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District heating and cooling networks with decentralised energy substations: Opportunities and barriers for holistic energy system decarbonisation

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ABSTRACT

Decarbonisation of the thermal grid whilst ensuring affordability and security of supply, requires a holistic approach which relies on sector coupling and energy storage. District heating and cooling networks with decentralised energy substations featuring heat pumps and thermal energy storage could provide such holistic heat decarbonisation. However, the extent of sector synergies, technoeconomic and market uptake hurdles are still unclear. This paper evaluates the opportunities and barriers related to technoeconomic performance, sector coupling facilitation and market uptake of district heating and cooling networks with decentralised energy substations. It follows a systematic literature review process and integrates its findings with insights from interviews held with 18 stakeholders from leading academic and industrial institutions. Findings suggest that high seasonal demand co-occurrence is crucial to minimize operational costs. Networks with a low number of prosumers can avoid hydraulic instabilities and control complexities and offer grid stability through voltage and frequency regulation when correctly coordinated. Novel mechanisms on business models, asset ownership and tariff structure are vital for a widespread market uptake. Overall, the system needs to be viewed as a tool in the arsenal of decarbonisation solutions with further research required on beneficial operation boundaries, hydraulic operation standardisation and business structure redefinition.

1. Introduction

One of the major challenges of our times, as highlighted by the EU Green Deal and the Glasgow Climate Pact from COP26 [1], is to keep the increase in average global temperature levels to within 1.5 °C and limit the effects of climate breakdown [2]. The IPCC hopes this can be achieved by mitigation, adaptation, finance, and collaboration. Despite the progress made in the electricity sector to meet this target, decarbonising heating and cooling in a cost-effective manner remains a key challenge [3], with heat for the domestic, industrial and commercial sector accounting for almost a third of EU's energy CO_2 emissions [4,5]. At the same time, cooling is the fastest growing energy use in buildings, with space cooling in Europe expected to triple due to the climate breakdown and heat island effect in urban centres by 2050 [6,7]. Currently, fossil fuels account for the biggest share of heating and cooling generation with only 23% relying on Renewable Energy Systems (RES) in 2020 according to Eurostat [8].

Most heating and cooling decarbonisation solutions rely on the decarbonisation of the electricity network [9]. However, if simple, individual solutions were used, such as direct electric heating or individual air source heat pumps (for heating and cooling), the electrification of the thermal system would induce significant pressures on the electricity grid [10,11]. For instance, if one employed direct electric heating in the UK, the country's electricity peak would likely double, with an additional requirement of 50 GW of electricity generation capacity [12]. Also, relying on such operationally expensive decentralised solutions could drive more people into fuel poverty, given that electricity prices are expected to rise further in the coming years as the grid is decarbonising [13,14]. Therefore, the concept of a holistic energy system approach to decarbonisation is attractive, as it comprises the sector coupling of cross-, inter- and intra-sectoral energy flow and energy storage [15]. Such a system depends on exploiting all possible synergies between thermal and electricity grids in order to reduce overall energy

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Abbreviation meaning

4GDHC	4th Generation District Heating and Cooling
5GDHC	5th Generation District Heating and Cooling
ATES	Aquifer Thermal Energy Storage
BEIS	UK's Department for Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
DC	District Cooling
DH	District Heating
DSM	Demand Side Management
ESCo	Energy Supply Company
HP	Heat Pump
MPC	Model Predictive Control
OPEX	Operational Expenditure
PV	Photovoltaic
RES	Renewable Energy Systems
SCOP	Seasonal Coefficient of Performance
SLR	Systematic Literature Review
TES	Thermal Energy Storage

system costs (RES capital expenditure and consumer tariffs), ensure grid stability, and to realise ambitious decarbonisation targets [16].

Thermal networks such as district heating (DH) and district cooling (DC) can provide such sector coupling via district energy systems which utilise centralised heat pumps (HP) and thermal energy storage (TES) [17]. Recently, the concept of combining DH and DC networks into one system has sparked interest, such as using sector coupling in "smart cities" to meet heating and cooling demands via the same thermal network [18]. This integrated system relies on an ambient temperature network capturing scattered low exergy waste heat and upscaling it via decentralised heat pumps for heating and cooling at flat/building/district level, balanced by a centralised TES or/and energy supply unit. The key advantage of the ambient temperature network over conventional DH or DC systems is that it allows circular economy practices by using low-grade thermal resources and introduces the "energy trading" concept enabled by energy bidirectionality in the network, as heating and cooling are met by the same system, making each point of connection a prosumer (producer and consumer) [4,18,19]. The key pillars of such a system are explored in many papers [6,10,18,20,21] and can be summarised as.

a) Circular economy;
b) Scattered wasted heat opportunities;
c) Rise of cooling needs; and
d) Shift from a monopolistic energy market to an open access one comprising active prosumers.

However, this new integrated approach to thermal systems may not be universally applicable as its economic and environmental performance is often inferior to conventional centralised thermal networks [22]. The role of such system within the heat decarbonisation arsenal is unclear as exemplified by the uncertainty over the system's official naming, with the prevalent names being 5th Generation District Heating and Cooling (5GDHC) or 4th Generation District Heating and Cooling (4GDHC). The term 5GDHC was proposed by [20] to capture the shift to decentralised energy substations meeting both heating and cooling demands through one network. This term has since been used in most publications and European projects past 2018 [23] however, it was not universally accepted, with the term 4GDHC being used by the IEA on District Heating and Cooling Implementation Guidebook [10]. The need for a universal definition is stressed in [24], where after a thorough bibliographic review, the term 4GDHC is proposed since the system still operates with within the definition of a 4G system, namely a low temperature system allowing efficient integration of RES. However, to the authors knowledge all key publications, academic and industrial projects and conferences still use the term 5GDHC. It is decided to use the term 4GDHC in this work due to the thorough reasoning presented in [24] but it is recognised that it may not replace 5GDHC due to its ubiquitous use.

This work aims to evaluate the opportunities and barriers that 4GDHC presents for a holistic energy system decarbonisation through sector coupling. To achieve that, a systematic literature review (SLR) is undertaken to answer three research questions.

- What are 4GDHC operational characteristics and how does the system compare to other decarbonisation strategies?
- How do components such as TES, HP, demand side management and control methodologies enable a holistic operation?
- How do current business models and project implementation parameters affect market uptake?

There have been some reviews over the past years on the system's characteristics, ranging from technical to business related components as shown in Table 1. Even though these reviews highlight the operation characteristics along with the key challenges of the technology, they do not investigate sector coupling and the impact on the electricity grid. A review on smart thermal grids not focused on 5GDHC was conducted by [25] while the role of heat pumps in smart grids was investigated in [26] but was limited to their integration on the electricity grid, without focusing on the thermal grid. There is a gap on what role can 4GDHC systems play in a holistic decarbonisation of the energy system along with the technical and market limitations for their uptake.

This review paper makes a step forward on existing literature by providing insights on the opportunities and barriers related to technoeconomic performance, sector coupling facilitation and market uptake of 4GDHC. In addition, due to the polarising views in both academia and industry of 4GDHC, this review includes stakeholder interviews from leading institutions in the field to provide qualitative arguments from empirical knowledge. The novelty in this paper is thus two-fold. Firstly, the systematic review allows for a comprehensive analysis of the opportunities and barriers related to the design and deployment of 4GDHC for holistic sector coupling, along with the technoeconomic characteristics and market uptake of 4GDHC systems. Secondly, these findings are integrated with the views of 18 experts on the aforementioned topics to create a complete narrative. Altogether, this work provides a comprehensive summary of findings and guidance for future academic research, as well as design and business-related considerations for adoption by industry.

Table 1
Relevant reviews on 5GDHC.

Year	Reference	Topic and focus
2017	[27]	Different generations of district energy systems introducing district heating and cooling
2018	[28]	Cold District Heating concept presents key principles of operation and technical challenges
2018	[20]	First definition of 5GDHC, presents a systematic literature review of existing operating systems and details their operational characteristics.
2020	[29]	Systematic literature review on simulation methodologies
2021	[30]	Detailed control and fault detection strategies
2022	[23]	Developments of technical and functional components, particularly on controls and simulation with a focus on Ectogrid.
2022	[31]	Analysis of existing 5GDHC systems in Germany for technical and business-related information

2. Methodology

The methodology used for the SLR and the stakeholder interviews is detailed below along with a scientometrics analysis of the SLR references.

2.1. Methodology for SLR

SLRs allow for transparency and replicability, ensuring an aggregative and algorithmic methodology is followed [32]. The search strategy to get the reference database from Scopus for the SLR was based on a comprehensive set of keywords and Boolean operators to address the research questions while remaining broad enough to ensure inclusivity. The selected keywords were clustered into 10 categories, shown in Table 2. The keywords within the same category were joint by the Boolean operator “AND”, while the categories where joint by the operator “OR”.

The search was then limited to scientific peer-reviewed journals, published in English in the last decade (after 2012) with relevant subject areas. References from international institutions (reports, projects and documentation) were added, followed by an initial screening of title and abstract based on the research questions and finally a thematic full-text analysis of the references. This SLR methodology is captured in Fig. 1 [33,34].

A scientometrics exercise (measuring and analysing scientific literature) was carried out to understand the links between the various keywords found in the SLR [29,35]. VOS Viewer software was used to visualise these links [36] (Fig. 2).

The visualisation confirms the hypothesis that a considerable amount of fragmented research has been undertaken mainly within the last five years. There are several clusters with concepts such as smart grid, heat pumps, energy modelling, economic analysis and hydraulic models having a small number of co-occurrences and links. This is further stressed by the large number of publications originating from different countries and institutions.

2.2. Methodology for stakeholder interviews

To provide an additional dimension to the findings of the SLR, 18 stakeholder interviews were carried out. The interviews were centred around five key themes, as captured in Fig. 3. A different focus was given in each interview, depending on the stakeholder’s expertise and background, following relevant guidelines [37,38]. A detailed breakdown of the list of questions along with the items included in the participant information sheet and the consent form are presented in Appendix A.

These stakeholders are industry professionals or academics in the field of 4GDHC from leading institutions from different countries (universities, research centres, contractors, engineering consultants and public officials) as shown in Table 3. The selection criteria for their participation depended on number of relevant publications and project participation for academics and industry professionals respectively. The resulting transcripts provide a diversified set of views, frequently conflicting each other, that give a valuable base for critical discussion of the SLR outputs. However, most stakeholders are from European institutions mainly due to the high number of industrial and academic projects on 4GDHC happening in Europe. It should be noted that the views collected might be focused to the European markets’ reality but not limited to it.

All information collected about the participants and their responses during the research will be kept strictly confidential. Any personal data collected are subject to UK guidelines for personal data protection principles to ensure data security [39]. The data are anonymized using the UK Data Service’s text anonymization tool [40]. An information sheet and a consent form approved by the research ethics committee of the University of Glasgow were signed by all participants.

Table 2
SLR search strategy [29].

Keyword categories	Keywords
Category 1	District, Heating
Category 2	District, Cooling
Category 3	Ambient, Temperature*, Network*
Category 4	Balance*, Energy, Network*
Category 5	Low-Temperature*, Network*
Category 6	Low*, Quality, Excess, Heat*
Category 7	Anergy, Network*
Category 8	Smart, Heat*, Pump, Grid*
Category 9	Thermal, Energy, Storage*
Category 10	Bidirectional, Flow*

3. Literature findings

The following section covers three key research questions. Firstly, the characteristics of operation of 4GDHC systems are discussed in comparison to other decarbonisation pathways. Secondly, the technical components in a 4GDHC system that allow sector coupling are discussed in detail, covering heat pumps, TES and demand side management. Finally, the softer components, namely business models, required to facilitate market uptake are presented.

3.1. 4GDHC operation characteristics and comparison to other decarbonisation strategies

As stated in section 1, decarbonisation solutions for heating and cooling rely on the decarbonisation of the electricity network. Individual and centralised (DH and DC) solutions include electric boilers and chillers, direct electric units and heat pumps coupled with TES. 4GDHC networks rely on decentralised heat pump substations and an ambient network to meet heating and cooling demands of a project area. By employing heating generation capacity relatively close to its point of use, the efficiency of the process is increased [4,41]. Given that the network is unlikely to be thermally balanced geographically or seasonally, ambient temperature heat sources, centralised energy transformation equipment or seasonal TES need to provide that balance [21,42]. Due to the lower temperatures of the network, it is possible to harness low exergy sources that would otherwise not be utilised (both natural and urban sources) [43]. In London for example, the total heat wasted from secondary sources and has been estimated to be larger than the city’s total heat demand [44]. It has been shown that reductions in primary energy consumption against conventional fuel based solutions could surpass 50% [4,45,46].

However, 4GDHC’s technoeconomic performance along with its energy use and overall quality of service is not always superior to other decarbonisation solutions [47]. DH and DC rely on economies of scale and demand diversification to improve the overall system efficiency and levelized cost of energy [17]. FLEXYNETS is one of the first key projects researching 4GDHC networks, covering all components of such a system in detail and highlighting their respective advantages and disadvantages [21]. They concluded that 4GDHC networks generally perform poorly against conventional DH and DC when cooling and heating demand are not comparable in magnitude. These findings were further supported by [22] via a thorough technoeconomic exercise, showing that the levelized cost of energy for 4GDHC networks meeting only heat demand is higher than DH for different source temperatures, using an extensive set of capital and operational cost data. [48,49] identified some scenarios where the economics of 4GDHC were better, all of which included a high share of cooling. [50] quantified the degree of demand balancing available for districts based on the demand time series’ simultaneity and it was found that, excluding thermal storage, 45% simultaneity is required for an economic benefit compared to centralised thermal networks.

In a 4GDHC system, the decentralised energy substations contain

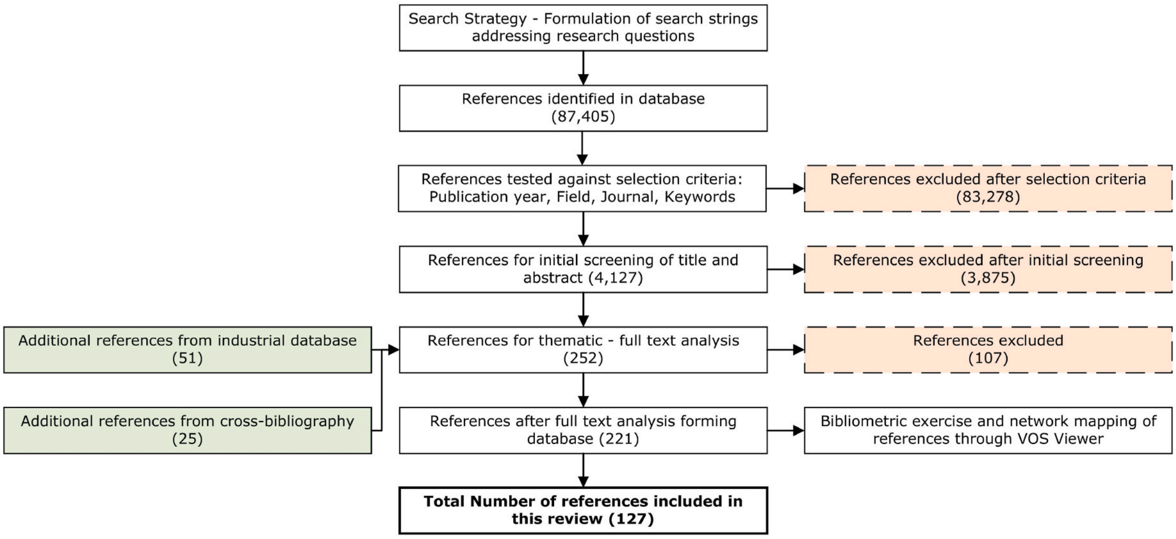

Fig. 1. SLR methodology [33].

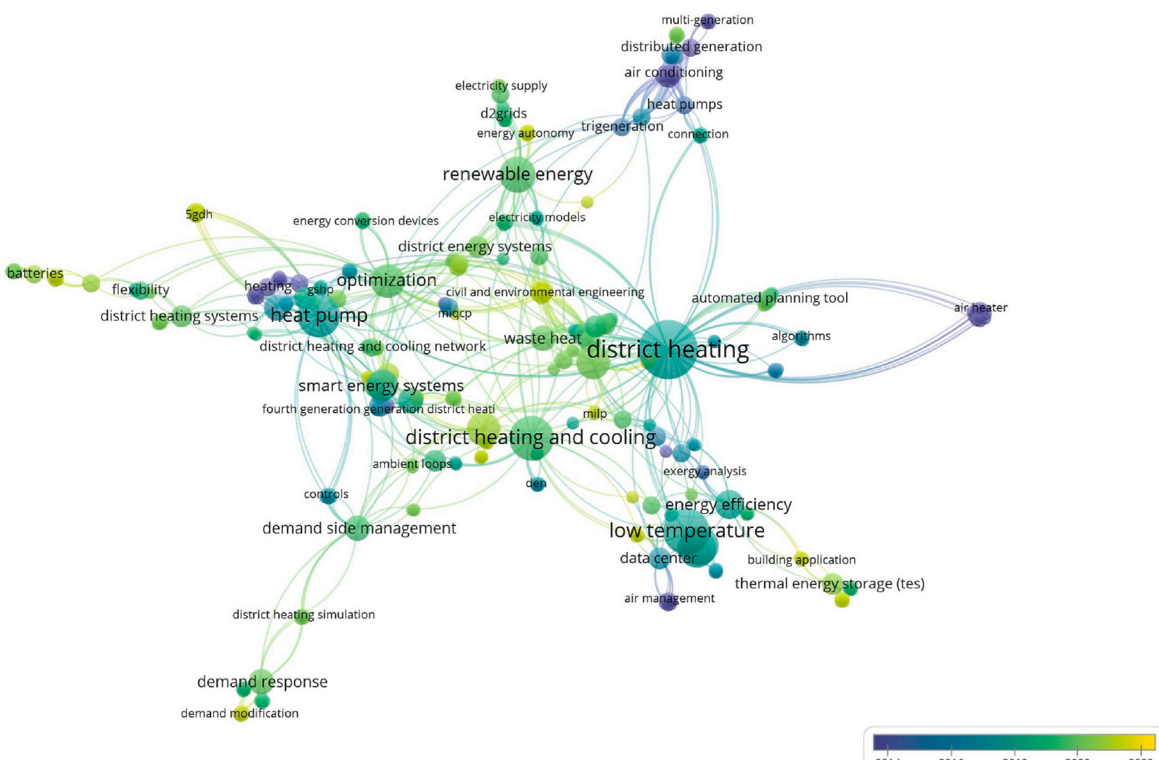

Fig. 2. VOS Viewer Visualisation Map of co-occurrence of keywords in SLR in terms of years.

water source heat pumps. Their design and performance is dictated by heat sources' availability and seasonal temperature profile, thermal capacity and stability along with the building side thermal requirements for space heating and domestic hot water [51]. Decentralising the energy transformation units has the problem of a higher overall cost but could also improve the economic feasibility of the project by allowing a phased CAPEX and potentially lower electrical upgrade costs when completely electrified [52]. Phasing the rollout of the network on a city scale could greatly improve the economic feasibility of a project mainly due to the discount rate's effect on the Net Present Value and the Levelised Cost of Energy [14]. Furthermore, phasing increases the flexibility to incorporate future technologies and plant diversity while it facilitates expansions by having multiple networks connecting to each other [53, 54]. In addition, this decentralised approach can cater for different temperature requirements which is a key challenge in project areas with varying consumer classes and levels of retrofitting [55].

To realise such a decentralised structure, a different approach to network topology and energy substation characteristics is required. Traditional thermal variable flow distribution networks tend to use a branched topology (radial grids) [56]. For 4GDHC, energy bidirectionality means that any node can produce and consume energy; therefore a branched topology, with a reduction of the pipe sizing, is not possible [57,58]. [59] suggested a ring or meshed topology is more suited to the bidirectional elements of a 4GDHC network, which was further

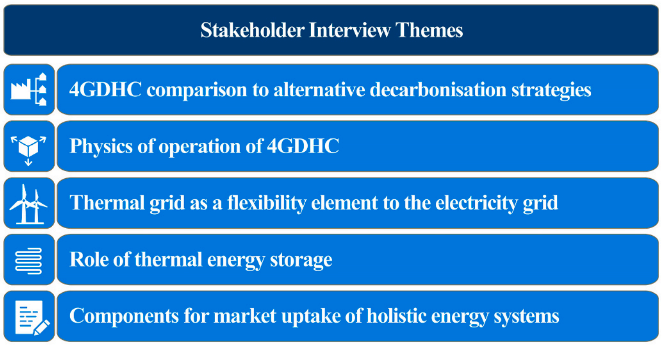

Fig. 3. Stakeholder interview themes.

Table 3
Stakeholder engagement details.

Occupation	Number	Countries
Academics	9	UK, Sweden, USA, Switzerland, Italy, Belgium
Contractors	2	UK
Engineering consultants	6	UK, Sweden, Denmark
Public officials	1	UK

confirmed by [60] via a technoeconomic comparison in Modelica. In networks with large load diversities and multiple prosumers where heating and cooling demands balance, meshed networks permit hydraulic sub-cycles and thus lower exergy losses along the network and higher security of supply [61]. Most operational 4GDHC networks have this topology, such as Anergy Grid of ETH Zurich, Mijnwater and Ectogrid [10,20,49]. Having a meshed network with prosumers requires different pressure and temperature controls to conventional unidirectional branched networks [30]. Firstly, according to [62] a 4GDHC network can be active or passive, depending on the existence of centralised pumping. Passive networks depend only on decentralised pumps to modulate the flow and have lower electricity consumption due to hydraulic sub-cycles from heating/cooling balancing, but are associated with dangers of hydraulic short circuiting (pump-to-pump hydraulic interactions referred to as “hunting”) [61]. Therefore, they are recommended for smaller networks (less than 100 consumers) [62]. Altogether, network CAPEX for 4GDHC ends up being similar to DH as the reduction of cost from using plastic pipes compared to insulated steel pipes is countered by the required internal diameters being approximately 1.5 times larger [12]. Compared to conventional unidirectional centralised solutions, a 4GDHC ring network with mass bidirectionality cannot take advantage of demand diversification, leading to larger pipe sizing for a given area along with higher installed capacity of energy transformation units [17,63].

To tie together the individual substation performance with the building energy needs and the overall network hydraulic stability, a centralised controller is required to combine the individual control strategies and unify them with a governing control philosophy [64]. For the Ectogrid network, the ectocloud is used [65], while for the Mijnwater, the STORM controller has been implemented [66], allowing peak-shaving, cell balancing (matching heating and cooling demands) and network expansion [67–69]. [70] highlighted that in Heerlen, through STORM’s increased cell balancing, dependency on outside sources decreased, leading to a capacity increase of 37–45% despite limited controllability of the heat loads in the test sites. Due to the decentralised approach and the larger volumes of water being circulated within the system, the pumping requirements can increase significantly [48]. In addition, the parasitic loads for the required controls described above would be larger, increasing the electricity needs even further [71]. An alternative to these complicated hydraulic configurations and extended control schemes is the adoption of a unidirectional-mass ring network which can prevent differential pressure instabilities and pump “hunting” [42]. [72] indicated that for equal parameterisation, the bidirectional system showed better economical results and led to a 60% reduction of the electricity used for pumping but stressed the need for a more detailed model to validate these results. [42] conducted dynamic simulations in Modelica, based on the Quayside network in Canada, to find that, under certain design conditions, the pumping energy requirements are almost identical for unidirectional and bidirectional systems with decentralised pumping. [73] further investigated this concept and proposed a reservoir network system, with a ring topology and heat pumps connected in series rather than in parallel, which can consume less electricity overall for large volumes of water.

Moreover, one of the key advantages of 4GDHC is its capacity to harness low temperature heat from ambient or waste heat sources and upscaling it to useful levels on the consumers’ substation [74]. For example, the annual waste heat from a supermarket’s refrigeration unit in Europe is equivalent to the energy needs of 200 homes [75]. In addition, by waste heat not being captured but rather released, the heat island effect (raise of temperature due to anthropogenic activities) is produced, resulting in higher cooling demands and prolonging this wasteful cycle [75]. The RewardHeat project’s Ospitaletto network is demonstrating how a scheme integrating multiple secondary waste heat opportunities in an urban setting could operate [76]. Moreover, ambient low exergy sources can be used in a 4GDHC, such as bodies of water and geothermal sources, each linked with some difficulties in fully harnessing their potential. To ensure sustainability, analysis of abstraction and injection site arrangement and flow rates is crucial. In regards to source water direction, hydrogeological assessments and cooperative planning of operation on district/wider system level are necessary [62,77,78]. However, when such waste heat sources are not available and energy balancing between cooling and heating demands is not sufficient year-round, additional centralised balancing energy supply units are required to meet the system’s demands, significantly lowering the system’s Seasonal Coefficient of Performance (SCOP) [79].

Finally, there is a range of other items that need to be taken into consideration for this comparison. Space constraints occur both above and below ground. On one hand, having multiple abstraction points and substations throughout the city could prove to be problematic for planning, but on the other hand, a large, centralised piece of land for the energy centre is no longer required [80]. Overall, the system’s risk is dropping in European markets as [31] identified in their survey of 4GDHC networks in Germany and to face the several organisation and technical challenges, a detailed procurement strategy was produced from [31]. Furthermore, one of the biggest limitations are the space constraints below ground for the pipes where in a 4GDHC network, the trench required would be less than half of one comprising both DH and DC pipes considering number of pipes, and minimum distances between them to avoid interference as specified in EN13941 [81].

Altogether, the system’s performance is highly dependent on the specific conditions present in the network, from co-occurrence of demand to waste heat availability. [20,31,82] argue that the key application of a prosumer dominant 4GDHC is a neighbourhood-based approach that benefits from a local flexible market while avoiding the technical complexities of energy exchange between multiple stakeholders. Following [27,55] categorization of thermal networks in terms of existing energy share, small markets such as the UK could follow city wide urban decarbonisation through the construction of multiple smaller 4GDHC networks rather than one large DH or DC spine. The following section investigates how would such a decentralised approach would influence the grid through the sector coupling capacity of 4GDHC.

3.2. Thermal grid as a flexibility element to the electricity grid

Holistic energy systems comprise a thermal grid that acts as a battery rather than an additional strain to the electricity grid and facilitates its smoother operation, avoiding large increments to its infrastructure capacity and disturbances to its control philosophy. In 4GDHC systems HPs in combination with TES (daily and seasonal) provide ancillary services to the power grid (grid-friendly operation), facilitate integration of RES on building and network level and could benefit from operation under variable electricity prices [26,28,63,83–85]. Additionally, the thermal inertia of buildings and a manipulation of the thermal request profiles, defined as Demand Side Management (DSM), can further increase peak shaving by shifting peaks to off-peak hours and load shifting [86,87].

3.2.1. Thermal storage role for sector coupling

TES plays a critical role in thermal networks as it allows HP to have higher running hours and reduce their number of start-stops, maximising in that way cost and emission reductions [85]. It also permits flattening of the demand profile by shifting peak production into hours of low demand [56]. There are two main types of TES as described in [88], seasonal and daily energy storages.

In 4GDHC, seasonal TES plays a vital part since it can act as a passive balancing unit, limiting the installation requirements of active balancing equipment (centralised energy transformation units such as HPs) by supplying heat/cooling stored during periods of high cooling/heat demand. [88] suggests that seasonal TES allows significant cost and emission reductions, reaching reductions of 50% for heat prices and 95% for CO_2 emissions. Lower network temperatures would require larger and costlier storages than conventional medium temperature approaches, but they also allow the safe utilisation of Aquifer TES (ATES) from an environmental perspective [89]. A worked example of ATES working as the sole energy source for a 4GDHC network was undertaken under the DATES program in Utrecht University at the Uithof campus [89,90]. The seasonal TES utilised a cold and a warm well acting as balancing units for both energy and hydraulic flows within the network, by incorporating a simple hydraulic connection via a heat exchanger and pump unit [89]. They also proved that the location of the wells (inside the loop rather than outside) yielded 35% lower CAPEX for piping. Seasonal TES shows the best economic performance at substation level, especially when the demand is peaky, reducing the total network investment cost by 4% [91].

Flooded mines can play an important role in the viability of 4GDHC due to their relatively constant seasonal temperature profile (13^{o}C–14 °C) and large TES capacity, especially when considering that water needs to be actively pumped irrespective of their use due to water quality deterioration concerns [77,92]. [77] presented 7 operational schemes with water source heat pumps using flooded mines as a source achieving SCOPs in the range of 3.5–5.5. In their detailed feasibility analysis on mine water usage for 4GDHC, they highlighted the technical components of both an open and closed loop system and concluded that the capacity of the mine, the depth and the proximity to the loads are the key variables influencing the balance between high pumping costs and OPEX to higher SCOP. They concluded that a geothermal plant of less than 1 MW does not reach the expected profitability, but that it highly depends on the country's electricity prices. The hydrochemical characteristics of mines and the extraction limitations are discussed in [93] with design guidelines to avoid mineral precipitation and pipe clogging.

Daily energy storage comes usually in the form of tanks and can be found at substation level. [91] suggested that for daily storage, building storage level is optimal as it requires the smallest CAPEX, has limited space requirements, and can smooth the energy demand profile with a capacity as low as 1 h discharge. [94] researched the optimal operation of a multi-energy system with both seasonal and daily TES through a MILP optimisation model. They showed that having both storage facilities allow for better operation of HPs, drastic reductions to CO2 emissions (87% reduction to conventional systems) and better flexibility when heating and cooling demands are different to each other. For low temperature differences (ΔT), it is also easier to ensure water stratification since the minimum diameter to height ratio can more easily be satisfied [56]. For cooling, the capacity requirements for storage are larger due to the lower system temperatures, but the effects on peak reduction are just as prevalent as for heating [95]. Since daily TES is an integral part of the energy substation and its effect should be studied along with HP operation, its role is further discussed in the following section (3.2.2) in more detail.

3.2.2. Heat pump operation for smart grid

The operation philosophy and control methodology of HPs in combination with building level daily TES can allow for the creation of a smart grid as discussed in [26], focusing on grid stability, RES integration and price reductions.

For RES integration, HP operation for heating is well matched with wind power generation due to higher wind resource during winter. For Photovoltaics (PVs) without TES, despite the seasonal mismatch, self-consumption can increase by 10%–14% without significantly lowering the HPs COP while the feed-in peaks from multiple small-scale PVs can be reduced by 30%–55% [26,83]. [96] further investigated the effect of coupling localised RES such as PVs with 4GDHC networks through a MILP optimisation model and concluded that 35% of the onsite generation could be used for HP, jumping to 77% if daily TES is used. Price-focus can be either static, using fixed tariffs, or dynamic, where tariffs change daily (day-ahead pricing) or on real time (real time pricing). Tariff structure has the capacity to incentivise the demand profile, reducing the network's OPEX [97]. In general, price focus leads to lower OPEX, but potentially to increased consumption and indoor comfort deterioration by shifting the demand peak [26,83]. HPs can offer grid stability through voltage control, congestion management and frequency regulation overcoming over-voltage problems especially prominent near PV installations and by operating when grid voltage levels are low to avoid transformer overloading [26]. Frequency regulation through spinning and non-spinning reserve can balance demand with time scales varying from a few seconds to minutes, by turning HPs on and off, but depends heavily on fast performing load controllers and HP dynamics [98]. For frequency regulation, Frequency Containment Reserve supplies instantaneous frequency restoration services supplemented after some seconds by Frequency Restoration Reserves to balance the grid [99,100]. Apart from the technical function, there is also a market function associated with Frequency Restoration Reserves, as there are monetary incentives to participate in these energy balancing schemes through weekly audits [83]. However, for 4GDHC there are participation challenges due to hard technical requirements (HP cycles are at least 10 min compared to power activation demands of seconds to a few minutes) and prohibitive logistics of multi-player day-ahead heat plan generation [83,98]. In 4GDHC, HP pool operation coupled with decentralised TES can enable meeting the technical requirements of short activation times and the participation threshold of 5 MW installed capacity shown by successful case studies of 54 HP units participating in frequency regulation markets but can prove difficult due to the required integrated control strategies [26].

Given the operation methodologies described above, a smart grid relies on the interaction of controls on all three levels of the network (power system, building, and energy substation) with variations arising on the autonomy level of individual energy substations. Passive systems rely on direct control with set values being centrally sent to individual units. Passive intelligent systems use centrally sent cost signals to set a boundary within which the individual units try to optimise operation. In active systems, units are seen as individual entities, and their control actions are negotiated interactively to achieve both network wide and individual goals of operation [26,83]. The exact control methodology can be shaped so that DSM measures can be applied and thus benefits of coupling the thermal and electricity grid are maximised as it was investigated by [101] for 4GDHC substations.

3.2.3. Demand side management

DSM measures can vary from retrofitting buildings to Indirect DSM (by modifying the tariff structure) and Direct DSM (modifying on/off schedule of energy units and applying a different regulation strategy) [86]. For 4GDHC, there is an increased interest on the impact of DSM programs, which can lead to peak shaving of 20%–30% in the domestic sector, and energy requirements can be reduced by up to 5% [21,86,102]. However, emission and cost reductions depend heavily on HP and TES size as well as the overall dynamic properties of the network [86]. The speed of response is limited by the rate of change of the compressor speed, turndown ratio (minimum load the HP can supply), minimum on-off pause time, and maximum number of on-offs within a year to avoid reducing the lifetime of the unit [26].

One of the most intricate and challenging components of Direct DSM is decision intelligence, especially for aggregating a pool of buildings which is applicable to 4GDHC networks [86]. Agent based control performed through MILP showed that a fixed ambient network temperature (for hot and cold pipe) allows for a reduced OPEX by exploiting the coordinated balancing efforts from the individual substations [20,84,103,104]. To accommodate the non-linear characteristics found in 4GDHC networks, other approaches could be more suitable. In a detailed literature review of network control strategies by [30], it was determined that despite Multi Agent Systems require less data manipulation and are easier to develop and use, Model Predictive Control has the capacity to include more parameters in the optimisation problem such as weather forecasting, consumer profiles and system disturbances. Artificial Neural Network MPC was further investigated in [102] for smart charging a 4GDHC substation's thermal store based on a receding prediction horizon. Despite some improvements in terms of lower costs (3.5%) and higher peak shaving (13%), the research was limited to a single substation without exploring the interconnection with other substations and the effect that could have. [105] combined Python with Modelica to test the effect of an MPC to an entire DH network supplied by HP and coupled with local PVs which resulted in energy cost savings of 5%. An additional feature to DSM would be to incorporate behavioural demand response analysis, to predict the expected behaviour of building occupants to DSM actions/events [106].

Prosumers can aggregate their asset activity to provide flexibility to the grid by using forecasting and day ahead trading, which becomes beneficial especially when a pool of consumers are bidding together [107,108]. [107] simulated a HP led 4GDHC network of 2200 houses and evaluated the flexibility offered to the grid with response to thermal comfort (internal temperature between 20 and 24 °C as stated in DIN EN ISO 7730 [109]). The installed heat supply systems role was tested through step response tests (radiators take 240 min to cool down while underfloor heating takes 1950 min) and polynomial equations for heat up and cool down times where determined that could be used in an MPC algorithm. However, financial compensation alone to exploit DSM is not sufficient to incentivise participation of prosumers, so additional benefits are required [86,108].

Currently, there are few holistic smart energy grids where the electricity network is seen as a key vector in its planning, especially within a 4GDHC setting which as claimed by [110] could provide true local heat to urban centres. The Balanced Energy Network at London South Bank University is one of the first 4GDHC to utilise active demand response in its operation but it is limited to two buildings [111]. There is an increased effort in understanding and modelling these utility interrelations and capabilities with few simulation tools currently available. Other than the technical aspects of sector coupling, the business models required to realise such a holistic approach need to be studied.

3.3. Market uptake of holistic 4GDHC system

This section investigates the inherent business intricacies of 4GDHC that need to be addressed, as well as current barriers and potential opportunities for its effective widespread adoption. Despite the focus on technical aspects mentioned so far and efforts to increase the efficiency of the system and thermal networks in general, a key obstacle to the widespread adoption of these technologies is economic and legislative [112]. In a workshop carried out by [55] with key stakeholders from various Horizon 2020 programs on 4GDHC, 55% of the attendees considered local authorities to be the key actors for facilitating thermal networks and 90% considered financial issues as the key obstacles to their extensive roll-out. This was also highlighted by [113], where the first key success factor to integrate RES and waste energy to thermal grids was national policies and a supportive regulation and legal framework. For example [74], states that multiple data centres are planning to utilise their waste heat to DH networks, but find it difficult due to the lack of structure and transparency on current business models.

As stated in [28], for a bidirectional system to be effective, a novel business model is necessary. 4GDHC presents the opportunity for a new business model based on the notion of prosumers [52,114]. The benefits from having active substations, as mentioned in [20], include a shift from the current monopolistic energy model, where large Energy Supply Companies (ESCos) sell heat to consumers, to a more involved open access market [115]. Such a switch offers a greater bargaining opportunity to the prosumers, and opportunities to energy suppliers by providing energy as a service, essentially selling comfort [75]. This open access market can adopt a bottom up approach rather than a top down where the citizens are actively participating in the energy market as demonstrated by the DRIMPAC project [116] and highlighted by the system's based approach followed in the GreenSCIES project for stakeholder engagement [117]. At the same time, there are multiple challenges present in such a switch including cost and asset allocation, energy exchange tracking and restrictions, market clearing processes and simulating and controlling such a network [82]. [10] suggests that ESCos potentially fail to develop new business models for new technologies due to limited awareness and short-term profit orientation. This is highlighted by the cost for transition to a net-zero network using conventional DH. For example, in the case of Glasgow, the cost of heat could rise from approximately 4p/kWh when using gas boilers to 12–15p/kWh [118].

To best capture this bottom up approach of active consumers, other than a strictly economic dimension, a complete shift in paradigm of the role of the citizen is necessary, something that is outlined in IEA's latest report on smart cities [16]. Therefore, a sociotechnical approach to energy communities where citizens have control and even ownership of their energy supply is recommended. In this way, the necessary digitalisation of the energy sector is undertaken in a democratic way, neither alienating its population, nor leading to monopolies that can only lead to increased fuel poverty [16,43]. Examples of such energy communities have been explored throughout Europe, trying to redefine the ownership structure while following the Business Model Canvas to investigate partnerships, resources and revenue streams [37]. In Jaegerspris, Denmark, the heat network for the town belongs to the consumer-owned Jaegerspris Kraftvarme DH utility and is operated by the Heat Supply Act's non-for-profit principle, where all profits are translated to lower heat tariffs [113]. The main obstacles to such business models are both technical (data models and standards) and business related (consumer risks and tariff structure), especially when the legal frameworks have yet to be updated [31,119].

Setting up a new tariff structure is challenging as striking a balance between benefit and cost is necessary to overcome limited prosumer engagement [10]. The smaller networks present in 4GDHC, with circular economy and decentralised assets in their core, make novel economic models such as doughnut economics [120] possible, allowing the smart city to reach its participatory and co-constructed targets [121]. Even the financing of such projects can be constructed in a different manner. Crowdfunding in the energy sector was initiated in 2012 and has reached over 300 million EUR of funding, but it has not been significantly used in the heating market [37]. Non-financial and financial

Table 4
Opportunities and barriers of 4GDHC in terms of technoeconomic performance, sector coupling facilitation and market uptake.

Topic	Indicators	Opportunities	Barriers
Technoeconomic performance	Economic performance	Phasing of CAPEX in urban scale [52]. No centralised energy centre [80].	Need for seasonal co-occurrence of demand [22,48–50]. No demand diversification - larger pipe sizing & higher installed capacity of energy transformation units [17,63].
	Energy Use	Hydraulic sub-cycles for lower exergy losses and higher security of supply [61]. Controls allowing peak-shaving, cell balancing (matching heating and cooling demands) and network expansion [67–70].	Low system SCOP when low demand co-occurrence [22]. Higher pumping requirements than conventional centralised system and parasitic loads [48,71].
	Robustness and Flexibility of application	Various levels of retrofitting (temperature requirements) supplied by same network [55]. Multiple networks connecting to each other [53,54]. Various topology and connection methodology options [59,60,73].	Complicated controls that could lead to hydronic instabilities (pump hunting) [30,61]. Prosumer technical complexities of energy exchange between multiple stakeholders [82].
	Excess heat utilisation	Ability to harness low exergy sources (both natural and urban sources) [43,44,76]. Reduction of heat island effect [75].	High dependency on excess heat for thermal balancing and efficient operation [21,42]. Hydrogeological assessments and cooperative planning requirements [62,77,78].
Sector coupling facilitation	TES utilisation	Safe utilisation of ATES from an environmental perspective [89]. Utilisation of abandoned flooded mines [77,92]. Daily storage for peak shaving and PV utilisation [20,91].	High capacity requirements for cool storage [95]. The hydrochemical characteristics of sources and extraction limitations [93].
	HP operation	Grid stability through voltage control, congestion management and frequency regulation [26,98].	Participation and coordination challenges due to multi-player day-ahead heat plan generation [83,98].
	Demand Side Management	Peak shaving and energy requirements reduction [21,86,102,106]. Prosumers can aggregate their asset activity to provide flexibility to the grid by using forecasting and day ahead trading [107,108].	Decision intelligence, especially for aggregating a pool of buildings with non-linear characteristics [86]. Financial compensation is not a sufficient incentive to exploit DSM [86,108].
Market uptake	Legislation	Political design decisions [31].	Legal frameworks have yet to be updated [119].
	Business models	Opportunity for a new business model based on the notion of prosumers [52,114]. More involved open access market [115]. Energy communities [37,113]. Novel economic models adaptation (doughnut economics) [82,120].	Lack of structure and transparency on current business models [74]. Cost and asset allocation, energy exchange tracking and restrictions, market clearing processes [82].
	Financing	New patterns of trade [115,124,125].	Financial viability [55].
	Public engagement	Citizens actively participating in the energy market [116].	Uncertainty of citizen appetite for participation [37].

crowdfunding are available depending on whether the individual's contribution is associated with a financial return [122].

Some additional aspects that can be facilitated through a different market structure within a smart city network are Artificial Intelligence, Blockchain, and the Internet of Things [123]. Such platforms allow the use of extensive metered data to unlock the potential for digitalising an open business model through their collection and management, especially when combined with Cloud computing, leading to new patterns of trade [115,124,125]. Blockchain is an example of how a new technology could be tailored around this new system with multiple writers being able to modify the database [126]. There are no case studies at the time of writing of such schemes, but there are suggestions to implement Blockchain in a pilot site as stated in [127].

It is evident that a discussion about a switch to a holistic system is inherently tied with socioeconomical parameters rather than strictly technical. Redefining the role of a citizen within the energy market and assessing different tariff structures, asset management and costing schemes is required. The key findings of the SLR are summarised in Table 4 and overlaid to the stakeholders' views on the following section to provide a comprehensive and inclusive review.

4. Discussion based on stakeholder interviews

4GDHC is a complex system with multidimensional parameters as highlighted in the literature findings, a statement that is also prevalent during the stakeholder interviews. In this section, a critical discussion of the SLR findings superimposed onto stakeholders' views is presented.

There is a rise in interest for 4GDHC projects throughout Europe indicated by multiple EU funded schemes, the uptake of the 4GDHC from large Energy Supply Companies (ESCo) and innovative start-ups and the research spike on 4GDHC over the last 5 years. Despite this increased attention, many stakeholders stressed that it would be easier to deploy centralised heating solutions with individual cooling solutions (and vice versa) since energy density of sufficient values would be very rare to come across. An engineering consultant on energy systems mentioned that finding the right seasonal balance between heating and cooling would occur in 1 out of 100 projects. They argued that the benefits of phasing, lower losses and scattered waste heat opportunities are countered by larger costs for substations, larger pipe diameters, and the overall complexity of the network, which increases the risk of investment, a view that is in line with the SLR findings presented in section 3. In addition, the larger number of HPs and space requirements for evaporators/condensers (compared to compact heat exchangers used in DH/DC) could limit the feasibility of projects, especially in urban centres with listed buildings. There is a fear that more focus is given on this technology in recent years simply because it is "*the new shiny thing but it can lead to a dead end*". Opportunities of local excess heat harnessing are wider with 4GDHC however they are linked with more stakeholders and intricate contracts that could block rather than facilitate thermal network uptake. Some stakeholders argued that having a community-based approach to a smart city without a centralised city-wide network is potentially better suited to some countries/cities due to citizen's mentalities of what the energy market should look like shaped by historical and political backgrounds. The system's boundaries of social, economic, technical and environmental performance compared to conventional thermal networks are still unclear with more research needed.

The challenges related to the physics of operation of the system are still not fully resolved within the industrial and academic community. There are multiple components that need to be considered to maximise energy recirculation between the system and optimise thermodynamic and hydraulic performance. Providing standards for connection methodologies and specifications for contractors seems highly challenging; specifically, the investigation of the substation pump and valve optimal operation point for handling pressure disturbances would be of interest.

Advanced building automation systems and data manipulation are critical for the operation of 4GDHC, but there is a gap in control competence between academia, pilot projects, and industrial applications. It is crucial to standardise the control systems and detail how multiple sensors and energy data can be utilised in a transparent and practical way. As one academic argued, 4GDHCs are in the process of simplifying the original idea to find the best configuration "*Hydraulics are more like art. Complexity is not the solution, rather it is simplicity and elegance.*"

HPs and TES can add grid stability and allow the widespread integration of RES. Most engineering consultants mentioned that additional research is needed on the integration of thermal networks with the electricity network. In general, the two utilities are viewed semi-separately from a design point of view, with different experts focusing on each without much overlap. Regarding DSM, there are few applied cases despite that most available models are better than the controllers employed nowadays (on/off and proportionate). For single building control, research is so far ahead from the industry, with MPC or similar controls being a necessary step to "*getting rid of archaic rules of thumb and simplistic controls*". On one hand, decentralising the energy transformation units would remove flexibility from the grid since the energy consumption is larger, at lower individual capacities and with more complicated controls to synchronise actions of turning HPs on and off. The benefits of co-operation with PVs are stripped by the seasonality mismatch and the electricity costs could be lower for big connections since "*it is easier to have 4 HPs rather than 1000 individual connections*". On the other hand, a leading academic on 4GDHC added that it depends on the structure of the RES grid. If there is a focus on local level with multiple building level PVs, flexibility is added since local self-use can be increased. Moreover, when discussing net zero schemes, conventional DH schemes could require massive electrical reinforcement costs if the back-up supply changes to electric boilers, a cost that would be significantly lower in a decentralised 4GDHC network due to smaller capacities per connection.

TES is an integral part of 4GDHC by maximising HPs' hours of operation and allowing shifting production profiles. Seasonal TES, such as ATES and flooded mines, are unique to low temperature networks, providing both thermodynamic and hydraulic balancing capacities. There are several questions related to the costs and technical viability of seasonal thermal storages that need to be taken into consideration especially in an urban environment. They can sometimes be viewed as a "*panacea for thermal networks, but they should only be considered as a storage, not a source*". For lower temperature networks, the volume of the TES is increased dramatically compared to traditional DH, due to much lower temperature differences between flow and return. Daily storage via thermal tanks faces similar space constraint challenges, especially due to the large number of required substations which are related to both floor area and height constraints, due to water stratification concerns.

Finally, all stakeholders agreed that improvements in legislation and redefined business models are the way forward for thermal networks. According to some stakeholders, 4GDHC is pushed by some ESCo, not as a competitor to 4GDH due to its better efficiency, but rather as a potential solution to consumers that cannot be reached with centralised networks. It was also suggested some resistance might be present from current operators to switch to 4GDHC, not wishing to move away from current, profitable solutions where they have more control on the system and less complicated ownership agreements with prosumers for both the assets and heat/coolth itself. Having such a paradigm shift from a monopolistic to an open access market, adopting a bottom-up approach, would redefine the role of the citizen within the energy sector, requiring a more active participation. Some stakeholders argued that simplicity and robust quality of service are the pinnacles of interest, avoiding complex equipment and an intricate business model. "*Frankly, having dedicated ESCo running the networks and owning all assets is the right paradigm. Why would the council, let alone the citizens, be involved in it? They are not experts; they want someone to wave a magic wand to shake and decarbonise the system.*" Countering this view, some stakeholders mentioned that citizens would be willing to connect and have a more active role if less variable electricity costs and less susceptibility to volatile electricity prices could be achieved. Going a step further, an engineering consultant mentioned that "*in the future, consumers will be willing to pay more for environmentally clean solutions, having a more community-based approach*." Identifying the balance between a participatory smart city consisting of energy communities and simplicity of service needs to be at the heart of 4GDHC to achieve the ambitious decarbonisation targets.

5. Recommendations for future research

The findings of this research indicate that 4GDHC has the capacity to provide a holistic solution to the energy sector decarbonisation problem our society faces but that there are multiple issues with its effective application. The following research topics are critical for better understanding where 4GDHC fits in the arsenal of holistic decarbonisation solutions.

5.1. Quantifying boundaries of beneficial operation

It is necessary to develop thorough technoeconomic models to analyse a series of building schedule scenarios with varying project characteristics. These would include consumer class mix, density, connections per property and share of heating, cooling and electricity demands. Through such an analysis, different levels of thermal zoning (completely decentralised to centralised systems) would need to be investigated to comprehend when 4GDHC would be economically beneficial over other energy supply options (DH, DC and individual standalone solutions such as air source HPs).

5.2. Simulating sector coupling potential

Developing a comprehensive simulation of a holistic 4GDHC system with daily and seasonal TES, grid profiles and characteristics and an overarching control strategy ensuring grid stability. Such a simulation needs to capture both hydraulic sub-cycles and heating/cooling energy trading opportunities as well as the impact of the electricity grid's characteristics (voltage and frequency profiles) as it gets decarbonised. Detailed simulation tools such as Modelica will be required with a fitting overarching multiagent control strategy on overall energy use and cost minimisation.

5.3. Business model structures for prosumer in a smart city

The opportunities 4GDHC presents for a just transition to a smart city need to be studied in conjunction with the stakeholders appetite for connection in novel business structures. Creating inclusive business models and legal frameworks that can minimize fuel poverty are necessary for 4GDHC which are tailormade to its prosumer structure. A work with both stakeholders and legal entities is proposed to understand and present options on tariff structure and asset ownership.

6. Conclusions

This study evaluates the opportunities and barriers for district heating and cooling networks with decentralised energy substations towards a holistic decarbonisation of the energy system. This can be achieved by coupling thermal and electricity grids whilst facilitating waste heat capture and exploiting synergies of heating and cooling demand and supply. The SLR combines fragmented research on the system and compares it with other decarbonisation strategies while highlighting the system's key technical and business components that allow sector coupling and widespread market uptake. The outputs were integrated with views from leading industry and academic professionals in the field which were collected through bespoke interviews.

Despite its poorer economic performance when little seasonal energy co-occurrence is present, 4GDHC can be beneficial if phasing and varying levels of retrofitting within the project area are taken into consideration. This is especially true for new markets with increasing cooling demands, little industrial waste heat available and a prevalence of scattered waste heat opportunities. However, the complex physics of operation arising from mass/energy bidirectionality can result in hydronic misbalancing, pressure instabilities and increased OPEX for pumping. Therefore, network topology and pipe sizing, substation design, and overall control methodology are critical. Controls are tied to individual energy substations' operation, which is inherently tied to the electricity grid via the use of HPs. A coordinated smart HP grid coupled with daily and seasonal TES and employing DSM practices can support the evolution of the energy grid to one comprising multiple distributed generation points by offering voltage control and frequency balancing opportunities. In addition, distributed daily TES and a centralised seasonal TES can allow improved operation of 4GDHC networks, increasing peak shaving and demand shifting potentials while providing thermodynamic and hydraulic balancing. The economic feasibility of the system relies on the business models, legal frameworks and modes of financing. Some business models have emerged that facilitate decarbonisation by the presence of prosumers in the network. However, there is no cohesive plan currently in place which suggests this field is open to extensive research. Overall, a neighbourhood approach to 4GDHC would allow to harness the benefits of energy trading and scattered waste heat while avoiding technical risks of hydronic misbalances and HP coordination. Such a limited number of prosumers can offer grid flexibility and facilitate implementation of new business models with novelties on asset ownership and tariff structure to facilitate a just transition to net zero. This neighbourhood approach could also allow a phased, bottom-up energy system development, especially fit to new markets and provide an economically viable holistic decarbonisation of the thermal grid.

A series of further research topics has been presented following a critical discussion of the key findings, opening the way for extensive research opportunities on 4GDHC networks, helping to clarify their benefits and operational details.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Appendix A. Stakeholder interview details

The structure of the stakeholder interviews along with details on supporting documentation and consent form is presented in this section.

General question.

- What is your overall understanding of DHC 4th Generation District Heating and Cooling Networks?

Main Themes of research.

- Comparison of 4GDHC to conventional thermal networks. What are the key benefits and shortfalls?
- What are the key physics of operation of a 4GDHC system featuring bidirectional flow and an ambient temperature network?
- What you think is the role of the thermal grid as a flexibility element to the electricity grid?
- What you think is the role of energy storage and how can it lead to excess heat maximization?
- What new business models are aware for this new technology that could facilitate market uptake?

Specific questions based on the stakeholder's background.

- These are questions based on their own research/work.

End of Interview.

- Questions for the research team and opportunities for further work.

The participant information sheet included potential risks and benefits of taking part, confidentiality statements and a detailed breakdown of how data will be stored and processed. A consent form was provided to all stakeholders to sign specifying the use of the accumulated data for academic research projects.

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