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Towards low-carbon district heating: Investigating the socio-technical challenges of the urban energy transition

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A B S T R A C T

District heating is a major energy infrastructure in many urban settlements in the world, contributing significantly to greenhouse gas emissions. Decarbonising district heating is an important step towards the realisation of a carbon-neutral society that entails considerable socio-technical change. Building on sustainability transitions literature that has dealt with socio-technical reconfiguration, this paper investigates the barriers to the implementation of a low-carbon district heating system that is based on biomass incineration minimisation and the total phasing out of fossil fuels. Empirically, the study relies on an extensive stakeholder analysis that involved 44 organisations representing technology providers, energy companies, industry organisations, policymakers, local authorities and researchers. The results show that while several stakeholder groups could converge on key issues such as the need to support certain technological niches and the danger of a biomass lock-in, divergences regarding barriers to be removed existed between policymakers, new entrant firms, and building owners. Cities were considered important actors for the implementation of the proposed low-carbon district heating concept. However, they should encourage building owners' participation in demand response schemes, decentralized renewable energy production, and the re-design of local electricity networks to support district heating electrification.

1. Introduction

In 2019, cities consumed two-thirds of global final energy and produced 75% of the planet's carbon dioxide emissions [1]. Therefore, cities play an important role in mitigating climate change. A transformation of district heating is key to local energy transitions as in numerous urban areas around the world, district heating provides a large share of heating and cooling services. For instance, in countries like Iceland, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Russia and northern China, more than 50 per cent of the local energy needs are met by district heating [2]. Therefore, the decarbonisation of district heating is of paramount importance to promoting a transition towards carbon neutrality in countries and cities where district heating represents a major part of the energy infrastructure [3,4].

The transition towards low-carbon district heating entails not only the further expansion of renewable energy but also the development of smart grids, energy storage, business models and financing mechanisms that enable the transformation of the current energy system [5,6]. Moreover, it requires an integration across electricity, heat and mobility sectors [7]. Recent studies suggest that smart energy technologies and the digitalisation of the district heating sector could push these systems towards very low CO2 emissions [8,9]. However, most of this literature focuses on technological innovation whereas the societal barriers that need to be overcome to accelerate the decarbonizing of district heating infrastructures have received far less attention.

Furthermore, given the systemic nature of the transformation, a better understanding of the dynamics of multi-technology and multi-sector interaction in urban energy transitions and the role key stakeholders (including energy suppliers, technology experts, politicians, city planners, industry, intermediaries and consumers) [10,11] play in enacting or hindering change is needed [12,13]. In this article, we answer calls for more attention to be given to actors

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Nomenclature

4GDH	4^{th} generation district heating
CHP	Combined heat and power
DH	District heating
DHC	District heating and cooling
ICT	Information and communication technology
ETS	Emissions Trading System
EU	European Union
HP	Heat pump
IPCC	Intergovernmental Panel on Climate Change
MLP	Multi-level perspective
R&D	Research and development
RES	Renewable energy sources

in urban energy transitions [14] by examining their interests and needs related to the transition to low-carbon district heating and cooling. As the study includes both technological and societal aspects, we frame the transition to a low-carbon district heating and cooling system as a socio-technical reconfiguration [15,16] of the existing district heating system. We formulate the research question of this study in the following way:

What socio-technical barriers hinder the reconfiguration of district heating and cooling systems?

The data for this study was obtained from a broad process of stakeholder engagement that aimed to explore the views that key transition actors hold with regard to the implementation of a concept for a low-carbon district heating and cooling system that was developed by the authors [17] building on [8,9,18]. Our analysis identified the barriers that stakeholders consider relevant to the implementation of the proposed low-carbon district heating and cooling system. The low-carbon district heating concept outlined in this paper is based on mature or almost-mature technologies, which can be implemented in existing district heating contexts around the world.

As a case for our analysis, we used Finland. We focused on Finland because it is better positioned in the transition pathway towards low-carbon district heating compared to other countries. Finland already has a high share of renewable district heating energy, about 42% in 2018 [19], and also has ambitious goals to reach climate neutrality (e.g., Finland plans to achieve carbon neutrality by 2035 [20]). The analysis of the Finnish case is relevant for other countries where district heating is used and societal pressure towards carbon neutrality is increasing [19], prompting a shift towards low-emissions technologies.

The paper contributes to the emerging stream of studies focussing on the design and planning of smart energy systems in the context of urban energy transitions [6]. We contribute to this literature in two ways. First, we provide a more refined concept for a low-carbon district heating and cooling system that is of relevance for countries with similar urban energy infrastructures as Finland. Second, we provide new empirical findings that enrich current research on multi-sectoral transitions [15,16] and the role of actors in societal transformation [12].

2. Conceptual framework

2.1. Change in socio-technical systems

As a socio-technical system, district heating is undergoing considerable change due to the ongoing transition towards renewable energy. Sustainability transition literature has highlighted that such transitions do not only entail technological change but also societal transformation. Therefore, socio-technical transition literature is well suited to explaining the various non-technical barriers frequently experienced in the transformation of fossil fuel-based district heating infrastructures. The multi-level perspective (MLP) on sustainability transitions [21] proposes that socio-technical transitions take place as the interaction of processes occurring at three distinct levels: the socio-technical regime, niche and landscape.

A socio-technical regime can be thought of as the conventional or mainstream way to fulfil a specific societal need, such as energy provision. It is defined as a ‘shared, stable and aligned sets of rules or routines directing the behaviour of actors on how to produce, regulate and use [e.g.] transportation, communication, food, [or] energy technologies’ [22]. The rules characterising a regime not only determine favourable institutional arrangements and regulations, but also the shared beliefs, lifestyles and practices of mainstream society [21]. Socio-technical regimes are formed over a long period by the interaction of various forces including technology, industry, science, culture and policy [21,23]. Regimes are not static entities, but rather tend to show ‘dynamic stability’ [24] and get locked into technologies that are considered mature but that may not necessarily be sustainable [25].

A niche describes the new and ‘unorthodox’ ways of fulfilling the same societal need [26]. Generally, niche technologies are not competitive with regime solutions in their early stages and therefore require some kind of ‘protection’ such as R&D programmes or subsidies [27]. Thus, niches can be regarded as incubators or test-beds in which radical innovations develop until they are mature enough to challenge the existing socio-technical regime [28] and eventually replace or transform it [29]. In contrast to regime technologies, niche technologies are considered less stable. The development of novel technologies such as deep geothermal heating, industrial heat pumps, thermal storage, demand response automation, and hybrid energy solutions combined in the industrial scale can be considered as niche activities.

The landscape refers to exogenous factors such as demographic changes, macro-economic trends, political ideologies, crises, societal values that intentionally or unintentionally destabilize or even stabilize socio-technical regimes [15,30]. When landscape factors put pressure on regimes this can generate opportunities for niche innovations to emerge. Examples of landscape forces putting pressure on the energy regime are climate change and the various policies connected to it.

According to MLP, socio-technical transitions take place when there is an alignment of processes within and between the three levels described above [15,31]. Therefore, when landscape forces put pressure on the regime such that this destabilises it, windows of opportunity open for niche innovations. If these niche innovations are mature enough, they can enter mainstream markets and compete with the incumbent technological solutions [22].

The MLP has been criticised for its weak conceptualisation of and sensitivity to the role of actors in transitions [12]. Moreover, recent studies on socio-technical change have found that transitions are not always triggered by radical niche innovations that replace conventional technologies, but are brought about by a combination of both radical innovations from niches and incremental change from regimes [16]. In addition, socio-technical transitions are characterized by interactions between multiple niche innovations and regimes [15,32]. For instance, a seminal study by Ref. [33] stated that ‘the identification of structural couplings in a regime may serve to recognise critical factors influencing transformation processes.’

Authors have called for more research focussing on whole-system reconfigurations [15,16] and multi-sector/technology interaction in transitions [10]. Whole-system reconfigurations can be defined as reconfigurations resulting from the adoption of niche-innovations within existing regimes or incremental, cumulative regime change, regime alignments, or new combinations between niche and regime elements that change system architectures [15]. In a whole-system reconfiguration approach, the unit of analysis exists at the level of entire socio-technical systems. As a result, multiple niche innovations and regime interactions are considered [31]. Moreover, in whole-system reconfigurations, transformation may include both changes in a single module or in the entire architecture of a system. According to Ref. [16], in the first case, one module of the system may face incremental change or be substituted. In the second, the entire structure of a system may be stretched or reshaped, creating new linkages between the modules of the larger system. Following Geels' call to broaden the unit of analysis from single green technologies to changes in entire provision systems, we conceptualise the transition towards a low-carbon district heating system as a system reconfiguration [31].

2.2. Recent developments in district heating

District heating concepts are often classified in terms of five 'generations'. The most advanced are not yet fully competitive and can therefore be regarded as technological niches. In recent years, a lot of attention has been given to the fourth generation of district heating (4GDH) [18]. One of its main features (see Fig. 1) is the lower and more flexible distribution temperature, which can increase the utilisation of renewable energy sources while meeting the requirements of low-energy buildings and energy conservation measures in the existing building stock [34]. The latest district heating concept is described as the fifth generation, which relies strongly on the very low temperature of the heat supplied to buildings [8]. As the low temperature requires major changes to be made to buildings, integrating this approach within the existing district heating infrastructures is difficult due to the significant investment costs in both the distribution network and the buildings.

European research and development in district heating technologies has been increasingly focussing on the role of prosumers' participation in cities' smart energy systems, which require more flexibility in terms of building automation [36]. The fourth and fifth generation district heating concepts allow for the drastic or partial reduction of greenhouse gas emissions, depending on the solutions adopted. These can range from the utilisation of renewable energy sources combined with more energy-efficient technologies to solutions that replace coal with less polluting fuels such as natural gas or biomass [37].

More advanced district heating systems can enable the effective integration of fluctuating energy generation, such as wind power [38]. Heat pump (HP) technology can bridge the electricity market with district heating infrastructures supporting the integration of the growing shares of intermittent renewable energy sources and balancing fluctuating electricity prices [39,40]. Introducing HPs into the existing district heating systems is already possible without jeopardising the profitability of the current district heating system, especially in district heating systems without combined heat and power (CHP) production [41].

A recent study showed that combining smart energy solutions with 4GDH has a high potential to fulfil national objectives for future low-carbon transitions [42]. Several authors have described the 'Smart Energy System' concept for achieving 100% renewable energy and transport in the future [38,43]. This concept focuses on synergies enabled by cross-energy markets, i.e. interactions with various intra-hour, hourly, daily, seasonal and biannual storage options that create the flexibility necessary to integrate large penetrations of fluctuating renewable energy sources [44]. The smart energy system concept represents a shift in the energy paradigm away from single-sector thinking to a more cohesive energy system, which underscores the crucial role of multi-sector interaction in the energy transition [45]. The concept for a low-carbon district heating and cooling system outlined in this study, goes beyond a merely technological focus as it builds on the integration and coordination of governance systems, ownership structures and communication; in other words, it relies on the bi-directional flow of information between upstream and downstream parties [46].

3. Methodology

Given the dynamics of multi-technology and multi-sector interaction in urban energy transitions as suggested by Ref. [11], we carried out stakeholder consultations and analysis to identify the barriers to the implementation of a concept for low-carbon district heating and cooling. This concept was created before carrying out the stakeholder analysis. The proposed low-carbon district heating concept (Fig. 2) was used to form the basis of our consultations with key stakeholders presenting it as a possible solution for decarbonising urban heat and cooling infrastructures. We present the concept in Section 3.1 and then illustrate the stakeholder engagement and data analysis process in Section 3.2.

3.1. Creation of a low-carbon district heating concept

The concept for a low-carbon district heating was developed from a rigorous study of existing technical research as well as a desktop study of piloted multi-sectorial technical solutions [17]. This is because our concept consists of a mix of solutions for the building, district heating and mobility sectors that rely on the interaction of different markets (e.g., electricity, heating and cooling). Two preconditions were defined for the creation of a low-carbon district heating concept, namely that it should be 100% free of fossil fuels and involve minimal incineration-based energy production.

It expands the 4GDH concept [18] described in Section 2.2 and the successive improvements [8,9], but minimises biomass combustion as a substitute for fossil fuels. Heat pumps as power-to-heat technology use ground, lake, sea, air and different excess heat sources to produce heating or cooling energy, and can use wind, solar, hydro and nuclear power as electricity. Modern HPs consume electricity in the range of 15–50% [47,48] per unit of produced heat or cooling energy. The electricity needed is produced with renewable power, mostly wind and solar PV, as their capital and operating costs have declined over the past decade. Due to fluctuating wind and solar energy production, energy storage, demand response and balancing backup power are essential elements in our low-carbon district heating concept. As a demand response solution, HPs provide flexibility in balancing fluctuations in the power grid [8]. These flexibility solutions can solve the seasonal, weekly, daily and momentary mismatch of energy production and demand. With demand response automation, short-term heat storage in buildings and electrical storage in batteries allows renewable energy to be stored for several hours, solving the daily mismatch of energy demand and renewable generation. Large heat storages [49,50] solve seasonal imbalances. Energy storages [51] are charged and hydrogen is produced during periods of excess wind power and solar electricity production, when electricity market prices are low or even negative. During summer, thermal energy storages are charged by solar heat collectors or by heat pumps producing cooling energy.

The capability to produce heating and cooling through heat

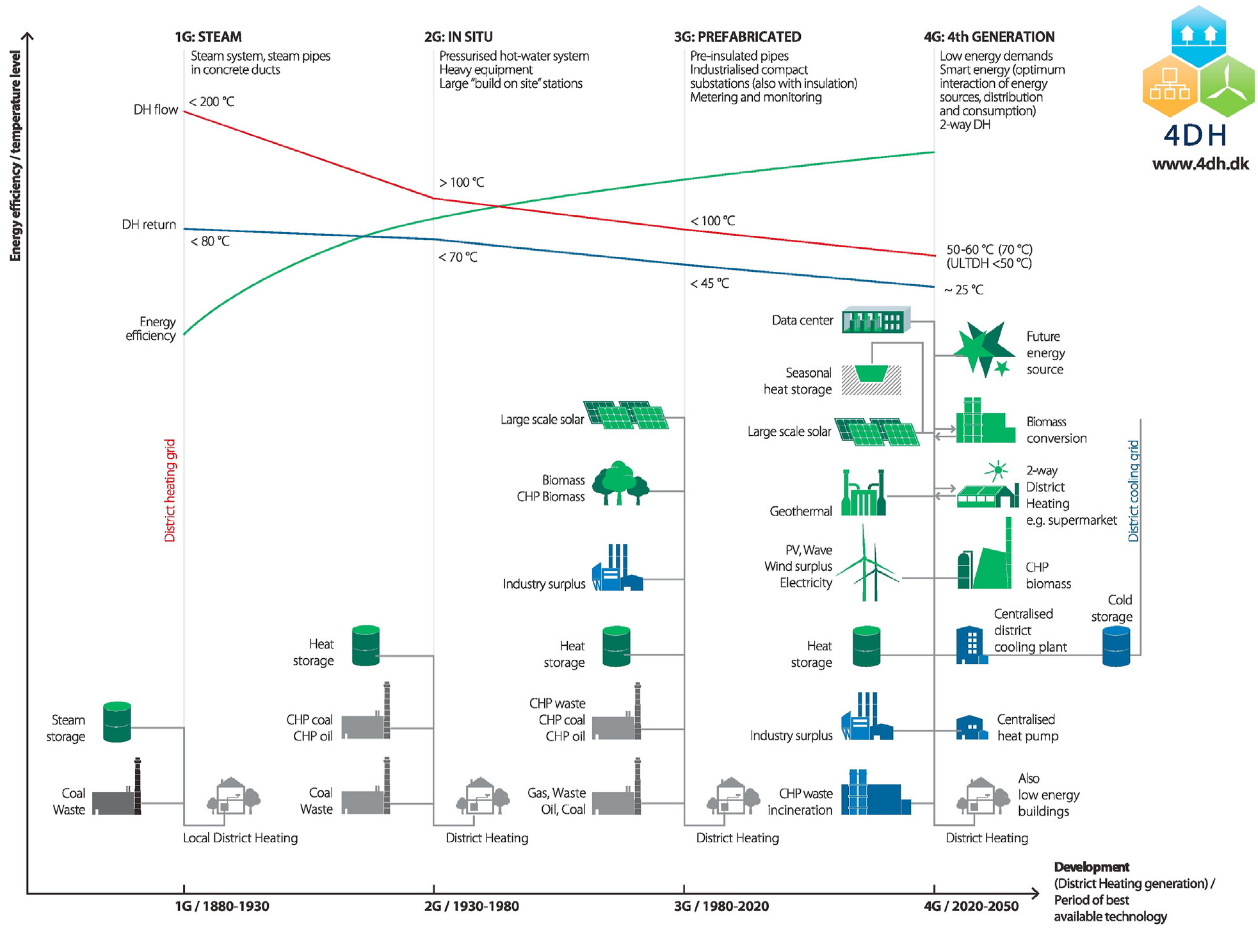

Fig. 1. The concept of 4GDH [35].

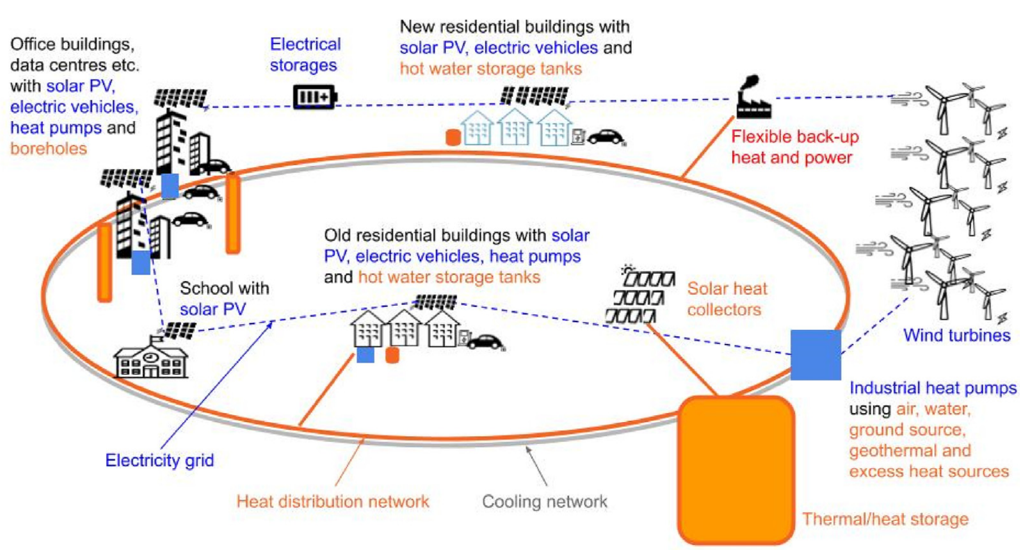

Fig. 2. Low-carbon district heating concept.

pumps is essential in cities where many buildings, such as offices, schools, restaurants, cinemas and shopping centres often also require cooling during the winter due to high internal heat gains, generating enough heat to require winter cooling to keep the indoor temperature at a comfortable level. During summers, the simultaneous heating of sanitary hot water and space cooling are needed. Therefore, the concept we propose includes a cooling distribution network in addition to heating distribution infrastructure.

Besides energy storage and demand response automation, flexible back-up power and heat production capacity is needed during times of low wind and solar power production or high energy demand periods. The use of renewable gas to produce heat and power as a back-up supply enables low-carbon energy systems. Renewable gas can be produced from bio-waste and hydrogen [52], for example.

Information and communication technologies are fundamental for the implementation of our low-carbon district heating concept, since smart control and automation functionalities are necessary to properly orchestrate the heat production, storage and consumption of energy flows. Moreover, smart control enables distributed technologies to be integrated into the energy distribution grids, transforming buildings from passive to active elements of the energy system.

3.2. Stakeholder consultations and analysis

In order to understand the position and influence of relevant actors on the implementation of the technological concept described in Section 3.1, we conducted a large process of stakeholder engagement and analysis. This process took place in the first half of 2019 and followed the stakeholder analysis of [53], which aimed to identify:

1. Key stakeholder groups who are relevant to the implementation of the proposed concept
2. Stakeholders' main interests and needs
3. Opportunities and barriers to the implementation of the proposed concept

Stakeholder engagement and data collection was conducted through different methods including one-to-one interviews, planned discussions in small groups, and large meetings/conferences for discussion of a topic with an audience, experts or industry representatives. In the case of interviews and planned discussions we used an interview guide that was loosely structured around the opportunities and challenges of specific niche innovations in district heating (e.g., technology reediness, technical applicability, market readiness, legal framework and social acceptance) and reconfiguration of energy regimes across multiple sectors including electricity and mobility. Large meetings/conferences were utilized to focus attention on the adoption of new district heating solutions, such as energy storage or demand response, and to raise public awareness of the challenges related to low–carbon heat production. In the case of large meetings/conferences, data was collected through audience response systems that allowed the audience to answer anonymously specific questions posed by the researchers, and through field notes. In total, we built on data obtained from 37 stakeholder engagement events in which the low-carbon district heating and cooling concept presented in Section 3.1 was discussed. During these events, 44 organisations and 90 experts expressed their views on the proposed concept for a low-carbon district heating (Table 1). The data was systematically collated in an Excel spreadsheet that included detailed information on the purpose of the events, the participants and their backgrounds, and their views regarding the proposed district heating concept.

The thematic analysis proposed by Miles et al. [54] was applied during the analysis of the data. We began by organising the large amount of qualitative data collected in two broad categories: 'barriers' and 'opportunities' related to the reconfiguration of district heating. Next, key themes and the related categories of stakeholders were identified through inductive coding. After the final themes and stakeholder categories emerged, they were reviewed and refined in accordance with the principle of 'internal and external heterogeneity' [55]. Finally, the identified overarching themes were analysed across the stakeholder categories to identify issues on which key actors converged and where divergence(s) existed (Table 2) [55]. We then used the insights we gained from our data analysis to examine aspects of system reconfiguration and multi-sector interaction (see Section 5) presented in our conceptual framework (Section 2).

4. Results

In this section, we summarise the results concerning the positions of various stakeholders regarding the low-carbon district heating concept presented above. The main stakeholder categories identified are energy companies, new entrant firms, sector associations, research organisations, policymakers, cities, public interest groups, and building owners.

4.1. Barriers to the implementation of the low-carbon district heating concept

Several barriers emerged from the discussion with the representatives of the various stakeholder groups. They are presented below for each main stakeholder group.

4.1.1. Energy companies

Most of the energy company representatives did not directly oppose the proposed concept. Instead, they questioned the pace of the proposed changes as they wanted to delay the transition towards new technologies to avoid a drop in the profitability of conventional energy generation. A large number of energy company representatives indicated their preference for using their fossil fuel combustion plants until the end of their natural lifetime. They were only prepared to switch to bioenergy and waste incineration plants as transition technologies and adopt non-combustion-based solutions, such as those presented in our concept (Fig. 2), in the long-term. The issue of profitability was also discussed in relation to the feasibility of demand response services, which some interviewees did not yet consider to be cost-effective for district heating companies or for small heat energy users.

The most recurrent barrier mentioned in this stakeholder group was what we refer to here as the 'biomass lock-in'. Following the decision of the Finnish Government to phase out coal by 2029, many energy companies believed that the easiest and most economically viable way to replace coal was by switching to biomass. Accordingly, energy companies began investing in either new multifuel CHP plants capable of using biomass and waste fuels, or replacing CHP plants with heat boilers that use biomass.

The positions of the energy company representatives varied between and even within companies. While senior managers were most concerned about a rapid transition, more junior managers believed that their company's internal barriers were the main factors slowing down the change towards more sustainable district heating solutions. According to one interviewee and to the best of our knowledge, no business model supporting the low-carbon district heating concept was under development.

Another issue that emerged from the interviews with the energy companies, industry organisations and researchers was the electricity tax, which was considered too high to allow profitable deployment of heat pumps on a large scale when compared to using tax-free bioenergy. When this study was conducted, district heating companies were categorized as regular electricity consumers, rather than as industrial electricity users [56]. Therefore, if district heating companies would have invested in power to heat technologies (like heat pumps, which are widely used in the proposed low carbon district heating concept), they would have been subject to high taxation, making the adoption of the proposed low

Table 1
Types of organisations, interviewees' position and number of organisations involved in the study.

Type of organisation	Interviewees' position in the organisation	Number of organisations in the analysis
Incumbent energy companies	Head of district heating, head of corporate affairs, energy utility manager, chair of the board, CEO, development director	6
Companies offering new energy solutions	Sales director, CEO, business development manager, sales manager	11
Consulting firms in the energy field	Director of operations, climate policy expert, climate specialist	2
Incumbent industry associations	Chief policy adviser, CEO, development director, lobbyist	3
Industry associations in the renewable energy field	Chief policy adviser, CEO, development director, lobbyist	2
Cities (with DH infrastructures)	Climate director, environmental director, development manager, energy expert	3
Ministries	Head of energy markets, energy specialist	2
Environmental organisations	Climate activist, climate campaigner, country manager	3
Think tanks focussing on climate policy	Climate specialist, director of operations	2
Research organisations in the energy field	Researcher, professor	5
Political parties with ties to the government	Politician, member of parliament, minister	3
Housing companies	Board member	2

carbon district heating concept not profitable. On the other hand, biomass was not taxed and available as economic replacement for fossil fuels. Thus, the Finnish Energy taxation condition (at the time we conducted our study) was reinforcing the biomass lock-in.

The interviewees from the energy companies indicated that the proposed technological solutions were immature, i.e. not readily available on a commercial scale or not suitable for district heating. For instance, one employee of a large energy company stated: '*companies can't simply order ground source heat pump systems with 1*—2 km *boreholes from the market*', which underscores the fact that industrial geo-heating plants are not yet available as turnkey solutions. A further issue mentioned was the apparent lack of excess heat sources that may already be economically feasible to cover the heating needs of large cities. A final reason for concern was the fact that the district heating networks were '*not yet smart*'. In other words, the IT and automation systems that allow the integration and control of different production and storage units, temperatures, pumps and pressures around the district heating network was not yet in place.

4.1.2. *New entrant firms*

The new entrant firms were a heterogeneous group of companies entering the energy sector with various solutions including renewable energy, excess heat recovery systems, ambient heat pump systems, energy efficiency, building automation and demand response services. Most of these companies believed that energy companies' resistance to change due to vested interests or an '*old mindset*' was the main obstacle to the proposed concept. Other new entrant firms felt that it is extremely difficult to introduce changes to the business models used by district heating companies since they control the distribution networks as local monopolies. However, these companies also expected the ongoing trend of ground source heat pumps to continue to diffuse in all kinds of buildings, causing them to disconnect from the local district heating networks and disrupt the business model of the incumbent energy companies.

Experts from new entrant firms reported that wind power in combination with heat pumps and thermal storage may already be a competitive alternative to fossil fuels or biomass generation. For instance, a representative of a large renewable energy developer stated that using industrial heat pumps in combination with wind power and natural gas as a back-up power was already a cost-effective alternative compared to bioenergy, as it is expected that the growing demand for biomass will make this fuel more expensive. Additionally, it emerged that district heating companies are mostly interested in very large and cheap excess heat sources, neglecting the smaller and distributed excess heat sources available, and especially ambient heat sources. One representative of a heat recovery firm estimated that Finland has a yearly exhaust heat potential of over 5 TW hours, which is not yet being utilized.

Another important obstacle was the fact that the current energy production capacity, such as that of fossil-fuel based CHP plants, prevents the penetration of renewable energy technologies. Recently, as electricity market prices have fallen, the business model of CHP power plants has primarily focused on heat production. The electricity generated comes as a sort of '*by-product*' even when it would not be economically viable to produce it. Therefore, CHP power plants have ended up dumping power into the electricity markets. As a result, electricity prices remain low, which hurts investments in wind power. According to some interviewees, slowly adjustable CHP plants should be replaced with separate heat production and fast adjusting power production in order to avoid such market distortions.

4.1.3. *Sector associations*

This category included sector associations that lobby for incumbent energy companies as well as organisations that support new entrant firms or other industries that are not directly linked to the energy sector. The position of the associations reflected the positions of their members. Therefore, sector associations advocating for the incumbent energy companies expressed the same concerns as their members regarding the technologies proposed, and were opposed to policy measures that would limit the use or increase the price of fossil fuels. For example, the argument related to the lack of excess heat sources and the immaturity of industrial ambient heat pump systems was repeated. Heat pumps were considered to be inadequate for producing heat of a high enough temperature for district heating networks. Moreover, these associations pointed out that there was a risk of legionella bacteria in low-temperature heating systems. The opening up of the district heating networks by separating generation from distribution businesses was opposed through arguments suggesting it would be a detrimental and non-cost-efficient policy intervention. For their part, natural gas and bioenergy were regarded as important '*bridge*' fuels supporting the energy transition.

In contrast, the sector associations supporting new entrant firms underscored the fact that energy companies and local authorities do not yet understand how energy systems based on intermittent

Table 2
Summary of the barriers to the implementation of the concept across the different stakeholder categories. The factors along the diagonal are the individual barriers for each stakeholder category, whereas the factors in bold below the diagonal are those shared among stakeholders.

	Energy companies	New entrant firms	Sector associations	Research organisations	Policymakers	Cities	Public interest groups	Building owners
Energy companies	*Biomass lock-in, sunk costs, profitability, building owners lack time and expertise, electricity tax, immature technology, lack of waste heat, lack of smart DH*							
New entrant firms	Lack of smart DH	*Energy companies' resistance, mindset, market distortions, permit procedures, lack of smart DH*						
Sector associations	Lack of waste heat, immature technology, electricity tax	Permit procedures	*Lack of waste heat, immature technology, RES intermittency, permit procedures, energy companies' resistance, electricity tax, lack of cooperation*					
Research organisations	Immature technology, biomass lock-in, lack of waste heat	Energy companies' resistance	Lack of waste heat, immature technology, energy companies' resistance	*Lack of incentives for thermal storage, immature technology, biomass lock-in, market functioning, lack of waste heat, energy companies' resistance*				
Policymakers	Immature technology, biomass lock-in, electricity tax	X	Immature technology, RES intermittency, electricity tax	Immature technology, biomass lock-in	*Energy security, immature technology, biomass lock-in, energy prices, conservative policies, electricity tax, RES intermittency, social acceptance*			
Cities	Immature technology	Energy companies' resistance	Immature technology, energy companies' resistance	Immature technology	Immature technology	*Limited influence on energy companies, energy companies' resistance, immature technology*		
Public interest groups	Sunk costs, biomass lock-in	Energy companies' resistance	Energy companies' resistance	Energy companies' resistance, biomass lock-in	Biomass lock-in	Energy companies' resistance	*Lack of awareness, complexity energy systems, conservative policies, sunk costs, energy companies' resistance, biomass lock-in*	
Building owners	Building owners lack time and expertise	Energy companies' resistance	Energy companies' resistance	Energy companies' resistance	X	Energy companies' resistance	Energy companies' resistance	*Building owners lack time and expertise, energy companies' resistance*

renewable energy sources energy work and, therefore, the energy companies were afraid of the risks related to new technologies. Some interviewees from these sector associations also stated that civil servants and urban planners are not aware of the benefits of clean electrification and the fact that sector coupling between the electricity, heating, industry and transport sectors is needed to reduce greenhouse gas emissions. In addition, they felt that energy companies were purposely trying to resist the deployment of heat pumps in buildings, for example by making the permit process slow or by not allowing customers' exhaust air heat pumps to be connected to the district heating network. Similarly, city permit procedures for the installation of exhaust air heat pumps and drilling boreholes were also believed to hinder the diffusion of these technologies. One element that the associations from both sides of the fence agreed upon was that electricity tax is too high to make ambient heat pumps economically viable in district heating production.

Some more neutral associations, on the other hand, highlighted that one of the main obstacles to a technological transition in the district heating sector is the lack of cooperation between new entrant and incumbent organisations. As a result, necessary information about the opportunities for consumers is largely missing. As one expert stated: '*It is quite unclear what building owners could do to save energy and money. And it is quite unclear to the politicians what they could do to improve the current situation*', implying that both citizens and policymakers lack relevant information for promoting technology investment.

4.1.4. Research organisations

In general, research organisations supported the proposed concept. Several researchers agreed on the potential of thermal storage as a cost-efficient and long-term solution for providing the flexibility needed to deal with intermittent renewable energy sources in temperate and polar climate regions. They stated that this solution is not understood well enough and the debate is dominated by electric batteries. Seasonal heat storage could, for example, make solar thermal energy a viable option for district heating. However, researchers identified several barriers to its implementation. Broadly speaking, economic incentives promoting seasonal heat storage do not yet exist. More specifically regarding the proposed concept, heat pumps are not yet a commercially mature technology for large, industrial-scale implementation. For this reason, heat pump systems are not ready to cover the heating needs of large cities. Consequently, as coal is being phased out, energy companies are driven to replace fossil fuels with bioenergy. For some researchers, energy companies should have been given more time to phase out coal in order to transition directly to industrial heat pump systems once they are deemed commercially mature. In their view, there was a risk that Finland's goal to phase out coal by 2029 could lock the energy system into an unsustainable bioenergy paradigm. Another concern related to heat pumps was their sizing in buildings; if they are too small, they can cause unwanted power demand peaks during winter. Hence, while for some researchers the proposed concept was promising, its rapid implementation could also be problematic in relation to the urgency imposed by climate change, as some technologies are still in the R&D phase, leading to energy companies resisting their adoption.

Another group of researchers pointed out that research is needed to understand how a market model for separating district heating networks from heat production would work. They believed that the adoption of an electricity market model in local district heating markets would not work. For example, in the Helsinki metropolitan area, three energy utilities (Helen, Vantaa Energy and Fortum) handle their own distribution networks, baseload and peak capacity separately. It was estimated that if the distribution networks and peak capacity were managed jointly in the Helsinki metropolitan area through the tendering of heat production, this model could generate considerable cost savings for consumers. Nevertheless, one expert stressed that adopting a new market model would not solve the challenge of it still not being economically feasible to produce high temperature heat from ambient heat sources or the lack of cost-efficient excess heat sources.

4.1.5. Policymakers

This group of stakeholders included both civil servants from ministries, members of parliament and representatives of various political parties with ties to the government. In the views of the civil servants, the main barrier to the implementation of the proposed clean district heating concept was energy security. They believed that the concept underestimates the need for developing enough power capacity, which, in Finland, is crucial during high demand periods. Therefore, closing CHP plants may increase energy security risks. Another concern regarding the proposed low-carbon district heating concept was its reliance on large-scale electrification, which implies a high share of intermittent energy production. The solutions proposed for reducing energy security risks were the production of synthetic liquid fuels and the improvement of market access for demand response capacity.

The political parties consulted included the Green, Centre and Social Democratic parties. Several representatives of the Green Party expressed scepticism towards the maturity of the proposed industrial heat pump solutions or their reliability and economic feasibility. Questions were posed about how to achieve the volumes required on a large scale with heat pumps. One interviewee advocated small modular nuclear reactors (SMR) as an alternative solution to industrial heat pump systems.

Other Green Party members referred to the biomass lock-in as one of the main barriers to the proposed concept. City councils were already handling permitting processes to replace local coal CHP plants with biomass plants. Therefore, as investment plans in biomass were already underway, the politicians wondered whether it made sense to oppose biomass-fired plants and whether implementing the low-carbon district heating concept now would be realistic or even a fast enough option. Another barrier related to the issue of the lack of technological maturity was the issue of whether heat pumps can generate the required temperatures. Other experts also mentioned factors such as low energy prices, conservative policymakers, and a lack of a sense of urgency. One proposed solution to increase competition and promote new energy services was for district heating companies to openly share their hourly district heating demand data.

Contrasting views also emerged from the Centre Party politicians. For instance, some party members believed that clean heat services would create more business opportunities and increase competition in the energy markets. Therefore, the relevant questions to be addressed concerned the issue of how energy taxation should be developed in order to promote the adoption of industrial heat pumps and, more generally, how the electricity tax should be modified to promote the decarbonisation of heat production. On the other hand, other members of the same party stated that wind and solar power were not reliable and could jeopardise national energy security and cause power outages.

For many people in this stakeholder group, one of the main barriers was social acceptance and, in particular, local resistance to wind farms, which would be pivotal in generating the power needed to cover the needs of heat pumps in cities. Interestingly, for all the party members consulted, bioenergy was clearly considered a non-sustainable option that should be limited in its use. Differences existed, however, in opinions regarding how to overcome the risk of remaining locked in a bioenergy paradigm.

4.1.6. Cities

The city employees interviewed reported that cities only have limited influence over local district heating companies and that energy companies' resistance to change was a major barrier. They felt that cities had better chances and more of an important role in influencing building owners. Some experts stated that heat pumps installed in buildings lead district heating companies to incur economic losses, which results in local energy firms being reluctant to accept exhaust air heat pumps in housing companies and making attempts to prevent their connection to district heating networks.

Other important issues that emerged was the fact that for city officers it is difficult to procure technologies such as those illustrated in the proposed concept or create favourable conditions for their uptake, because these solutions are still in a piloting phase and may only become commercially mature after 5–10 years. When cities did want to adopt exhaust air heat pumps in their building stock, for example, very few companies were actually providing them. In this regard, one city representative reported the case of a tendering round that did not receive any bids. Consequently, it was crucially important for city planners to have more evidence and demonstration projects showing how the decarbonisation of urban heating based on the proposed solutions could work.

4.1.7. Public interest groups

This group of stakeholders included think tanks and environmental organisations. One of the most important themes that emerged from the interviews was the role of policymakers and lobbying. The implementation of the proposed concept is difficult because policymakers are not aware of the great potential of energy efficiency and renewable energy generation in the building sector. Furthermore, decisions are often difficult for policymakers owing to the extreme complexity of the energy sector. According to one expert, this lack of knowledge has led to conservative policies that do not advance the transition to more sustainable district heating. In his words: '*municipalities have a central role in urban energy transitions, but their actions are insufficient and policies are not adequate*'. In contrast, cities with an ambitious agenda to become carbon neutral have not fully taken into consideration the challenges that this implies for municipal energy companies in terms of sunk costs and the pace of change.

In order to overcome policy inertia, policymakers needed more information and examples. In addition, the current inertia among policymakers stems from the effective lobbying by the energy companies and their sector associations that resist change. For this reason, policymakers are receiving a mixed message. Some representatives of think tanks and NGOs stated that even if citizens wanted to support the decarbonisation of local district heating networks by switching to heat pumps in housing companies, for example, they were not supported by the Finnish Government and their efforts were hindered by energy companies attempting to protect their old business models and assets. Other experts also referred to the biomass lock-in that slows down the transition towards the development of the technological solutions proposed in our concept.

4.1.8. Building owners

According to building owners, two essential aspects have the potential for preventing the adoption of heat pumps and smart energy technologies in buildings. Firstly, dealing with new technologies requires time and new expertise, which most of the members of housing companies did not have. Secondly, investment in the proposed solutions were perceived as risky, because housing companies do not have the required expertise to manage the new technologies should there be failure in the system or devices that do not work properly. In addition, building owners were also concerned about the fact that even if they would like to invest in exhaust air heat pumps, energy companies could impinge upon the profitability of their investment by changing their pricing structures.

4.2. Summary of stakeholder positions and barriers to implementation

Table 2 shows a summary of the identified barriers across the eight stakeholder categories discussed above. As can be seen, the positions of the new entrant and energy companies were diametrically opposed. Moreover, whereas most of the stakeholder groups could converge on one or more key barriers hindering the transition to low-carbon district heating, there was no common ground between actors involved in policymaking (i.e., ministries and political parties) and new entrant firms, on the one hand, and building owners on the other. These gaps are indicated with an 'X' in Table 2.

5. Discussion

5.1. Socio-technical reconfiguration aspects of the transition towards low-carbon district heating

Our results show that although some stakeholders were concerned about the lack of competitiveness and commercial maturity of the emerging technological niches, only a few individual niche technologies, namely certain storage technologies and deep and medium-depth geothermal energy, were considered by most experts to be immature, both technically and commercially. More often, the concerns of the stakeholders were related to specific aspects of the new linkages between the regimes, such as the price and taxation of electricity, or the lack of 'smartness' to manage the fluctuation of renewable electricity production.

Regime actors such as the energy companies presented the barriers as specific factors that cannot be changed at a reasonable cost in the short term. In addition, the stakeholders often more broadly referred to the barrier caused by the 'complexity of the system'. This is in line with transition literature, according to which, complexity in socio-technical regimes is related to systemic interconnections; meaning that socio-technical regimes take the form of interaction between many actors, institutions and networks [57]. As can be expected, the incumbent companies desire to move more slowly than the new entrants [58] due to their sunk costs both in fossil fuel generation and biomass-fuelled CHPs. However, in line with [59], this is not always the case as incumbent companies do also experiment with radical niche innovation such as smart energy technologies.

Company structure and a conservative mind-set are seen by the more proactive representatives of the energy companies as a barrier to change. This underpins the argument that incumbent energy companies are not a homogeneous group sharing a common set of values and business model innovation attitudes [60]. New entrants tend to promote some changes in certain individual elements of the district heating system and do not have the resources to change it wholly [61]. Therefore, many of the solutions, such as building-specific power to heat systems (heat pumps), are viewed by many stakeholders as niches competing with district heating rather than elements of an emerging new district heating (socio-technical) configuration. This echoes Geels' [62] third phase of transitions, in which sustainable innovation starts to break through more widely and compete with the established regime. The results of the study illustrate that new entrant firms and actors involved in policymaking (ministries and political parties) do not share common ground on the barriers to the implementation of the proposed concept, but policymakers and incumbent energy companies share many concerns. As transition literature has shown the role of industries and energy lobbies in influencing policymakers [63], this may indicate that the current niche innovations are seen by policymakers as a possible threat to the energy companies.

The trend towards the phasing-out of fossil fuels by increasing their cost through higher EU ETS prices [64], national taxes or a ban on the energy use of coal (in the case of Finland, by 2029) represents the landscape pressure that the district heating system is currently experiencing. Replacing fossil fuels with biomass in heat production requires very minor changes to the district heating regime. Therefore, it is not surprising that it is seen by many regime actors as the most feasible solution; incumbent actors tend to favour emerging niches that most easily fit into the existing regime structures [65]. However, many stakeholders believe that this solution will create a new technological lock-in Ref. [25]. Similarly, the replacement of fossil fuels with small and medium nuclear reactors allows the current regime to remain largely unchanged and emphasises large, centralised production units.

Cities face a paradoxical situation. On one hand, they are committed to their climate change mitigation goals, while on the other, their own energy companies (municipal utilities) contribute to reinforcing the very same regime structures that undermine their climate targets. Energy efficiency and distributed energy production in buildings cause district heating companies to incur economic losses in their current business model. This shows that the processes that lead to the development of individual niches, for instance the convergence and concretisation of expectations, reshaping market structures, the creation of new stable networks, standardisation of smart energy technologies and learning through experimentation are still needed to create a clear vision of the system among stakeholders at the societal level [66].

5.2. Multi-sector interactions in low-carbon district heating transformation

Using the framework of [16], it is possible to recognise three main types of new linkages in the proposed district heating system (Table 3, Fig. 2). Firstly, heat pump technology creates a coupling of the electricity and heating sectors. Secondly, both heat pumps and solar energy create increased energy production in buildings and the need to be connected to heating, cooling and electricity distribution networks. Thirdly, demand response creates new couplings between buildings, electric vehicles, and energy production and distribution networks. These lead to the architectural reshaping of the district heating infrastructure [44]. .

The heat and electricity sectors are traditionally coupled in the production phase (CHP). Fossil-fuel CHP capacity will decrease during the low-carbon transition and, when heat pumps are used instead, the district heating will require more electricity production and transfer capacity from the electricity grid. This can be characterised as architectural stretching. Therefore, it is not surprising that most barriers mentioned by the stakeholders reflect the major change in the configuration of the district heating system. The change in the configuration is an incremental solution in which the linkages between the system components remain essentially the same [15,16], even if the energy production regime changes (Table 3).

Our findings show the reconfiguration of the energy system by sector coupling (Fig. 3). The low-carbon energy system creates numerous new linkages in the production, distribution and consumption phases. For instance the combined heat and power units, which are commonly used in district heating networks, have created a one-way connection between the electricity and heat marked by pushing electricity to the electricity network (orange arrow from the “combined heat and power production” box to the grey “electricity network” box, Fig. 3). The heat pumps, which are the core technology of the proposed low carbon energy concept, create a new connection between the electricity network and the heat market in the other direction (orange arrow from the “grey electricity network” box to the “heat pumps” blue box, Fig. 3). The mobility regime will become increasingly connected to the electricity system through electric vehicle batteries for grid services and demand response, for instance. Even if this study does not analyse the development of the whole system in detail, it clearly shows the additional challenges caused by the reconfiguration of the whole district heating system when phasing out fossil fuels. This confirms the value of broadening the unit of analysis from one regime to multiple and interacting regimes when studying low-carbon energy transitions [33,67].

6. Conclusions

The aim of this study was to investigate the socio-technical barriers hindering the reconfiguration of district heating infrastructures. To this end, we investigated the various opinions and positions that key stakeholders hold with regard to the implementation of a concept for a low-carbon district heating and cooling system.

The results show that while several stakeholder groups could converge on key issues, such as the need to support certain technological niches and the danger of a biomass lock-in, building owners and new entrant firms had divergent views from policymakers regarding the barriers to be removed. Therefore, whereas incumbent energy companies and policymakers were roughly aligned in the way they perceived barriers to a low-carbon district heating, no common views were found between policymakers and technology advocates on how to facilitate the integration of niche-innovations such as excess heat recovery systems, ambient heat pumps, building automation, and demand response that are key to decarbonisation. Consequently, the reconfiguration of the district heating system in Finland appears to be currently oriented towards gradual regime improvement and absorption of some niche-innovations, such as building automation and demand response, that are considered more mature.

Our findings also illustrated the challenges that cities face in reconciling their climate policy objectives with the economic interests of municipal energy companies. They should step up efforts in increasing their influence through ownership on district heating companies. Furthermore, cities should encourage building owners' participation in urban energy transition in order to enable demand response schemes, and decentralized renewable energy production and ownership. Finally, cities should orchestrate the re-design of local electricity networks to realize the low-carbon district heating concept facilitating the participation of transmission and distribution operators to promote district heating electrification.

The paper makes two important contributions. First, it contributes to the emerging stream of studies focussing on the design and planning of smart energy systems with a more refined low-carbon district heating and cooling concept, which combines elements of the fourth-generation district heating and smart energy systems that phase out fossil fuels and minimise biomass combustion. Second, it enriches sustainability transition literature by showing how the shift to a low-carbon energy system creates numerous new linkages along the entire energy value chain, which means in the production, distribution and consumption phases.

Although this study revealed some of the most important barriers to the reconfiguration of district heating infrastructures, it has some important limitations. The results of the analysis and stakeholder consultation process may not be entirely applicable in other

Table 3
Main changes in the district heating system fitted into the typology proposed by McMeekin et al. [16]. Reinforcement of the core concepts represents changes that are incremental in nature. Substitution of the core concept refers to radical changes. In the upper row, the changes occur within a module and the lower row shows changes that create new linkages between the system modules.

		Core concepts	
Linkages (coupling) between system components		Reinforced	Substituted
	Unchanged	**Modular incrementalism** - Efficiency improvements in buildings	**Modular substitution** - Biomass CHP and heating-only boilers - Small modular nuclear reactors
	Changed	**Architectural stretching** - Electricity demand for heating increases (requiring more electricity production and grid capacity)	**Architectural reshaping** - Large-scale heat pumps - Energy storage - Demand-side management of buildings and e-vehicles - Purchase of low temperature excess heat from buildings and industrial/production processes - Smart control system of production units and distribution networks - Lowering temperature in existing DH networks - Two-way DH networks - Low-temperature DH networks

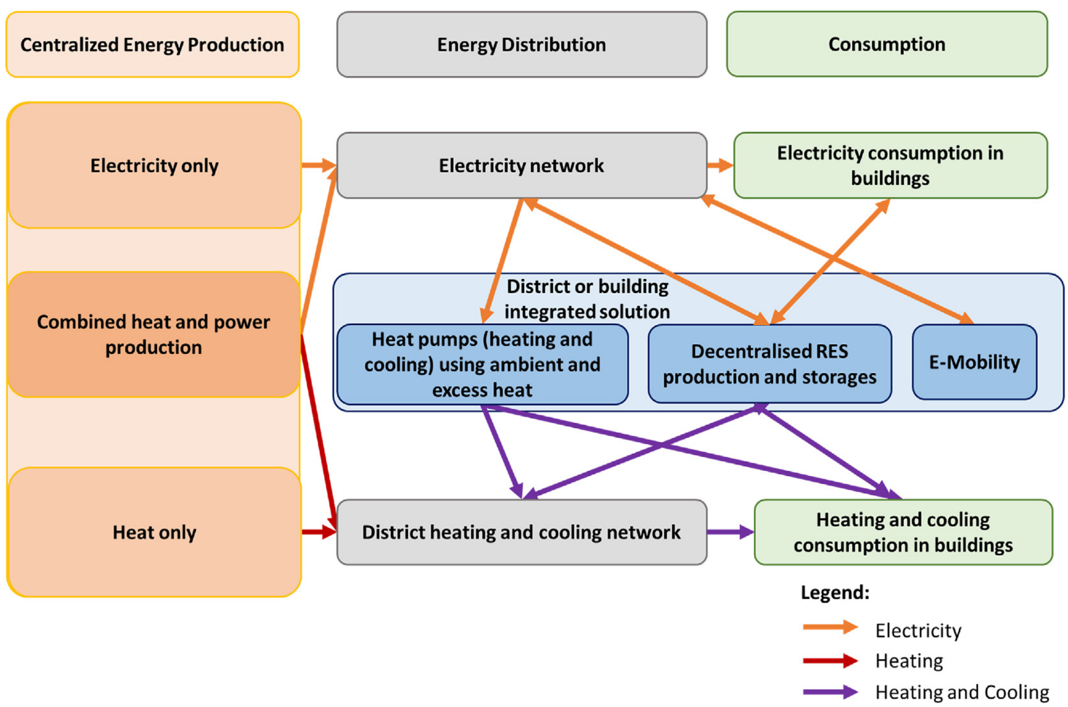

Fig. 3. Schematic representation of the district heating socio-technical system (after [16]). *Note: The current regime is shown in orange, grey and green boxes and the elements of the new concept in blue boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)*

countries. This is because the energy market structures, local conditions, regulations and institutions can significantly differ between countries. However, the low-carbon district heating concept and the outlined considerations regarding its implementation are based on innovative and almost-mature technologies that are of relevance for enabling the urban energy transition in other countries. Finally, innovation breakthroughs for low or entirely emissions-free district heating technologies may appear in the near future making some of the solutions proposed in this paper obsolete.

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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