Section the benefits and challenges of this integration are reviewed, with a summary given in Table 5.

Firstly, the integration of energy geostructures into 5GDHC benefits the network with a higher share of cost-effective renewable energy leading to more environmental-friendly heating and cooling production along with enhancing the network efficiency. Moreover, the integration of energy geostructures into thermal networks benefits the energy geostructures not to be limited to provide geothermal energy only for the users of its own infrastructure, such as Zurich airport [100] or Vienna Metro station [109]. Instead, a wider range of energy users including residential and non-residential buildings is possible, which leads to more effective geothermal energy yield and enhancing the thermal performance of the system. This is significantly advantageous in infrastructure projects where the users of thermal energy are not necessarily the producer of the heat. Hence, connecting to the thermal network can be seen as the only feasible solution for proper energy geostructure implementation in some cases. The fifth generation thermal energy network's schematic concept integrated with energy geostructures is illustrated in Fig. 8.

Energy geostructures are potentially particularly suited for use with 5GDHC networks since they work in synergy with the key characteristics of these networks. For example, energy geostructures are a local place based solution that will operate at low temperature. They also readily contribute heat within a diversity of sources. In fact it is notable that some energy geostructure schemes, e.g. the One New Change Development in London, and a basement energy wall in Northern Italy, already work in combination with other heat sources, in these cases open loop ground sourced heat [107,110,138]. Therefore, energy geostructures are already demonstrating their similarities to typical 5GDHC networks and hence their potential to be incorporated into such systems.

Another advantage of using energy geostructures with thermal networks is their ability to be used for thermal storage over a range of timescales including inter-seasonal storage. It is well known that ground coupled heat exchangers offer higher transfer rates when balanced between heating and cooling. A number of energy geostructures, including piles and walls, are also already operating to

Table 5
The main advantages and limitations of the integration of energy geostructures into 5GDHC networks in terms of technological, economic aspects.

	Advantages	Challenges
Technological aspects	• Exploitation of shallow geothermal energy in the network leading to increasing the share of local renewable energy sources which otherwise could not be used. • Providing both heating and cooling demands of the networks. • Playing the role of thermal energy storage over various timescales. • In some cases, offering additional sources of heat to the network, for example for "hot tunnels" containing sewerage or allowing for train braking.	• Absence of design approaches, guidelines and standards for designers and planners. • Requiring detailed specific assessment for each case in the stages of planning, design and management. • The need to keep the energy geostructures within reasonable operating temperatures in networks. • Higher level of network complexity both in design, planning and control.
Economic aspects	• Reducing the cost of geothermal energy supply in networks. • Reducing the investment cost of thermal energy storage installation. • Income for energy geostructure owners from sale of thermal energy to the network.	• Additional costs for the energy geostructure owner of embedding heat transfer pipes in their infrastructure. • Lack of the investment strategy and incentives could decrease the cost-effectiveness of such integration. • Lack of regulations for selling thermal energy from energy geostructures.

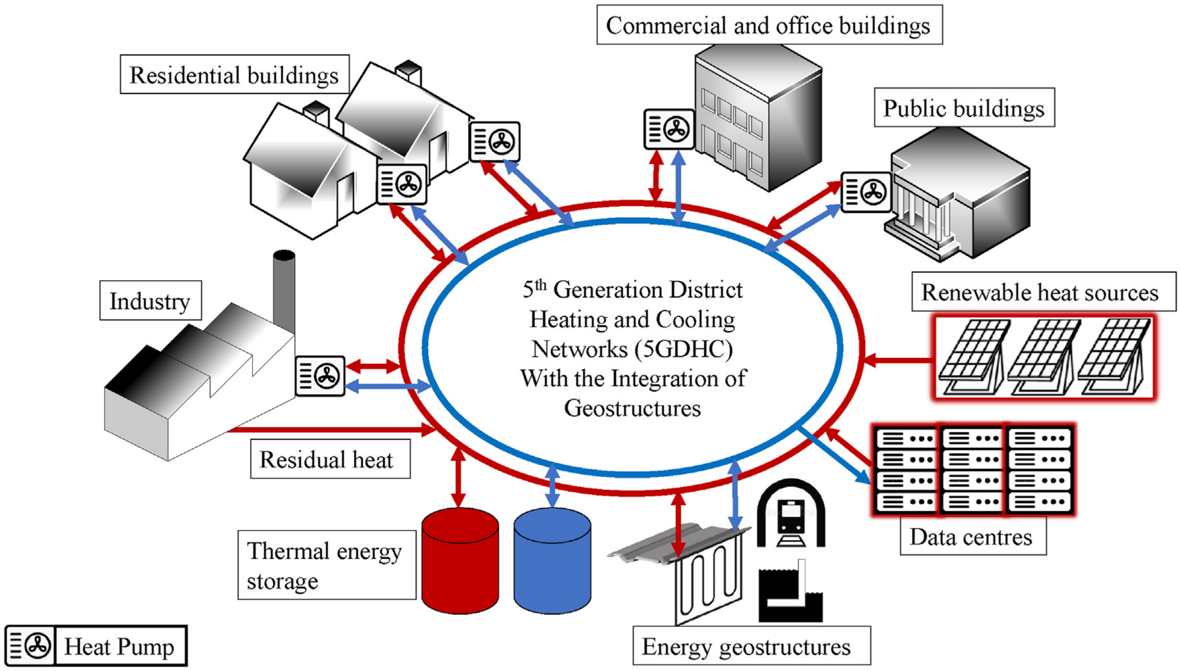

Fig. 8. A future representation of a fifth generation district heating network integrated energy geostructures.

provide inter seasonal storage at the scale of large commercial buildings [102,113]. Therefore, the most efficient use of energy geostructures in 5GDHC networks may be to take waste heat and the excess thermal energy from the network and store it for effective recovery. While energy geostructures will have a lesser unit thermal storage capacity compared with water tank storage, they will benefit from lower costs since no special purpose excavations will need to be made. They may be expected to behave in a similar manner to smaller borehole or aquifer thermal energy storage schemes, whose use with district heating networks is reviewed by Guelpa et al. [139]. Therefore, while energy geostructures may not be capable of provider the largest TES capacity for city scale DHNs, their potential in smaller scale local systems should be routinely considered. Similarly, energy geostructures will also work well with high simultaneity of heating and cooling demands that favour 5GDHC network efficiency.

Additional costs for integration of energy geostructures into 5GDHC are also relatively low. First, considering the conversion of the geostructure into an energy source/store, it is accepted that this will be cheaper than construction of special purpose inter-seasonal storage such as borehole thermal energy storage. For example, Barla et al. [140] indicated the additional costs for thermal activation of a section of the Turin Metro extension were less than 0.8% of the total project costs and estimated the pay-back time to be less than five years with respect to the energy produced via conventional heating/cooling systems. Second, the costs of integration of the energy geostructure to the thermal energy network would be comparable to that for traditional geothermal energy sources or stores.

However, a number of challenges for energy geostructure integration into 5GDHC networks may arise related to the complexity of meeting varying temporal thermal demands of the networks. The more buildings which are connected to the network, the more complex the temporal thermal demand profile will be. These challenges need to be appropriately addressed in the design stage of the networks, else the benefits of the integration of energy geostructures may fall behind its drawbacks both in terms of economics and energy efficiency of the networks.

In particular, demand prediction is an important consideration for energy geostructures since they need to operate within certain temperature limits. The range of operating temperatures of the 5GDHC network should therefore be determined based on energy demands prediction of networks to ensure operating temperatures is between temperature limits of energy geostructures. Higher temperature than the limits can adversely impact the structural protection and geotechnical performance of an energy geostructures. On the other hand, lower operating temperature than the limits, typically below 0−2 °C, can lead to ground freezing and consequently the failure of the structure [11]. As discussed in Section 3.4, tools such as EnergyPlus used with a physical bottom up approach may be best suited to the task of demand prediction. However, this area is still relatively under investigated and there are no recommended design or analysis approaches for routine practical implementation.

Given the above challenges and also the energy load diversity in fifth generation networks, thermal assessment and management of demand-side behaviour of the end-users is especially important. Appropriate analysis and use of control systems to ensure the optimal operation of networks without failure to deliver efficient heating and cooling to energy users is therefore relevant. This will be especially true at peak times. Lack of proper demand-side management can also lead to higher electricity consumption at the substation heat pumps which considerably reduces the energy efficiency and cost effectiveness of the overall system.

Coupled with demand prediction and control, it is also important to recognise that both the design of ultra-low temperature thermal networks and the thermal design of energy geostructures themselves remain in their infancy. Dynamic thermal behaviour of pipelines is only now starting to be fully considered [55,56] and the trade off between different pipeline topologies still requires detailed consideration. While it is clear that double-pipelines configurations are most appropriate for networks connected to energy geostructures, network load diversity analysis on fifth generation network topologies is at the early stage and further developments are required for optimized design of pipeline layouts and network topologies connecting the energy geostructures. Nonetheless, as shown in Fig. 6 flexible radial networks will be well suited to energy geostructure integration. Mesh networks will additionally deal well with demand diversity, but full cost-benefit trade offs remain to be determined.

For the energy geostructures themselves, as discussed in Section 4.3, most existing design approaches for energy walls and tunnels are limited to either simple design charts or time consuming numerical simulation. This presents an important knowledge gap for integration of energy geostructures into thermal networks. For rigorous detailed design it will be necessary to integrate thermal analysis of the thermal network, the demand requirements and the geostructure acting as a thermal store. This will require development of fast run time analytical solutions which are currently lacking for most energy geostructures, except piles.

Finally it must be recognized that despite the clear advantages of the use of energy geostructures, other socio-economic challenges remain to be overcome before routine adoption of the technology into thermal networks. These challenges include the absence of a culture for thermal networks in places like the UK, and a strong incumbency for the continued use for heating via well developed gas networks which already reach most properties [141]. To change that culture and make 5GDHC networks connected to energy geostructures and other heat sources more attractive will require continued innovation to reduce capital costs, and appropriate incentives and funding models to allow investors to be rewarded [142]. There may also be country specific challenges, for example, the fact that in the UK heat remains absent from the list of statutory utilities is also likely to be hindering change. The absence of a skilled workforce to deliver new networks and new energy geostructures, and the lack of standards and guidance documents required to maintain quality in design and construction additionally remains a barrier. Further research on the technical challenges described above will help in this respect. Above all, political leadership at local and national level to support research and development, incentives and demonstrator projects are likely to be required [142,143].

6. Conclusions

A novel concept of integration of energy geostructures into the fifth generation district heating and cooling networks has been introduced in this paper. Energy geostructures bring many of the advantages of other shallow geothermal technologies, but with additional cost efficiency during construction. Existing fifth generation district heating and cooling networks often use the ground or groundwater as heat sources or stores, but closed loop energy geostructures have yet to be implemented.

The potential advantages and challenges of the integration of energy geostructures into the fifth generation thermal networks have been also discussed in this paper. The main benefits of this integration can be summarized as below:

- Enhancing the sustainability, flexibility and resiliency of the thermal network by using a higher share of cost-effective and environmental-friendly geothermal energy from a local source.
- Being able to act as a thermal store over different timescales, hence providing both heating and cooling demand, which is required in the concept of fifth generation thermal energy networks.
- Enabling to effectively recover the waste heat or excess thermal energy of the thermal network.
- Involving lower capital investment cost to exploit geothermal energy from energy geostructures compared with other types of geothermal heat exchangers, e.g. borehole heat exchangers.
- In some cases offering additional sources of heat, for example for “hot tunnels” containing sewerage or allowing for train braking.
- Enabling wider implementations of energy geostructures in the urban environments and hence harvesting more geothermal energy which without integration into the thermal network would be impractical and infeasible to be exploited.

However, some challenges still need to be overcome for the routine successful integration of energy geostructures into fifth generation district heating and cooling networks. These include:

- The complexity of fifth generation networks, combined with the need to maintain energy geostructures within reasonable operating temperatures, means that prediction of the thermal demand of the network and the dynamic thermal behaviour of prosumers is especially important. Bottom up physical approaches are likely the most suitable in this context, but greater experience of these techniques is required
- In addition further development is required to model the dynamic behavior of fifth generation networks connected with energy geostructures, and of the energy geostructures themselves. Fast run time approaches that allow couple of the different aspects of the network (source, pipeline, users) are required.
- Due to the novelty and complexity of connecting energy geostructures to prosumers through bidirectional low temperature networks, more advances and developments are much needed for optimal design of pipeline topology, including sizes, layouts and structures.
- Along with the above technical development socio-economic challenges related to culture, incumbency, skills, incentives and investment strategy also require further development, especially in countries like the UK with lesser historical experience of district heating networks.

In future work, the dynamic behaviour of fifth generation district heating and cooling networks in actual candidate sites in the urban areas with the possibility of connecting with the energy geostructures should be analysed. This will permit detailed assessment of the magnitude of the opportunity, and quantify the benefits that integration of energy geostructures into thermal networks offers in terms of providing more cost-effective, energy-efficient and eco-friendly heating and cooling. Therefore, applicable thermodynamic and thermo-economic analysis methods and tools will be needed to be developed to enable comprehensive assessment of integration of energy geostructures into fifth generation networks for both growing and built urban areas.

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.

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