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Decarbonization of district heating: A systematic review of carbon footprint and key mitigation strategies

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ABSTRACT

This paper provides a comprehensive analysis and comparison of the carbon footprint of decarbonization strategies for district heating. By reviewing data from 42 Life Cycle Assessment (LCA) studies encompassing 160 heating configurations, the study highlights a predominant focus on supply-side factors, while demand-side and regulatory strategies remain underexplored. Results show that renewable-based systems yield the lowest emissions, ranging from −0.001 to 0.0909 kg CO_2e/MJ of heat, with waste heat and geothermal at the lower end and solar thermal and certain biomass categories at the higher end. Biomass emissions are highly variable, ranging from very low to levels comparable with gas boilers, while solar thermal systems without heat storage present the highest emissions among renewable options, similar to those of gas boilers. Fossil fuels-based systems exhibit the highest emissions, ranging from 0.031 to 0.371 kg CO_2e/MJ. Systems combining renewable and fossil sources range between 0.0003 and 0.136 kg CO_2e/MJ. Analysis of energy conversion technologies indicates that Combined Heat and Power (CHP) systems significantly reduce emissions compared to traditional boilers, with reductions ranging from 16 % for multifuel systems to 70 % for geothermal systems. Heat pumps, especially when integrated with renewable energy sources, achieve an average emissions reduction of 64 % compared to gas boilers. Low temperature district heating (4GDH and 5GDH) improves efficiency and lowers emissions by 70 % relative to existing networks (3GDH). The implementation of heat storage results in 50–60 % emission reductions in solar thermal and multifuel setups, though its impact is less pronounced with geothermal systems. Additionally, subsidies for renewable heat technologies contribute to a 2–10 % decrease in emissions, underscoring the importance of supportive policy frameworks. Notable emission reductions are observed with CHP systems and heat pumps compared to gas boilers, as well as with heat storage in solar thermal and multifuel setups. The paper reveals inconsistencies and research gaps in previous studies and suggests the need for further investigation and standardized methodologies.

1. Introduction

Human-induced climate change is a critical global issue, steadily advancing and profoundly affecting our lives. Initiatives like the Paris Climate Agreement and the European Green Deal aim to tackle this challenge by reducing greenhouse gas emissions and promoting sustainable energy systems [1–3].

The heating and cooling sector is crucial for achieving decarbonization targets but presents significant challenges. It accounts for 42 % of the EU's primary energy consumption, with 75 % coming from fossil fuels [4]. On a global scale, it accounts for 15 % of the emissions [5]. The sector suffers from low efficiencies, high losses, and aging infrastructure. District heating offers a promising solution in Europe [5], especially since 60 % of the population have access to it [6]. It enables the use of renewable heat sources and industrial surplus heat, enhancing energy efficiency and reducing CO_2 emissions. Moreover, district heating diversifies and strengthens the energy supply by using a wide range of energy sources [7,8]. Economies of scale allow cost savings, serving many users per pipe meter [9] and facilitating the use of renewable and waste heat sources [10]. District heating's role in Europe is set to

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expand, with its share of the total heat supply expected to grow from 12.5 % today to 50 % by 2050 [6,11–13]. However, challenges remain, as it currently depends largely on fossil fuels, with renewables contributing to only 30 % [12].

Europe's district heating systems, mostly third generation (3GDH), suffer from inefficiencies due to high operating temperatures, outdated designs, significant energy, and distribution losses, and poor integration with renewable energies [4,12,14,15]. Current research primarily focuses on future-oriented 4th and 5th-generation district heating networks (4GDH and 5GDH). 4GDH systems, designed for low-temperature operation (50–70 °C), have minimal thermal losses, high efficiency, and compatibility with renewable energy sources [16].

Despite most of Europe's district heating systems being of the third generation, only a few studies have examined methods to decarbonize these networks, either through specific strategies or broader decarbonization scenarios. Research on individual strategies includes the analysis of Colmenar-Santos et al. on cogeneration and district heating [17]; a review of converting to low-temperature systems by Guelpa et al. [18]; an analysis of integrating large heat pumps by Kontu et al. [19]; and studies on incorporating waste heat (e.g., flue gas condensation and wastewater treatment plants, data centers, etc.) and heat pumps by Refs. [20–22]. Thomaßen et al. [23] examined the electrification of the heat sector and estimated emission reductions by up to 17 % when combined with the expansion of low-carbon electricity generation. Monzani et al. examined the impact of the Emission Trading Scheme on decarbonization [24]. On scenarios, Lerbinger et al. looked at retrofitting and carbon capture for waste incinerators [25]; Popovski et al. assessed various decarbonization paths for a German network using detailed building stock models [26]; Gonzalez-Salazar et al. explored coal phase-out strategies in Berlin [27] and modeling approaches [28]; Brown et al. reviewed different modeling approaches to simulate existing district heating systems including technologies for reducing emissions [29]; Sporleder et al. discussed optimization methods for decarbonizing district heating [30]; and Horak et al. provide a comprehensive overview of urban energy system modeling for decarbonization strategies [31].

An important gap identified in the literature is the lack of studies reviewing and comparing LCA and more precisely the carbon footprint (CF) of strategies for decarbonizing district heating systems. This paper aims to address this gap. The main objective of this paper is to review and compare the CO_2 emissions of different strategies, collected from available LCA studies. This analysis is expected to offer important insights to guide research and assess technology improvements as well as to provide inputs for energy models optimizing district heating systems.

The paper is structured as follows. Section 2 discusses the characteristics of existing district heating networks and their supply chain. Section 3 describes the methodology used to review and analyze published data. Section 4 reviews existing LCA studies and identifies strategies to decarbonize district heating systems investigated in these studies. Section 5 discusses the characteristics, potential and challenges of the different decarbonization strategies identified in the previous section. Section 6 compares and discusses the associated CF of the different decarbonization strategies, collected from available LCAs. Section 7 discusses the most significant results of the investigation, describes policy implications, limitations and recommendations for future studies. Finally, Section 8 presents the conclusions.

2. Existing district heating networks

District heating networks emerged in the 1880s in the United States, with Europe following suit in the 1920s [32]. These systems have undergone several generational changes, each characterized by technological improvements and increased efficiency [32]. The first generation of district heating (1GDH) primarily used fossil fuels to generate steam at temperatures above 200 °C, distributed through steam pipes in concrete ducts [32]. The second generation (2GDH), introduced in the 1930s, shifted to pressurized water systems at temperatures above 100 °C, offering improved efficiency and safety. By the 1970s and 1980s, the third generation (3GDH) emerged, using pressurized water, employing underground pre-insulated pipes, and integrating combined heat and power systems (CHP) to improve the overall efficiency [32]. The fourth generation (4GDH) is currently under development and implementation and focuses on reducing supply temperatures to 50–70 °C, minimizing grid losses, and integrating renewable energy sources (RES) and waste heat [32]. District heating systems in Europe embrace 1GDH to 4GDH infrastructure, with the majority belonging to the third generation [33].

From an energy and environmental perspective, it is useful to consider the supply chain of district heating systems, see Fig. 1. The overall goal of this supply chain is to provide a regular and consistent supply of heating to end users. The supply chain of the district heating system could be defined as the transformation of raw energy into heating and can be divided into two sides namely, supply and demand [34]. The supply side consists of four stages, i.e. energy source, conversion, energy management, and distribution. In the first stage, energy resources are procured, collected, stored, and pre-processed. Energy resources could be categorized according to their carbon intensity into low-carbon intensity (e.g., geothermal, biomass, solar, etc.) or fossil fuels (e.g., coal, natural gas, oil, etc.), and according to the degree of conversion into primary or secondary energy resources. Primary energy resources are those that have not been subject to any conversion process, like raw biomass. Secondary energy resources are those that must be produced by the conversion of primary resources, like electricity.

In the conversion stage, energy resources are converted into heat using different technologies that are subject to thermal efficiencies and conversion losses. Some technologies convert resources into heat-only, like heat-only boilers (HOB) and heat pumps. Other technologies like CHP plants convert resources into heat and power. While electricity could arguably be perceived as a by-product of the district heating network, it is one of the strongest economic drivers of the entire system, as electricity is often more valuable than heat [35]. In the energy management stage, the supply of the generated heat is optimized through different technologies like energy storage (subject to thermal losses) or digitalization. These enable the integration of renewables, maximize profitability, and reduce the need for peaking capacity. In the last stage on the supply side, the heat generated is then distributed to the end-users via a network of insulated pipes. Commonly, district heating systems consist of supply and return lines, although three-line systems also exist, which offer potentially higher flexibility and reliability [27]. The distribution network is subject to transmission losses that are largely dependent on the supply temperatures [36] and that range between 10 and 15 % of the generated heat [37]. On the demand side, heat exchangers are used to connect to and transfer the heat from the district heating network to the end user 's heating system. The end user could apply additional technologies or strategies for energy management, aiming to reduce heat demand, improve energy efficiency, and cut overall costs. These include additional energy storage, electric boilers, heat pumps, IoT, as well as upgrading the thermal efficiency of the building.

3. Method

The goal of this paper is to review and compare the carbon footprint of different strategies to decarbonize district heating systems. To accomplish this goal, a three-step approach is used. First, relevant LCA studies on district heating systems are collected from scientific literature. Second, strategies to reduce carbon emissions in these studies are identified and discussed. Third, the carbon footprint of the identified strategies is systematically compared and analyzed. These three steps are discussed in more detail in the following sections.

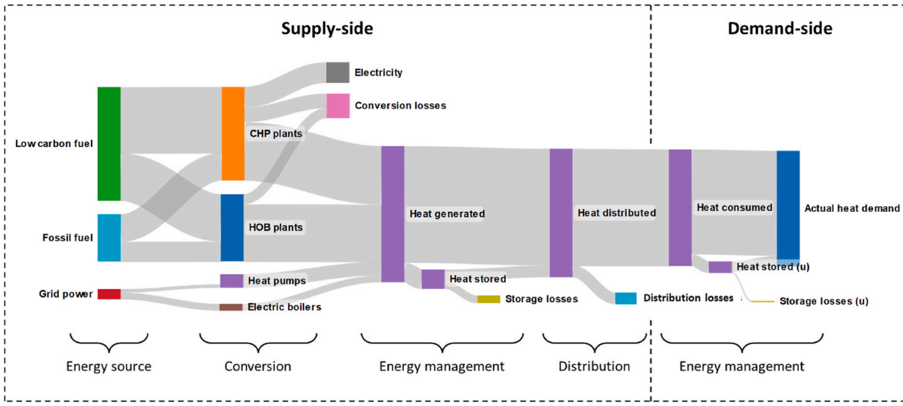

Fig. 1. Supply chain of district heating systems [34].

3.1. Data collection – LCA/CF studies

The search and screen strategy to find relevant LCA studies is summarized in Fig. 2. A search of LCA was preferred over a search of “carbon footprint” for two reasons. First, LCA studies generally follow standardized methodologies (e.g., ISO 14040/14044), ensuring a consistent and comparable approach to environmental impact assessment, including carbon footprint. Second, not all carbon footprints follow standardized methodologies and there are a large number of methods to assess it, which are not harmonized [38]. This suggests that the carbon footprint data reported in LCA studies are likely to be more methodologically sound compared to studies that only focus on carbon footprint without the broader context of LCA. Data was collected from scientific publications and reports (reshuffled in database) between March 2024 and January 2025. The search strategy employed the following three sets of keywords: Set 1 included (“district heating” OR “heat network”). Set 2 comprised (“LCA” OR “life cycle assessment”). Set 3 contained (“CO2” OR “climate change” OR “emissions”). Set 4 cover (”low temperature district heating” OR ”5GDH/fifth generation” OR ”4GDH/fourth generation”) Databases and search engines used included Scopus/Science Direct, IEEE Xplore, SpringerLink, MDPI, and Google Scholar.

In a second step, a preliminary screening of the papers was conducted by quickly assessing the relevance of the titles or abstracts [39–41]. Subsequently, various filters were utilized to refine search results. First, only studies published since 2011 were considered (with some exceptions for studies using earlier data sources e.g., Ecoinvent 2007). Second, only studies in English language were included. Third, the focus was on peer-reviewed journal articles, but potentially relevant master theses and conference proceedings were also considered. Fourth, studies directly addressing the LCA of heating systems were targeted. Then, duplicates were removed. Finally, forward, and backward snowballing techniques were employed to identify additional relevant studies from the reference lists of retrieved studies. The software ‘Tableau’ was used for data analysis and visualization.

3.2. Discussion of the decarbonization strategies

Strategies identified in available LCA studies to decarbonize district heating systems are discussed and their advantages and disadvantages are analyzed. For this purpose, published scientific papers and reports are searched in databases and search engines such as Scopus, Science Direct, IEEE Xplore, SpringerLink, MDPI, and Google Scholar. Emphasis was placed on the most recent insights, prioritizing peer-reviewed articles from 2011.

3.3. Comparison of the carbon footprint

To enable meaningful comparison across studies, a harmonized functional unit of 1 MJ of delivered heat has been defined. Greenhouse gas emissions are reported in kg of CO_2 equivalent. It is important to note that some LCA/CF studies employed methodologies incompatible with others, due to differences in system boundaries, assumptions, impact categories, or reporting units. Studies with these inconsistencies were excluded to maintain data integrity and comparability [39]. Furthermore, the study examined the environmental impact of various heating systems, considering factors like the heating source, conversion technology, range of operating temperatures of the system (either 3GDH or 4GDH/5GDH) and infrastructure processes—from fuel extraction through plant operation to dismantling. We conducted a rigorous selection process (Fig. 2) to identify relevant LCA studies on district heating systems, initially identifying 172 studies. After screening, 42 met our criteria, covering 160 district heating setups—148 classified as 3GDH and 12 as 4GDH or 5GDH. Our final analysis provides a comprehensive assessment of CO_2 emissions, highlighting the most and least sustainable options and key factors influencing overall emissions. Details are shown in Table 1 in the Appendix.

4. Decarbonization strategies in existing LCA/CF studies

Fig. 3 shows the availability of LCA/CF studies in green along the supply chain of district heating systems. Most LCA/CF studies focus on supply-side strategies to reduce emissions, particularly energy sources and conversion, with some attention to energy storage and subsidies. However, demand-side and regulatory strategies have been less explored. Notably, strategies like hydrogen, nuclear, electric boilers, CCS, and building renovation remain largely unexamined. These strategies are discussed in Section 5.

5. Discussion of the decarbonization strategies

This section discusses the characteristics, potential and challenges of the different decarbonization strategies identified in the previous section.

5.1. Energy source

These strategies aim to reduce the emissions associated with the energy sources used for district heating by transitioning from high-carbon intensity fuels to low-carbon intensity options like biomass, solar thermal, waste heat, and geothermal. This shift leads to a direct reduction of CO_2 emissions that otherwise could result from burning fossil fuels such as coal, oil, and natural gas.

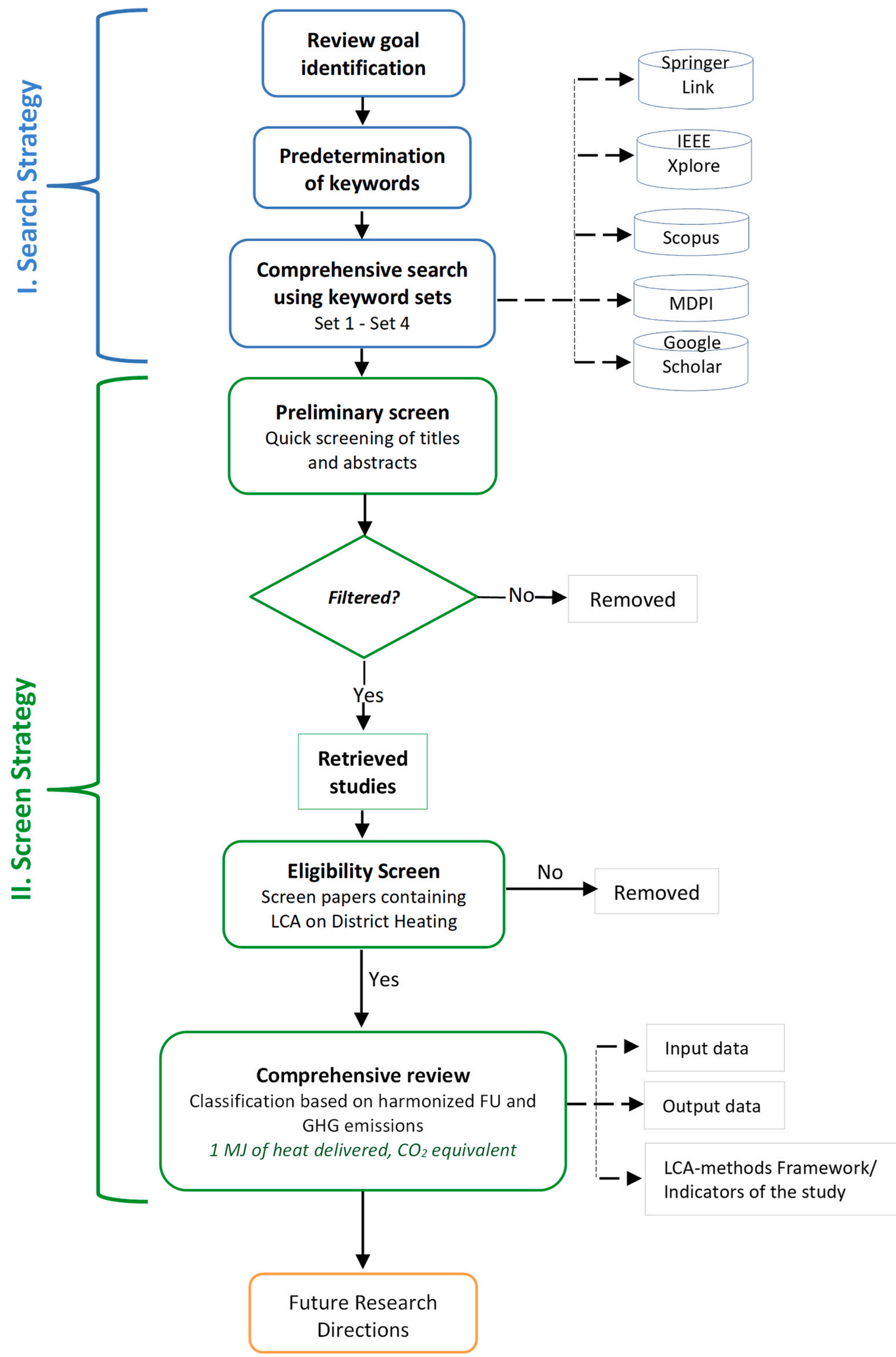

Fig. 2. Search and screen strategies to review LCA studies.

5.1.1. Biomass

Biomass, including wood waste, agricultural residues, and biofuels, is a key renewable energy source in European district heating, with countries like Spain or Sweden already utilizing it for 70-80 % of its district heating needs [42]. This technology, mature and widely adopted, uses boilers to convert biomass into heat [33], releasing the CO_2 absorbed during growth back into the atmosphere. The net CO_2 emissions from biomass are currently deemed carbon-neutral [11], though this view is subject to debate due to environmental concerns [43]. Biomass is economically viable, especially in regions with abundant supplies, and dominates the heating sector in Eastern and Baltic European countries due to its regional availability and cost-effectiveness [23, 44]. Despite its benefits, biomass faces challenges such as regional disparities in availability and cost, risks of overuse leading to deforestation, and sustainability concerns, particularly regarding forest carbon sinks and lower energy density compared to fossil fuels [8,11,44]. Nevertheless, biomass continues to be integral to Europe's district heating, with countries like Denmark transitioning major coal-fired CHP plants to

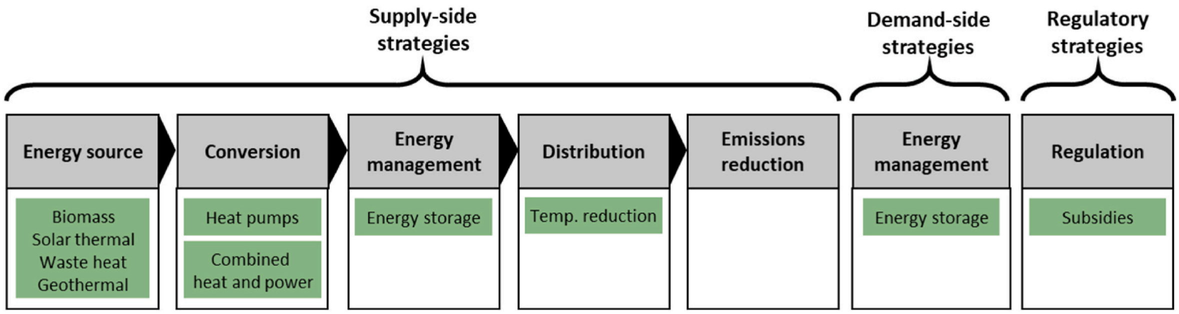

Fig. 3. Availability of LCA/CF studies along the supply chain of district heating systems.

biomass by 2025 and Germany with biomass and operated by private individuals and municipalities [45,46]. This reflects a stable but gradually increasing role in the energy mix, influenced by the shift towards electric heating solutions [23,47–50].

5.1.2. Solar thermal energy

Solar thermal energy, increasingly vital for decarbonizing district heating, captures solar radiation via collectors (flat plate or evacuated tube) and transfers heat to heating networks [33]. Recent studies demonstrate its potential to cut CO_2 emissions by 60 % and achieve up to 95 % solar fraction in heating, respectively [51,52]. Solar thermal energy is adaptable to various scales, from small residential areas to large urban networks, offering significant operational cost reductions [8,53,54], especially in CHP plant-based systems [55], and high land-use efficiency with up to 2 GWh production per hectare annually [56]. However, it faces challenges, including high initial investment costs, the pronounced seasonality of heat generation, and the need for substantial storage capacities, impacting its overall economic and operational feasibility [57]. Solar thermal for district heating is a mature and commercially available technology. However, solar thermal is not as widely deployed as photovoltaics (PV), due to higher investment costs and more complex systems. Despite this, solar thermal's future in district heating is promising, expected to grow as a major renewable source, integrating well with other renewables to reduce fossil fuel dependence [57,58].

5.1.3. Waste heat

Waste heat, the surplus thermal energy from industrial, commercial, or residential processes, is increasingly harnessed for district heating, reducing additional fuel consumption and emissions. Its integration is gaining momentum in European cities, offering significant cost savings and enhancing energy efficiency [18,53,59]. Sources such as industrial waste heat, waste incineration plants, river water and data centers are being utilized more frequently [19,60,61]. This approach not only increases flexibility and reduces reliance on fossil fuels [62,63] but also pairs well with other technologies like heat pumps [48]. However, integrating waste heat faces challenges. Its effectiveness is dependent on the proximity of heat sources to demand areas, limiting its use where industrial and residential zones are far apart. Additionally, incorporating waste heat into existing systems often requires complex and significant infrastructure changes. Consistency and reliability of heat supply are further challenges, as waste heat's temperature and availability vary with the operational status of source facilities [42,64]. Integrating low-temperature waste heat requires transitioning to low-temperature grids over time [65]. There are also regulatory, contractual, and financial hurdles to overcome [66], including potential grid losses and high costs, particularly from industrial sources [8,67]. Despite these obstacles, the future of waste heat is promising, and expected to grow due to its role in increasing efficiency, reducing fossil fuel dependence, and lowering carbon footprints, especially in countries with extensive district heating networks [68].

5.1.4. Geothermal energy

Geothermal energy, harnessing underground reservoirs of hot water or steam for generating heat, is a reliable and relatively constant renewable resource, unlike other weather-dependent renewables [11]. It is a mature approach with almost negligible 'fuel' costs [47] that can lead to cost savings and enhanced energy security. Geothermal energy seamlessly integrates with heat pumps [69] and is particularly effective for base and mid-load heat demands, potentially freeing other renewables for peak demands. Its application in district heating networks is prevalent across Europe, with countries like Germany, France, Hungary, and Italy boasting a rich history of geothermal district heating systems [11]. Europe currently operates over 240 geothermal district heating networks, each exceeding 50 MW in capacity [11]. While regions like Iceland rely entirely on geothermal heating, globally, its contribution to district heating is around 12 % [11]. Projections for Germany suggest that deep geothermal energy could supply between 5 and 10 TWh by 2030, though details on borehole depths remain unspecified [7]. Near-surface geothermal is expected to play a pivotal role in the development of 5GDH [42,70,71]. Despite its advantages, it faces challenges like high initial setup costs, location-dependent feasibility, environmental impacts like land subsidence and gas emissions (i.e. hydrogen sulfide), societal acceptance issues, and varied legal frameworks across Europe [7,71]. Nonetheless, geothermal energy's potential for decarbonizing district heating is significant, offering a consistent, low-energy heat source year-round.

5.2. Conversion technologies

These strategies aim to reduce emissions by employing cleaner and more efficient technologies to transform primary or secondary energy sources into heat. These strategies include heat pumps and combined heat and power (CHP).

5.2.1. Heat pumps

Heat pumps extract low-temperature heat from different sources (e.g., air, water, ground, solar thermal, waste heat) and upgrade it to a higher temperature, using a thermodynamic cycle that is power-driven. Heat pumps are highly efficient, as they transfer heat rather than generate heat, in contrast to other technologies. Heat pumps can transfer 3–6 MJ per each MJ of electricity consumed [72]. Driving heat pumps with electricity from renewable sources can significantly reduce primary energy demand and CO_2 emissions compared to conventional systems [51,53,73]. They could increase renewable energy share in district heating by up to 90 % [57,74] and support the future development of 4GDH and 5GDH [65,75]. In countries like Finland and Sweden, heat pumps account today for 10–25 % of heat generation [19]. The potential for using heat pumps in Europe is significant, particularly as the EU aims to ramp up the manufacturing and installation of 30 million heat pumps by 2030, which could result in a 36 % reduction in gas and oil consumption in buildings and a 28 % reduction of emissions [76]. However, challenges like higher costs and potential performance limitations in decentralized setups or extremely cold climates exist [67,77]. Urban installation limitations and grid strain are also concerns [78–80]. Despite these, the potential for decarbonization of heat pumps is large, as they are essential for integrating renewables into district heating, requiring collaboration among housing, district heating operators, and power companies for optimal integration [26,50,79].

5.2.2. Combined heat and power (CHP)

CHP systems use a fuel source to generate both electricity and heat, with the latter being distributed in the district heating network [53,81]. CHP systems can achieve efficiencies of over 80 %, compared to 40–50 % in conventional power plants. This increased efficiency leads to reduced fuel consumption and when powered by low-carbon fuels can significantly reduce emissions [81]. CHP systems could have negative emissions if they are biomass-fired and integrated with carbon capture and storage (CCS), as seen in Sweden [60,80]. CHP's fuel flexibility is high, including options like natural gas, biomass, coal, and hydrogen, which enables them to meet diverse energy demands efficiently [18]. Additionally, CHP systems provide a reliable and localized energy supply that can reduce the strain on the electrical grid. Despite the benefits, there are also challenges including potential revenue losses due to renewable energy price competition [82,83]. Limited availability and environmental concerns for biomass-fired CHP systems may affect their rapid spread [79]. A more profound criticism of CHP for district heating when it is fossil-fuel based (like in Germany), is that it 'misuses' part of the fuel for generating fossil-fuel-based electricity. This has three negative consequences [84]. First, part of the fuel is used for electricity rather than for heat generation. Second, fossil-fuel-based electricity hampers the integration of electricity from other renewable sources. Third, higher emissions can be expected compared to the separate generation of fossil-fuel heat and renewable (or less carbon-intensive) electricity. Moreover, in Germany, the Combined Heat and Power Act already poses a challenge, as it conditions the decarbonization of heat grids through CHP by financing the use of unsustainable natural gas [7]. Despite these challenges, the potential of CHP to decarbonize district heating in Europe is significant, primarily due to its efficiency and the ability to utilize various fuel sources, including renewables.

5.3. Others

Other strategies to reduce emissions in district heating systems include energy storage and subsidies. These two options share the common feature that could be applicable to the supply- and the demand-side of the district heating system.

5.3.1. Temperature reduction

Lowering district heating temperatures from ~100 °C in 3GDH to 50–70 °C in 4GDH and near-ambient levels in 5GDH is a key step in decarbonization. This shift reduces thermal losses, improves efficiency, and lowers primary energy demand [70,85,86]. It also enables greater integration of low-temperature waste heat and renewables, significantly cutting emissions compared to 3GDH [70,85,86]. However, the transition presents challenges, including hydraulic constraints for retrofitting, high adaptation costs, changes in consumer equipment, and potential difficulties in meeting peak demand [18].

5.3.2. Energy storage

Energy storage in district heating networks can be categorized into thermal and battery storage. Thermal energy storage (TES) allows for the accumulation of excess thermal energy during periods of low demand, which is released during peak periods. TES duration could range from minutes to several months, enhancing the balance of supply and demand, reducing operational costs, and minimizing the use of peak plants [50,51]. Moreover, TES enhances the integration of renewable energy sources and waste heat, which contributes to reducing emissions and increasing reliability [58]. However, TES faces challenges like significant initial investment, especially for seasonal storage, reduced capacity with smaller temperature differentials, and spatial constraints in dense areas [18,87]. TES deployment is expected to grow, especially in 4GDH and 5GDH, but also in 3GDH [42,88]. District heating networks could benefit not only from TES but also from electricity storage [79], even though the latter is currently less common. An example is a hybrid plant combining lithium-ion batteries with an electric boiler and a CHP plant for a versatile generation of heat and power [89]. Battery storage, while useful for storing surplus electricity, is costlier, more complex, and less durable than thermal storage [82]. Overall, the integration of storage technologies, especially TES, is expected to play an increasingly important role, by enhancing the integration of renewables and increasing the efficiency and cost-effectiveness of the system.

5.3.3. Subsidies

These specific subsidies are financial support mechanisms from governments or international bodies to facilitate the transition towards low-carbon heating solutions. Subsidies may stimulate investment in green technologies, accelerating the shift away from fossil fuels, and potentially reducing greenhouse gas emissions [23,68]. Successful examples include Denmark's national motivation tariff to promote temperature reduction in district heating systems [18], Estonia's mechanisms to boost the efficient use of CHP plants [42,90,91] and the EU's incentives for low-carbon heating and cooling research and innovation [42]. However, there are also various examples of how inefficient policies and inadequate subsidies hinder the adoption of efficient district heating systems [18]. Subsidies favoring fossil fuels can deter eco-friendly alternatives, as seen in Germany's Combined Heat and Power Act [7,84]. Overcoming these obstacles may require measures like CO_2 taxation and long-term financing strategies [7,23]. In summary, while subsidies are a potent tool for promoting efficient, green technologies in district heating, their success depends on careful planning with science-based demonstration of emissions reduction.

6. Comparison of the carbon footprint (CF)

The carbon footprint (i.e., CO_2 emissions equivalent) of various district heating systems based on the data collected from the LCA/CF studies are compared and analyzed. Since most of the LCA/CF studies concentrate on the energy source, energy conversion, and management, it is helpful to carry out a more accurate breakdown. Not all the LCA/CF studies evaluate or propose options to reduce emissions in district heating. Some LCA/CF studies quantify the emissions associated with the use of fossil fuels or combinations of fossil fuels with renewable sources. These studies are very insightful, as they allow a comparison between different energy sources. For categorizing the LCA/CF studies, we propose four criteria, see Fig. 4. First, the carbon intensity of the energy source. It is 'low', if the energy source is renewable, for example geothermal or biomass. It is 'high' if the energy source is fossil fuel-based, e.g., natural gas or coal. It is 'mid' if it is a combination of 'low' and 'high' energy sources, including municipal solid waste (MSW) incineration. Second, the type of energy conversion technology. It could be a boiler, a CHP system, a heat pump, or a direct heat exchanger in some applications. Third, the life cycle stages of the process or technology included in the LCA analysis. It is 'I' if it considers all life cycle stages, e.g., facility construction; fuel extraction, processing, transport; operation; and end of life (EOL). It is 'II' if it considers from facility construction to operation, but not the end of life. It is 'III' if it considers only fuel extraction, processing, and transport to operation. Fourth, other characteristics, for example, consideration of energy storage, reduction in operating temperatures, and subsidies.

6.1. Analysis according to the carbon intensity of the energy source

LCA/CF studies are grouped into three categories according to the carbon intensity of the energy source: low-, mid-, and high-carbon intensity. These categories are further categorized into single or

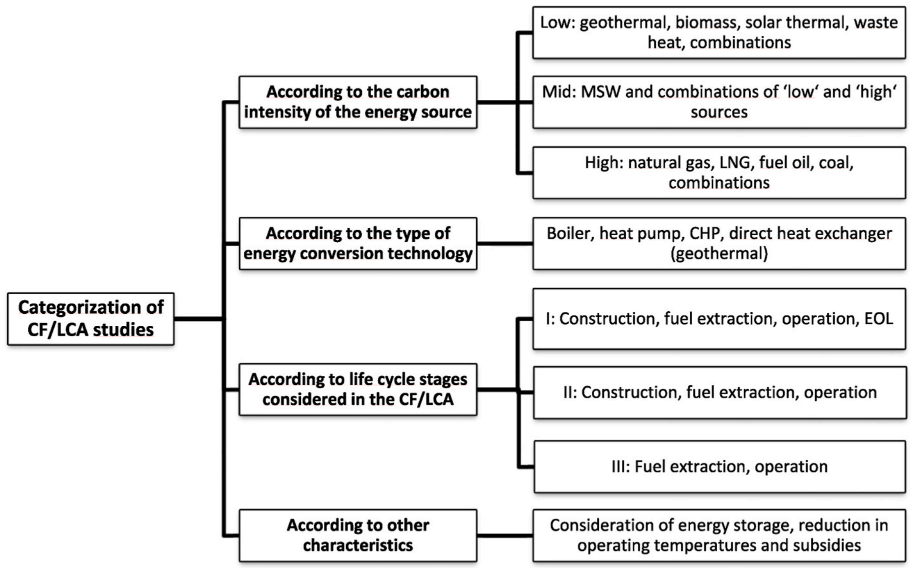

Fig. 4. Categorization of LCA/CF studies.

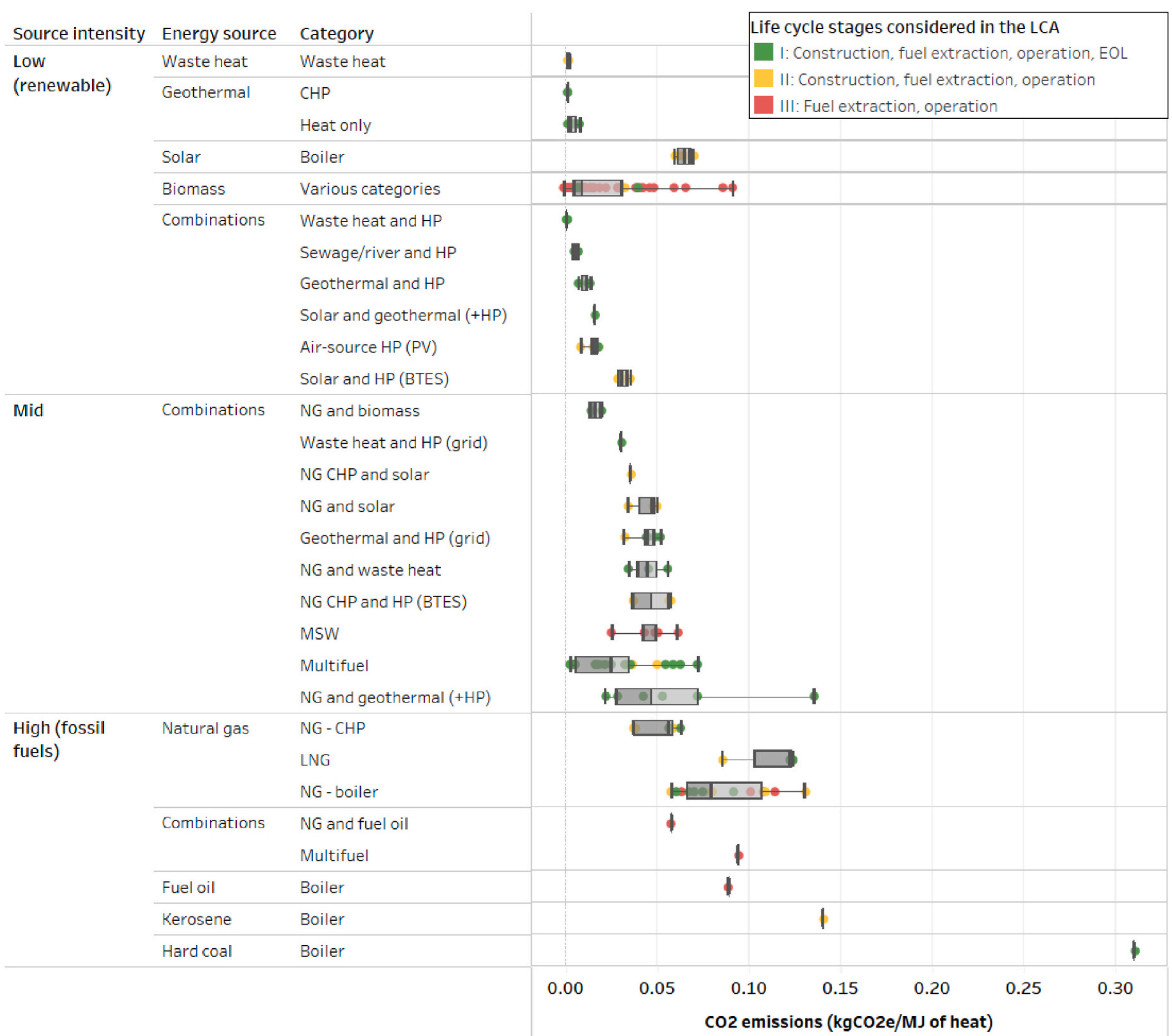

Fig. 5. Comparison of the CF of various district heating systems according to the intensity of the energy source.

'multifuel' sources and then into more detailed technology subcategories, see Fig. 5. The color of the entries in this figure represents the different life cycle stages considered in the LCA/CF study. It is important to note that not all studies can be compared consistently, as two studies within the same category can consider different life cycle stages, which could lead to different results. Nonetheless, the comparison provides useful insights into the associated emissions of the different energy sources.

6.1.1. Low-carbon intensity

Sources with low carbon intensity include geothermal, biomass, solar thermal, waste heat, water from a nearby river, and combinations. Typical conversion technologies used in this category include solar thermal collectors, boilers, heat exchangers, CHP, and heat pumps, often paired with thermal energy storage (TES). CO_2 emissions range from −0.001 to 0.0909 kg CO_2e/MJ. Categories with the lowest emissions include waste heat, geothermal CHP, and some types of biomasses. However, biomass offers at the same time the largest emissions in this category, and a large spread.

Ómarsson et al. assessed Reyðarfjörður's district heating in Iceland [92], proposing two systems—closed-loop and open-loop—that utilize waste heat from a nearby aluminum plant. These systems offer emissions between 0.0012 and 0.0017 kg CO_2e/MJ. Pratiwi et al. and Gkousis et al. conducted LCA studies on geothermal using CHP and direct heat exchangers, with emissions ranging from 0.0009 to 0.0010 kg CO_2e/MJ, respectively [93,94]. Lower emissions are expected when renewable power is used during pumping operation [93] and when shallower reservoirs with higher permeability are employed [94]. Karlsson et al. and Douziech et al. discussed the significance of material selection and infrastructure, presenting a scenario where emissions can reach as low as 0.0016 kg CO_2e/MJ [95,96].

Welsch et al. demonstrate the potential of solar thermal, showing emissions of 0.0595–0.0694 kg CO_2e/MJ—up to a 40 % reduction compared to traditional heating systems [97]. Biomass studies, covering ten LCA analyses with 48 scenarios, demonstrate a broad emission spectrum from −0.001 to 0.0909 kg CO_2e/MJ. Kimming et al. identified scenarios using agricultural fuels like Salix and straw, achieving emissions as low as −0.001 to 0.0180 kg CO_2e/MJ, significantly lower than conventional natural gas [98]. Additionally, studies by Björnsson et al. [99] and Livingstone et al. [100] underscore the benefits of integrating biomass with pyrolysis and advanced processing techniques, with emissions as low as 0.0016 kg CO_2e/MJ for bio-oil. Most biomass LCA/CF studies included only emissions from fuel extraction, processing, transport, and operation. Emissions from facility construction and end-of-life are not commonly included.

Combinations of heat pumps with renewable power and various heat sources like waste heat and sewage have been explored by Brattebø et al. [101] and Ghafghazi et al. [102], with emissions ranging from 0 to 0.007 kg CO_2e/MJ. Air-source heat pumps powered by photovoltaics was investigated by Guillén-Lambea et al. [103], with emissions between 0.0145 and 0.0172 kg CO_2e/MJ. These studies collectively highlight a strategic shift towards more sustainable and efficient heating solutions across diverse settings.

6.1.2. Mid-carbon intensity

Sources with mid-carbon intensity are here defined as a combination of sources with low and high (fossil fuels) intensities. Various subcategories emerged from the analysis.

Municipal solid waste (MSW) is considered here as a mixture of residues with low- and high-carbon intensities. Lausselet et al. demonstrated that MSW incinerators significantly reduce CO_2 emissions compared to traditional landfill methods, with emissions ranging from 0.0250 to 0.0610 kg CO_2e/MJ [104]. Analysis of 22 scenarios shows that emission outcomes depend heavily on waste composition and energy efficiency.

Combining geothermal energy with heat pumps not solely driven by renewable power yields emissions between 0.0318 and 0.0519 kg CO_2e/MJ. This variability is largely influenced by the emissions from the electricity powering the heat pump and the specific characteristics of the geothermal site [105,106]. These emissions are expected to be reduced in the future, as the European electricity continues to decarbonize.

Natural gas combined with other sources is explored in various LCA/CF studies, revealing a significant range, spanning from 0.0139 to 0.1355 kg CO_2e/MJ. Santagata et al. evaluated natural gas and geothermal utilizing heat pumps, documenting an emission range from 0.0216 to 0.1355 kg CO_2e/MJ. While the construction phase generates some initial emissions due to material and machinery use, these are offset by the operational emissions savings over the system's lifespan. Integrating waste heat into natural gas district heating networks resulted in emissions of 0.0447 kg CO_2e/MJ [107]. The combination of biomass boilers and natural gas district heating systems was evaluated by Jeandaux et al., with emissions of 0.0139 kg CO_2e/MJ [108]. The integration of solar thermal collectors with natural gas backup systems was investigated by Welsch et al., with emissions ranging between 0.0285 and 0.0351 kg CO_2e/MJ [109].

The 'multifuel' sub-category that combines more than two energy sources, emissions vary widely from 0.0041 to 0.0721 kg CO_2e/MJ [58,95,97,103,110–114]. This variation is due to differences in the carbon intensity of energy sources and their conversion processes. Harter et al. reported emissions ranging from 0.00543 to 0.0627 kg CO_2e/MJ for systems that integrate heat pumps with geothermal and other energy sources [110]. Additionally, Guilén-Lambea et al. estimated emissions of solar heating plants with heat pumps and seasonal storage in Spain as low as 0.0317 kg CO_2e/MJ [103]. The system's effectiveness is particularly notable in regions with significant temperature fluctuations, benefiting from a solar fraction exceeding 50 %. Pratiwi et al. [112] considers various combinations of shallow to medium-depth geothermal sources (90 %), natural gas (5 %) and waste incineration (5 %), with emissions ranging between 0.0041 and 0.0053 kg CO_2e/MJ. Karlsson et al. analyzes district heating systems utilizing various fuels, including household and industrial waste, bio-oil, wood products, and peat [95], with emissions of 0.0319 kg CO_2e/MJ (allocation based on energy content). A combination of solar collectors, borehole thermal energy storage, heat pumps powered by grid electricity (partially fossil fuel-based), and diesel boilers was evaluated Wu [113], with emissions of 0.0721 kg CO_2e/MJ.

6.1.3. High-carbon intensity

Fossil fuel-based district heating offers the highest CO_2 emission ranges. The highest emissions in this category are found for coal, followed by fuel oil and natural gas. Emissions from natural gas vary from 0.0371 to 0.1306 kg CO_2e/MJ, with lower emissions for CHP systems than boilers. CHP systems emit between 0.0371 and 0.0583 kg CO_2e/MJ [108], while boilers emit between 0.0577 and 0.1306 kg CO_2e/MJ [66,96–98,103,105,108,115]. Converting natural gas into liquefied natural gas (LNG) for long-distance transportation significantly increases energy use. When regasified LNG is used in district heating, it results emissions ranging from 0.0855 to 0.1240 kg CO_2e/MJ [116,117]. Emissions of fuel oil reach 0.0887 kg CO_2e/MJ [100], while those of hard coal go as high as 0.31 kg CO_2e/MJ, as documented by Kotagodahetti et al. [117]. The multifuel scenarios studied by Rehl et al. comprise a combination of 41 % fuel oil, 1 % hard coal, and 50 % natural gas, reaching 0.0575 kg CO_2e/MJ [118].

6.2. Analysis according to the type of conversion technology and other characteristics

6.2.1. Reduction in operating temperatures

Lowering the supply and return temperatures of district heating networks offers several advantages, including reduced thermal losses, lower primary energy demand, improved system efficiency, and greater integration of low-temperature renewable and waste heat sources.

Compared to third-generation district heating (3GDH), these benefits could contribute to overall emission reductions. Multiple LCA/CF studies have reported emissions for fourth- and fifth-generation district heating networks (4GDH, 5GDH). These findings were compared to studies assessing 3GDH using equivalent energy sources and conversion technologies (see Fig. 6a). The results indicate that, across most impact categories, 4GDH and 5GDH achieve lower emissions than 3GDH. Notably, substantial reductions were observed for multifuel systems (90 %), natural gas combined with waste heat (30 %), and air-source heat pumps (20 %). However, for biomass, the results remain inconclusive due to significant uncertainties—emissions could either increase or decrease compared to 3GDH. Additionally, in two categories—geothermal with heat pumps and sewage/water heat with heat pumps—4GDH and 5GDH showed higher emissions than 3GDH. One possible explanation for this discrepancy is the time gap between studies: while 3GDH emissions were assessed in a single 2011 study, the 4GDH and 5GDH studies were conducted in 2024. Other factors contributing to these differences remain unidentified. When district heating configurations are aggregated by operating temperature, 4GDH and 5GDH systems, on average, exhibit 69 % lower emissions than 3GDH (see Fig. 6b).

6.2.2. *Combined heat and power (CHP) vs. boilers*

Natural gas boilers, commonly used for heating in many countries, convert fuel to heat with 75–85 % efficiency. CHP systems enhance fuel efficiency by generating both electricity and useable heat, thereby reducing CO_2 emissions per unit of energy. LCA/CF studies report emissions for CHP and boilers using geothermal, natural gas, and multifuel sources (see Fig. 7). It is important to note that geothermal setups use heat exchangers for direct heat transfer instead of boilers. CHP systems consistently produce lower emissions than boilers, reducing emissions by approximately 70 % for geothermal, 35 % for natural gas, and 16 % for multifuel systems. However, in some cases, multifuel systems with more than three energy sources outperform CHP systems in emission reduction. These discrepancies likely arise because the combination of energy sources for CHP systems and boilers is not entirely compatible, which suggests a need for further investigation.

6.2.3. *Heat pumps vs. gas-based boilers and CHP*

Emissions of heat pumps were compared to those conventional technologies like gas-based boilers and CHP (see Fig. 8). Heat pumps are typically found in combination with other heat sources. These integrations are categorized by the carbon intensity of the heat source: low-carbon when based on renewables, and mid-carbon when mixing renewables with fossil fuels. Low-carbon heat pump systems emit between 0.0003 and 0.0035 kg CO_2e/MJ, always lower than gas or oil boilers and gas-based CHP. In mid-carbon systems, two types of heat pumps are found. First, geothermal heat pumps driven by electricity that mix renewables and fossil fuels emit between 0.0318 and 0.0519 kg CO_2e/MJ, lower than oil and gas boilers and comparable to gas-based CHP. Second, combinations of heat pumps, geothermal, and natural gas, produce emissions ranging from 0.0216 to 0.1355 kg CO_2e/MJ. This option increases emissions compared to geothermal alone but remains generally lower than oil and gas boilers, though it can exceed gas-based CHP. When combining all results of heat pumps into a single category and comparing them to those of gas-based boilers, heat pumps average 64 % lower emissions than boilers. The greatest advantages are observed when heat pumps are powered by renewable electricity.

6.2.4. *Heat storage*

Emissions from heat storage across three energy sources are compared in Fig. 9. In solar thermal applications, heat storage significantly reduces emissions compared to systems without storage. Heat storage allows a more efficient resource use, reducing peak capacity needs, and balancing demand and supply. This results in an average emission reduction of 50 %, from 0.059 to 0.069 kg CO_2e/MJ to

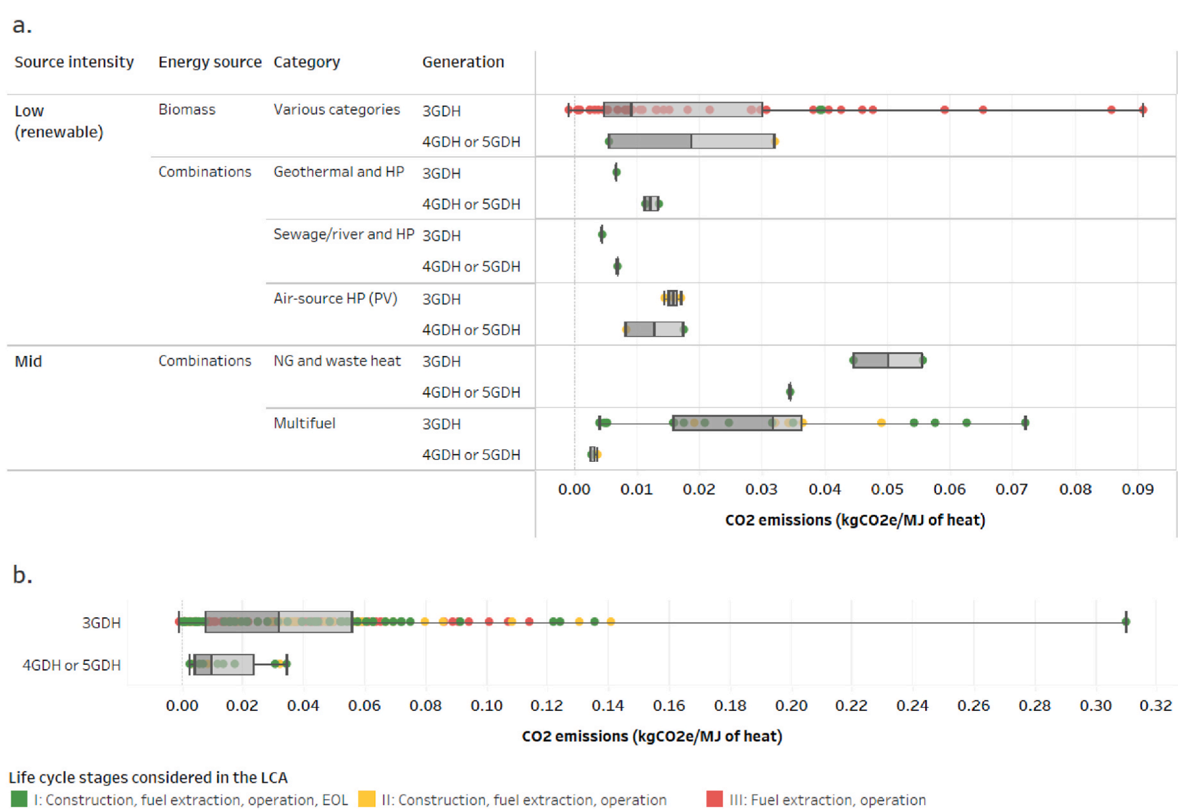

Fig. 6. (a) Comparison of the carbon footprint of third, fourth and fifth generation district heating networks for different energy sources and conversion technologies. (b) Average of the carbon footprint of aggregated third and fourth or fifth district heating networks.

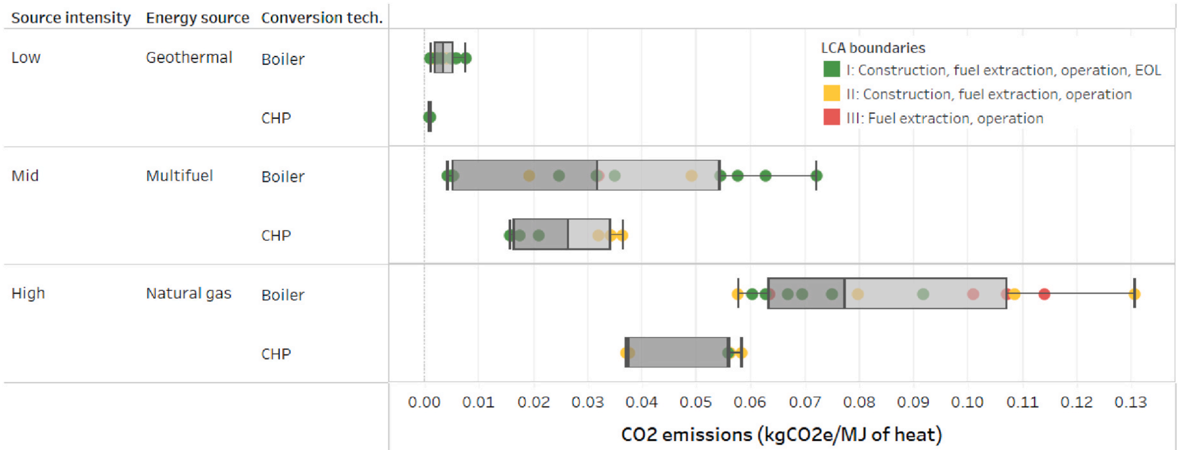

Fig. 7. Comparison of the CF of CHP systems and boilers for different energy sources.

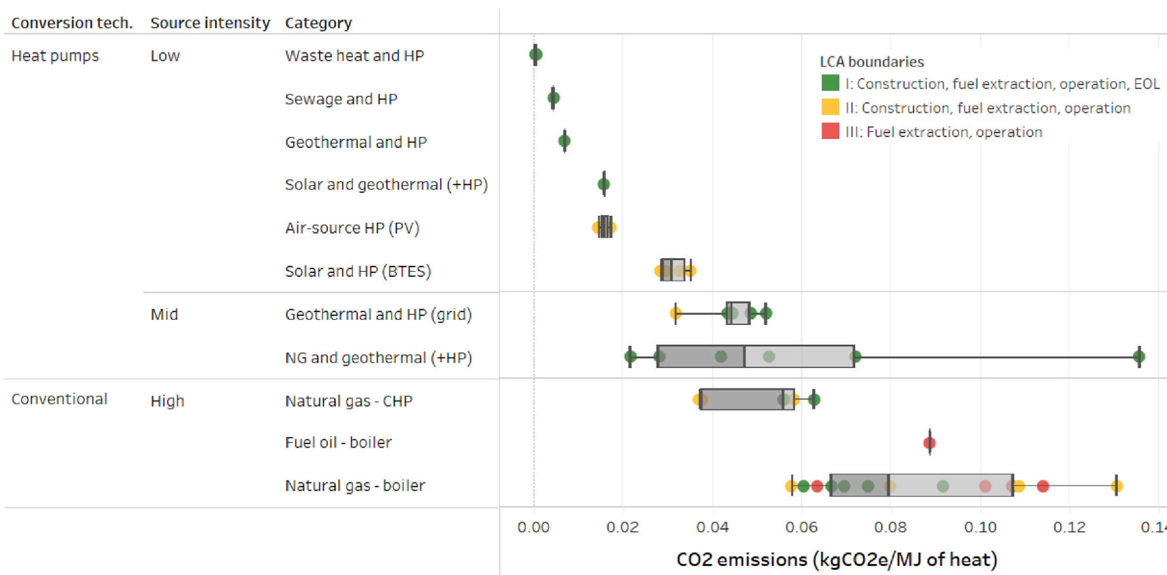

Fig. 8. Comparison of the CF of systems using heat pumps compared to gas-based boilers and CHP.

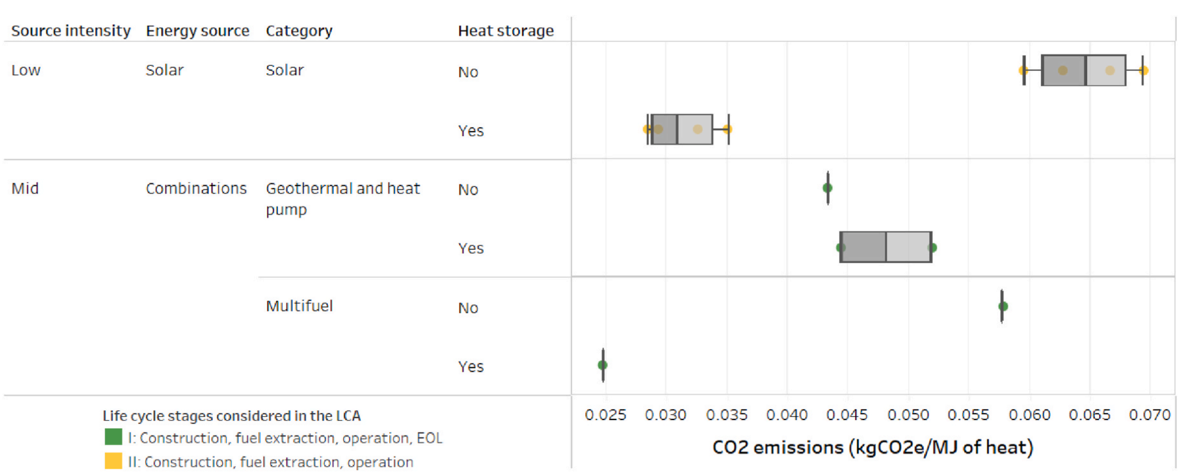

Fig. 9. Comparison of the CF of heat storage.

0.028–0.035 kg CO_2e/MJ. In multifuel systems, heat storage achieves nearly a 60 % reduction, lowering emissions from 0.058 to 0.025 kg CO_2e/MJ. However, for geothermal combined with heat pumps, only one LCA/CF study has evaluated heat storage [106], showing an increase in emissions. This increase is attributed in that study to the use of heat pumps with a lower coefficient of performance (COP). Further research is needed to validate these findings.

6.2.5. Subsidies

A single LCA/CF study, conducted by Welsch et al. [97], examined the impact of subsidies on emissions across various technology routes in district heating. The study assessed the environmental effects of different technologies, categorized by their carbon intensity, ranging from low-to high-carbon intensity (see Fig. 10). These technologies include solar thermal systems and its combination with heat pumps in the category of low-carbon intensity; combinations of gas, solar thermal and heat pumps, as well as multifuel systems in the category of mid-carbon intensity; and natural gas-based boiler and CHP in the category of high-carbon intensity. Overall, the study found that emissions are generally reduced across all categories when subsidies are implemented, except for gas-based boilers. On average, emission savings range from 2 % for the combination of natural gas-based CHP and heat pumps to 10 % for solar thermal energy. These findings suggest that subsidies have the potential to modestly reduce emissions in district heating systems, particularly when focused on renewable heat sources rather than fossil fuels.

7. Discussion

In this section the main results of this investigation are presented, followed by a discussion of the associated policy implications. Finally, the limitations of this research study are outlined, and recommendations for the future are made.

7.1. Discussion of the results

This paper follows a comprehensive approach to compare the carbon footprint of different strategies for decarbonizing district heating. LCA studies that assess the carbon footprint of different decarbonization strategies were evaluated. In total, 42 publications and 160 heating configurations were reviewed and discussed.

The CO_2 emissions reported in these studies were compared according to different criteria, including the intensity of the energy source, the type of conversion technology, the range of operating temperatures of the system (either 3GDH or 4GDH/5GDH) and LCA boundaries. Most LCA/CF studies focus on supply-side factors, particularly energy sources and conversion, with some attention to energy storage and temperature reduction. In contrast, demand-side and regulatory strategies, such as subsidies and energy storage, have been less explored. Areas not yet investigated include hydrogen, electric boilers, building renovations, CCS, etc. LCA/CF studies are compared according to their type of energy source, energy conversion technology, life cycle stages evaluated, and other characteristics.

Remarkably, results show that waste heat, geothermal alone, and in combination with heat pumps offer the lowest emissions. They are followed by other options such as combined solar and geothermal, air source heat pumps, and combinations of natural gas with biomass and solar. Biomass is characterized by having a large spread of emissions, with some options offering emissions as low as waste heat and geothermal, and others having emissions as high as those of gas boilers. Among the renewable heat sources, solar thermal is the option having the highest emissions, comparable also to those of gas boilers. For comparison, emissions of fossil fuel-based systems are also included. The highest emissions are for hard coal boilers, followed by fuel oil and natural gas boilers, and gas-based CHP systems.

Regarding the operating temperature of the system, it was found that 4GDH and 5GDH systems, which operate at lower temperatures, reduce thermal losses, enhance efficiency, and achieve an average emission reduction of 69 % compared to 3GDH.

Emissions were also compared according to the type of energy conversion technology. Results show that emissions of CHP systems are on average between 16 and 70 % lower than those of boilers, depending on the energy source (lowest for multifuel systems, highest for geothermal). Similarly, it was found that emissions of systems involving heat pumps are on average 64 % lower than those of gas boilers. The advantages of heat pumps are greater when they are combined with renewable energy sources and driven by renewable power. Heat storage was also found to reduce average emissions by 50–60 % in solar thermal and multifuel applications but was not particularly effective in reducing emissions in geothermal systems. Finally, it was also found that the implementation of subsidies leads to emissions reductions ranging between 2 and 10 % for different technologies, with the highest reduction associated with subsidies to renewable heat sources.

To consider the results from a different angle, the average emissions

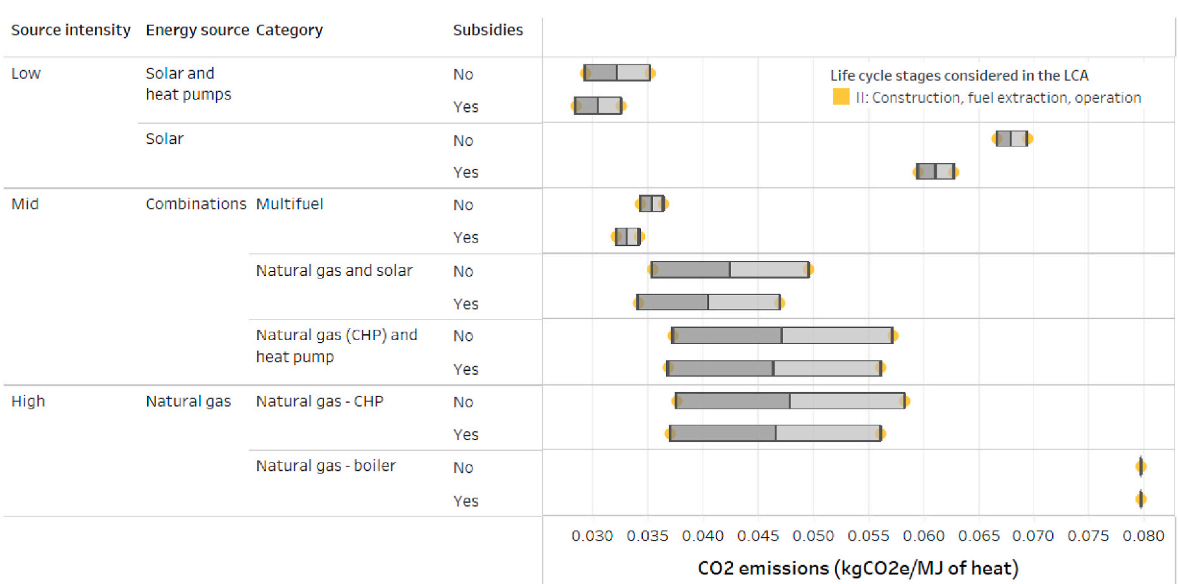

Fig. 10. Comparison of the CF associated with subsidies.

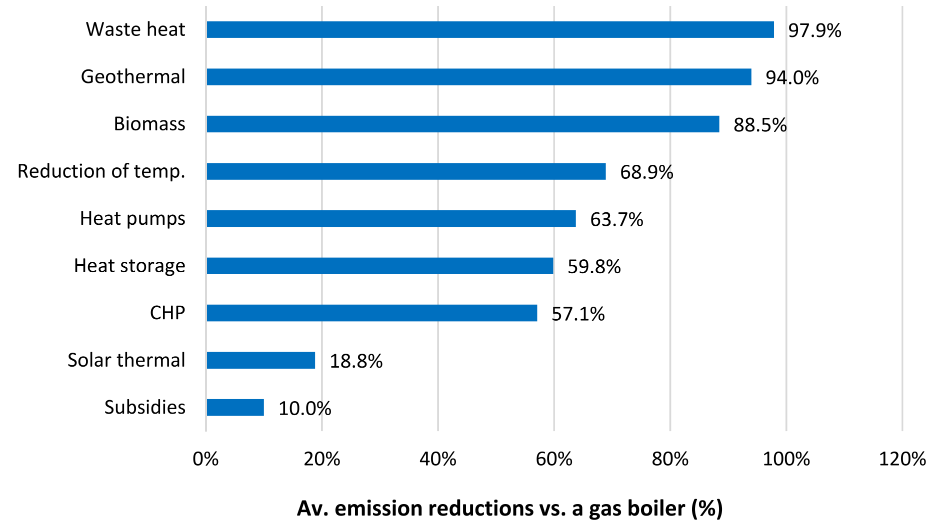

Fig. 11. Average emissions reduction compared to an average gas boiler for the different strategies.

reduction for the different strategies are compared against a gas boiler, see Fig. 11. A typical gas boiler is used for this comparison, as it is widely distributed and commonly used in different countries. This figure highlights various important insights. A first group of strategies, focused on the energy source, offer the highest potential for emissions reduction (90–100 %) compared to a gas boiler. These include waste heat, geothermal and biomass. It is worth noting that while biomass offers a significant average reduction, it has a large variation in carbon footprint, which is associated with the high number of feedstocks. A second group of strategies, focused on more efficient distribution, conversion and storage technologies, offer emissions reductions in the range of 55–70 % compared to a gas boiler. These strategies include reducing the operating temperatures of networks, using heat pumps, heat storage and CHP. These strategies are not mutually exclusive with the ones of the first group and combining them could result in added benefits. A third group of strategies offer a limited emissions reduction. This group includes solar thermal and subsidies, which could reduce emissions by 19 % and 10 % compared to a gas boiler, respectively. The importance of subsidies is highlighted and indicates that right policies could incentivize technology adoption, which leads to emissions reductions. The potential for reductions for solar thermal is limited and substantially lower than other renewable heat sources. This suggests that not all low-carbon intensity or renewable heat sources have the same carbon footprint, which should be considered when prioritizing policies, subsidies and incentives. Finally, there are various strategies, whose lifecycle emissions have not been investigated in the literature and that future research should address. These include electric boilers, building renovation, hydrogen, CCS, etc.

7.2. Policy implications

The findings of this study may provide insights to policymakers in the field of district heating at the country and EU levels. The policy implications include the following.

- Policies should prioritize support for technologies offering high potential for reducing emissions, for example waste heat, geothermal, biomass, reduction of operating temperatures (e.g., 4GDH/5GDH), heat pumps, heat storage and CHP. This could include funding in R&D, subsidizing implementation, and introducing or refining a policy framework that encourages its adoption.
- Not all renewable sources offer the same potential for emission reductions. For example, solar thermal offers lower emissions than a gas boiler, but its potential is very limited compared to the other options described above. Policymakers could prioritize incentives to renewable heat sources, based on their carbon footprint.
- Despite significant progress in LCA research on district heating, critical gaps remain in assessing the role of building renovation, and emerging technologies such as electric boilers, hydrogen, and CCS. The lack of integrated studies evaluating these factors limits our ability to quantify their full impact. For instance, improved building renovation would reduce heat demand, thereby affecting the relative emissions of different heating configurations shown in Figs. 6–9. More research is needed to integrate these aspects into LCA studies, ensuring a more comprehensive assessment of district heating decarbonization pathways.
- LCA/CF studies evaluating the impact of different decarbonization strategies should consider all life cycle stages involved in the district heating system, from construction, through fuel extraction and operation to EOL.
- The integration of the electricity and heating sectors highlighted in the paper should be strengthened by policy makers. This could improve the efficiency and resilience of the overall energy system.
- The variance in emissions across different technologies suggests the need for a differentiated policy approach that considers the specific characteristics and emissions profiles of each technology. For example, while biomass has a wide range of emissions outcomes, targeted R&D could optimize its use where it is most effective.

7.3. Limitations of this study and future recommendations

This study has various limitations worth noting. Various LCA/CF studies of district heating systems according to the energy source, conversion technology, and the considered LCA boundaries have been reviewed. The various ways LCA/CF studies are conducted pose a major challenge. They make it difficult to directly compare the results and may hide the potential environmental advantages of specific technologies or fuels. Due to heterogeneity in LCA methodologies and boundaries, not all results are comparable consistently. For example, two studies that consider the same energy source and conversion technology can lead to different results if they consider different life cycle stages. LCA boundaries should be kept in mind when considering the results presented here. To overcome these shortcomings, future research should: i) conduct more detailed LCA studies, including electric boilers, temperature reduction in the networks, building renovation, hydrogen, CCS, etc. and ii) develop standardized LCA methodologies and approaches utilizing databases, methodology frameworks, system boundaries, and software tools to improve comparability and reliability.

8. Conclusions

This paper analyzes and compares decarbonization strategies for district heating and their associated carbon footprint (CF). It reviews data from 42 Life Cycle Assessment (LCA) studies and 160 heating configurations. It evaluates district heating systems by analyzing energy sources, conversion technologies, operating temperatures (3GDH vs. 4GDH/5GDH), and other technical characteristics, as well as the life cycle stages considered in LCA/CF studies.

LCA/CF studies focus predominantly on supply-side factors, while demand-side and regulatory strategies are less explored. When analyzed according to the carbon intensity of the heat source, results show that waste heat and geothermal, used alone or with heat pumps, yield the lowest emissions among the different options. These are closely followed by combinations of solar and geothermal energy, air source heat pumps, and hybrid systems involving natural gas with biomass or solar. Biomass exhibits variable emissions, ranging from very low comparable to waste heat and geothermal, to as high as gas boilers. Of all renewable options, solar thermal (without heat storage) shows the highest emissions, similar to those of gas boilers. The analysis extends to fossil fuel systems, with hard coal boilers emitting the most, followed by fuel oil, natural gas boilers, and gas-based CHP.

When evaluated according to the operating temperature of the system, results show that 4GDH and 5GDH systems, which operate at lower temperatures, reduce thermal losses and increase efficiency, achieve an average emission reduction of 70 % compared to 3GDH. When analyzed according to the energy conversion technology, results show that CHP systems can significantly reduce emissions compared to traditional boilers. Reductions range from 16 % for multifuel systems to 35 % for natural gas systems and up to 70 % for geothermal systems. Heat pumps, especially when combined with renewable energies, cut emissions by an average of 64 % compared to gas boilers. Heat storage reduces emissions by 50–60 % in solar thermal and multifuel setups, though it's less effective with geothermal systems. Additionally, implementing subsidies for renewable heat technologies can decrease emissions by 2–10 %, underscoring the importance of supportive policy frameworks.

The paper revealed inconsistencies and gaps in previous LCA/CF studies. It is particularly noteworthy that there is a lack of research encompassing all types of heating systems and fuel sources. This study provides insights into the complexities involved in assessing environmental impacts, highlighting the crucial role played by the type of energy source, conversion technology, efficiency, and local factors. This reinforces the notion that there is no universally optimal solution, and optimal configurations depend on contextual factors like location and available renewable resources.

The findings of this investigation hold significance for district heating operators willing to decarbonize their systems, for technology providers aiming to plan future technology and product developments, and most importantly, to policymakers prioritizing measures, subsidies, and R&D funding. Various aspects require further in-depth investigation.

Future research should address several key areas to overcome current limitations in decarbonization strategies. This includes performing comprehensive LCAs of various less explored strategies and developing standardized LCA methodologies and approaches. These efforts are crucial for improving comparability and reliability of sustainable heating solutions.

Nomenclature

Acronyms	
1GDH	1st generation district heating
2GDH	2nd generation district heating
3GDH	3rd generation district heating
4GDH	4th generation district heating
5GDH	5th generation district heating
ASHP	Air source heat pump
ASI	Avoid-Shift-Improve
CF	Carbon footprint
CFB	Circulating Fluidized Bed
CHP	Combined heat and power
COP	Coefficient of performance
CSHPSS	Central solar heating plants with seasonal storage
DGH	Deep geothermal heating
DH	District heating
DHS	District heating system
DHWS	Domestic hot water
EGS	Enhanced Geothermal System
EOL	End of life
ETS	Emissions Trading Scheme
FU	Functional unit
GAHP	Absorption heat pump
GSHP	Ground source heat pump
GWHP	Ground water heat pump
GWP	Global warming potential
HOB	Heat only boiler
HP	Heat pump
IHR	Industrial Heat Recovery
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Live cycle impact assessment
LNG	Liquified natural gas
LTDH	Low temperature district heating
MSW	Municipal solid waste
NG	Natural gas
ORC	Organic Rankine Cycle
PV	Solar photovoltaics
RES	Renewable energy sources
SDH	Solar district heating
SHS	Seasonal heat storage
STC	Solar thermal collectors
TES	Thermal energy storage
TRL	Technology readiness level
WH	Waste Heat
WHP	Waste Heat-Fed Heat Pump
WSHP	Water source heat pump
WtE	Waste-to-Energy

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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Appendix

Table 1
Comparison of the different LCA studies for district heating systems.

Author	Year	LCA-Boundaries	Heating Technology (Equipment/Process)	Fuel Type	GHG-Emissions kg CO_2e/MJ	Reference
Bartolozzi et al.	2017	I	Individual GSHP and GSHP-DHS, Individual GB and Boiler-DHS	Geothermal, NG and Biomass (Woodchip)	0.03936 - 0.07314	[119]
Björsson et al.	2021	III	CHP - CFB (Bio-Boiler)	Biomass (Sawdust, Logging Residues, Bark, mixed wood fuels)	0.00044 - 0.00800	[99]
Bonamente & Aquino	2017	I	GSHP with TES and HE	Geothermal and Electricity for HE and GSHP (grid)	0.04333 - 0.05194	[120]
Brattebø & Reenaas	2012	I	Boiler (Mass-burn waste incineration with heat recovery)	MSW and other energy sources (NG, Light fuel oil, Propane, Butane, Biomass, Electricity, Biofuel, WH, Landfill gas) for back-up and peak load demand.	0.00032 - 0.00052	[101]
Diaz et al.	2020	II	Low-temperature Boiler	Biomass	0.03205	[121]
Douziech et al.	2021	I	EGS with HE, Conventional Heating methods	Geothermal, NG	0.0694 - 0.00106	[96]
Famiglietti et al.	2021	I	3GDH (Boilers, CHP, WtE, IHR), 4GDH (STC, GWHP using R134a Gas, 3GDH as backup)	NG, WH, MSW, Solar, Geothermal and Electricity (grid)	0.02256 - 0.05778	[122]
Formhals et al.	2021	I	STC, BTES-HP, CHP-Boiler	Solar, Geothermal, NG	0.01572 - 0.05244	[114]
Ghafghazi et al.	2011	I	Boilers (GB and Bio-Boiler), Sewer WH and Geothermal HP	NG and Biomass (Pellets), WH (Sewer), Geothermal and Electricity (grid)	0.00439 - 0.0667	[102]
Gjoka et al.	2024	I	5GDH (PV, ASHP, WSHP, GSHP, TES, BES)	ASHP, waste heat, solar, geothermal	0.006995 - 0.01752	[61]
Gkousis et al.	2022	I	DGH-Plant	Geothermal	0.01918 - 0.07443	[94]
Greening & Azapagic	2012	I	ASHP, GSHP, WSHP, GB	Geothermal and Electricity (grid), NG	0.05250 - 0.08167	[123]
Guillén-Lambea et al.	2021	II	GB, Reversible HP, TES, PV Panels	NG, Electricity (grid), Paraffin and SAT for TES, Solar	0.01449 - 0.10855	[103]
Harter et al.	2023	I	DHS, HP	Mix of Renewables, Non-Renewable and Fossil Sources	0.05427 - 0.06268	[110]
Jeandaux et al.	2021	I	DHS-CHP, Boilers, ASHP and WSHP	NG, Geothermal, Biomass, WH, Electricity	0.00667 - 0.08361	[108]
Karlsdottir et al.	2014	II	HE	Geothermal	0.00161	[124]
Karlsson et al.	2018	III	CHP	MSW, bio-oil, light fuel oil, Woody biomass, slaughterhouse-waste-derived product, and peat	0.03194	[95]
Kimming et al.	2015	III	GB, Bio-Boiler	NG, Biomass (Forest residues, Salix, Pellets, and Straw)	−0.00100 - 0.11377	[98]
Kotagodahetti et al.	2022	I	Liquefaction - GB	NG (from Canada) converted to LNG compared to coal	0.12200 - 0.31000	[117]
Lausselet et al.	2016	III	WtE Plant (Boiler)	Various waste compositions, such as car fluff, clinical waste, and wood waste.	0.02500 - 0.06100	[104]
Livingstone et al.	2022	III	Boiler	Biomass (Willow chip) and Fuel oil	0.00260 - 0.08870	[100]
Mahon et al.	2022	II	WHP-DH, Biomass CHP DHS, Individual GB	WH, Biomass (Woodchips), NG and Electricity (grid)	0.01918 - 0.07444	[111]
Maione et al.	2022	I	HE, HP and PV, GB,	Geothermal, Electricity (grid and PV), NG and Biogas	0.00479 - 0.23713	[107]
Martin et al.	2024	I	4GDH, 5GDH	Multifuel, various renewable and non-renewable	0.00162 - 0.00276	[125]
McCay et al.	2019	II	DGH-Plant	Geothermal	0.003.88	[126]
Murphy et al.	2024	I	5GDH	WSHP, GB, Electricity, Waste heat	0.03031 - 0.03444	[127]
Neirotti et al.	2022	II	CHP with HE, GB	NG-DH, NG-Individual GB	0.07500 - 0.13056	[128]
Nie et al.	2020	II	Heat Plant (GB)	Canadian-sourced LNG	0.08552	[116]
Nitkiewicz & Sekret	2014	II	HP, GAHP, GB	Geothermal and Electricity (grid), NG	0.03178 - 0.05769	[105]
Olsson	2021	I	LTDH-Network - CHP	Biomass (Wood residues) and Biofuels	0.00568	[129]
Ómarsson	202	II	HE	WH and Electricity (grid)	0.00120 - 0.00170	[92]
Pa et al.	2011	III	Gasifier, GB	Biomass (Pellets), NG	0.00889 - 0.05749	[130]
Pieratti et al.	2020	III	Biomass-based heating plants (Bio-Boiler)	Biomass (Woodchips)	0.00531 - 0.09090	[131]
Pratiwi & Trutnevyte	2021	I	Connected decentralized HPs, DH and cooling with a HP, DH and cooling without a HP	Geothermal heating based on the depth of geothermal wells (shallow to medium depth)	0.00272 - 0.00525	[112]
Pratiwi et al.	2018	I	EGS with HE	Geothermal	0.0009922 - 0.00222	[93]
Raluy et al.	2014	I	STC, SHS + HE + HP, GB	Solar, Electricity (grid), NG	0.3487	[132]

(*continued on next page*)

Table 1 (*continued*)

Author	Year	LCA-Boundaries	Heating Technology (Equipment/ Process)	Fuel Type	GHG-Emissions kg CO_2e/MJ	Reference
Raluy et al.	2021	I	CSHPSS (STC, SHS assisted by HP, DHWS, HE, GB)	Solar, NG, Electricity (grid)	0.03167	[133]
Rehl & Müller	2013	III	CHP, Boiler	NG and mix of other fuels (fossil source)	0.06968 - 0.09492	[118]
Wang et al.	2020	III	Gasifier (Anaerobic digestion gasification for district heating)	Biomass (Crop residues, Wood waste, Wood residues, Wood logs)	0.00396 - 0.01046	[116]
Wang et al.	2021	III	CHP, Bio-Boiler	NG, Biomass (Forestry waste materials)	0.00916 - 0.06340	[115]
Welsch et al.	2018	II	CHP, GB, BTES assisted by HPs, STC	NG, Electricity (from the system and grid), Solar	0.02933 - 0.07972	[109]
Wirtz et al.	2020	II	5GDH	ASHP, PV, Electric GB, NG CHP	0.00367 - 0.00831	[134]
Wu	2021	I	SDH with BTES, Boiler	Solar, Electricity for HP (grid - fossil sources), Diesel	0.07206 - 0.09290	[113]

Data availability

Data will be made available on request.

References

[1] IPCC. Working group III contribution to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York: Cambridge University Press; 2022.

[2] European Commission. European climate law [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119. [Accessed 1 March 2024].

[3] Pathak M, Slade R, Shukla P, Skea J, Pichs-Madruga R, Ürge-Vorsatz D. Technical summary. In: Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022.

[4] Kavvadias K, Jimenez Navarro J, Thomassen G. Decarbonising the EU heating sector: integration of the power and heating sector [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC114758; 2019.

[5] Gaballo F, Nielsen P, Khan BS, Heller A. „The role of district heating in the future European energy system. In: IEEE international conference on power and energy; 2022. p. 420–5.

[6] Connolly D, Mathiesen B, Østergaard P, Möller B, Nielsen S, Lund H, Trier D, Persson U, Nilsson D, Werner S. Heat roadmap Europe 2050 study for the EU27. Strategic research centre for the 4th generation district heating. 2012.

[7] Ortner S, Pehnt M. M. Over und S. Blömer, „Dekarbonisierung von Energieinfrastrukturen: Ein politischer Unterstutzungsrahmen fur das Beispiel Warmenetze. Berlin: Umweltbundesamt; 2023.

[8] Nielsen S, Möller B. „Excess heat production of future net zero energy buildings within district heating areas in Denmark. Energy, Bd 2012;48(1):23–31.

[9] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76.

[10] Krikser T, Profeta A, Grimm S, Huther H. Willingness-to-pay for district heating from renewables of private households in Germany. Sustainability 2020;12(10).

[11] Jodeiri AM, Goldsworthy MJ, Buffa S, Cozzini M. Role of sustainable heat sources in transition towards fourth generation district heating–A review. Renew Sustain Energy Rev 2022;158:112156.

[12] European Commission. ENER/C1/2018-494 – renewable space heating under the revised renewable energy directive. Brussels: European Commission; 2022.

[13] Fallahnejad M, Kranzl L, Haas R, Hummel M, Müller A, Sánchez García L, Persson U. District heating potential in the EU-27: evaluating the impacts of the heat demand reduction and market share growth. Appl Energy 2024:122154.

[14] AGFW. AGFW hauptbericht (main report) [Online]. Available: https://www.agfw.de/zahlen-und-statistiken/agfw-hauptbericht; 2021.

[15] Triebs M, Papadis E, Cramer H, Tsatsaronis G. Landscape of district heating systems in Germany - status quo and categorization. Energy Convers Manag X 2021;9.

[16] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen J, Hvelplund F, Mathiesen B. 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11.

[17] Colmenar-Santos A, Rosales-Asensio E, Borge-Diez D, Blanes-Peiró J. „District heating and cogeneration in the EU-28: current situation, potential and proposed energy strategy for its generalisation. Renew Sustain Energy Rev, Bd 2016;62:621–39.

[18] Guelpa E, Capone M, Sciacovelli A, Vasset N, Baviere R, Verda V. Reduction of supply temperature in existing district heating: a review of strategies and implementations. Energy 2022:125363.

[19] Kontu K, Rinne S, Junnila S. Introducing modern heat pumps to existing district heating systems–Global lessons from viable decarbonizing of district heating in Finland. Energy 2019;166:862–70.

[20] Pakere I, Feofilovs M, Lepiksaar K, Vitolins V, Blumberga D. Multi-source district heating system full decarbonization strategies: technical, economic, and environmental assessment. Energy 2023;285:129296.

[21] Auvinen K, Meriläinen T, Saikku L, Hyysalo S, Juntunen J. Accelerating transition toward district heating-system decarbonization by policy co-design with key investors: opportunities and challenges. Sustain Sci Pract Pol 2023;19(1).

[22] Divkovic D, Knorr L, Meschede H. Design approach to extend and decarbonise existing district heating systems-case study for German cities. Int J Sustain Energy Plann Manag 2023;38:141–56.

[23] Thomassen G, Kavvadias K, Jimenez Navarro J. The decarbonisation of the EU heating sector through electrification: a parametric analysis. Energy Policy 2021;148.

[24] Monzani C, Abdin G, Poggio A. The role of the Emission Trading Scheme in the decarbonization of existing district heating systems. Energy Sources B Energy Econ Plann 2024;19(1).

[25] Lerbinger A, Petkov I, Mavromatidis G, Knoeri C. Optimal decarbonization strategies for existing districts considering energy systems and retrofits. Appl Energy 2023;352:121863.

[26] Popovski E, Ragwitz M, Brugger H. Decarbonization of district heating and deep retrofits of buildings as competing or synergetic strategies. Smart Energy 2023;10.

[27] Gonzalez-Salazar M, Langrock T, Koch C, Spieß J, Noack A, Witt M, Ritzau M, Michels A. Evaluation of energy transition pathways to phase out coal for district heating in Berlin. Energies 2020;13(23).

[28] Gonzalez-Salazar M, Klossek J, Dubucq P, Punde T. Portfolio optimization in district heating: merit order or mixed integer linear programming? Energy 2023;265:126277.

[29] Brown A, Foley A, Laverty D, McLoone S, Keatly P. Heating and cooling networks: a comprehensive review of modelling approaches to map future directions. Energy, Vols. 2022;261(Part B):125060.

[30] Sporleder M, Rath M, Ragwitz M. Design optimization of district heating systems: a review. Front Energy Res 2022;10.

[31] Horak D, Hainoun G, Neugebauer und G, Stoeglehner G. A review of spatio-temporal urban energy system modeling for urban decarbonization strategy formulation. Renew Sustain Energy Rev 2022;Bd. 162(Nr):112426.

[32] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen J, Hvelplund und F, Mathiesen B. „4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. Energy, Bd 2014;68:1–11.

[33] European Commission. District heating and cooling in the European Union. Overview of district heating and cooling markets and regulatory frameworks under the revised Renewable Energy Directive. Brussels: European Commission; 2022.

[34] Malcher und X, Gonzalez-Salazar M. Strategies for decarbonizing European district heating: evaluation of their effectiveness in Sweden, France, Germany, and Poland. Energy, Bd 2024;304.

[35] Ürge-Vorsatz D, Cabeza L, Serrano S, Barreneche und C, Petrichenko K. „Heating and cooling energy trends and drivers in buildings. Renew Sustain Energy Rev, Bd 2015;41:85–98.

[36] Ommen T, Markussen und W, Elmegaard B. „Lowering district heating temperatures - impact to system performance in current and future Danish energy scenarios. Energy, Bd 2016;94:273–91.

[37] EU. „EU energy balances. European Union; 2023. https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html [Zugriff am 2024].

[38] Gao T, Liu Q, Wang J. A comparative study of carbon footprint and assessment standards. Int J Low Carbon Technol 2014;9:237–43.

[39] Prawiti AS, Trutnevyte E. Review of life cycle assessments of geothermal heating systems. In: World geothermal congress 2020. Reykjavik; 2020.

[40] Wang H, Zheng Y, He S, Yan J, Zeng X, Li S, Tian Z, Lei L, Chen Y, Deng S. Can bioenergy with carbon capture and storage deliver negative emissions? A critical review of life cycle assessment. Journal of Clearner Production 2024;434:139839.
[41] Moutik B, Summerscales J, Graham-Jones J, Pemberton R. Life cycle assessment research trends and implications: a bibliometric analysis. Sustainability 2023;15 (18).
[42] García-Céspedes J, Herms I, Arnó G, de Felipe JJ. Fifth-generation district heating and cooling networks based on shallow geothermal energy: a review and possible solutions for mediterranean Europe. Energies 2023;16(1):147.
[43] Mäki E, Kannari L, Hannula I, Shemeikka J. „Decarbonization of a district heating system with a combination of solar heat and bioenergy: a techno-economic case study in the Northern European context. Renewable Energy, Bd 2021;175: 1174–99.
[44] Pitz-Paal R, Krüger J, Hinsch J, Lokurlu A, Scheuerer und M, Schlecht M. „Decarbonizing the German industrial thermal energy use with solar, hydrogen, and other options–Recommendations for the world, 3. Solar Compass, Nr.; 2022, 100029.
[45] Leurent M, Jasserand F, Locatelli G, Palm J, Rämä und M, Trianni A. „Driving forces and obstacles to nuclear cogeneration in Europe: lessons learnt from Finland. Energy Policy, Bd 2017;107:138–50.
[46] McKenna R, Merkel und E, Fichtner W. „Energy autonomy in residential buildings: a techno-economic model-based analysis of the scale effects. Applied Energy, Bd 2017;189:800–15.
[47] Averfalk und H, Werner S. „Economic benefits of fourth generation district heating. Energy, Bd 2020;193:116727. Nr.
[48] Patureau R, Tran CT, Gavan V, Stabat P. „The new generation of District heating & cooling networks and their potential development in France,“ Bd. 2021. p. 236.
[49] Feijoo F, Pfeifer A, Herc L, Groppi und D, Duić N. A long-term capacity investment and operational energy planning model with power-to-X and flexibility technologies. Renew Sustain Energy Rev 2022;Nr. 112781:167.
[50] Boldrini A, Navarro J, Crijns-Graus WHJ, van den Broek MA. „The role of district heating systems to provide balancing services in the European Union. Renew Sustain Energy Rev, Bd 2022:111853. 154.
[51] Kim MH, Kim D, Heo J, Lee DW. Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. Energy, Bd 2019;187(Nr):115916.
[52] Abokersh M, Gangwar S, Spiekman M, Valles M, Jiménez L, Boer D. „Sustainability insights on emerging solar district heating technologies to boost the nearly zero energy building concept. Renew Energy, Bd 2021;180:893–913.
[53] Heinisch V, Göransson L, Erlandsson R, Hodel H, Johnsson und F, Odenberger M. Smart electric vehicle charging strategies for sectoral coupling in a city energy system. Appl Energy 2021;Bd. 288.
[54] Pans Castillo MA, Claudio G, Eames P. „Theoretical cost and energy optimisation of a 4th generation net-zero district heating system with different thermal energy storage technologie. 2023, 4423578. Nr.
[55] Winterscheid C, Dalenbäck J, Holler S. „Integration of solar thermal systems in existing district heating systems. Energy, Bd 2017;137:579–85.
[56] van de Ven D, Capellan-Perez I, Arto I, Cazcarro I, de Castro C, Patel P, Gonzalez-Eguino M. „The potential land requirements and related land use change emissions of solar energy. Sci Rep, Bd 2021;11:2907.
[57] Garay-Martinez R, Meir M. „Decarbonization of district heating. Waste heat streams and solar district heating. S. I. Publishing, Hrsg.; 2022. p. 13–32.
[58] Famiglietti J, Gerevini L, Spirito G, Pozzi M, Dénarié A, Scoccia R, Motta M. „Environmental Life Cycle Assessment scenarios for a district heating network. An Italian case study. Energy Reports, Bd 2021;7:368–79.
[59] Pozzi M, Spirito G, Fattori F, Dénarié A, Famiglietti J, Motta M. „Synergies between buildings retrofit and district heating. The role of DH in a decarbonized scenario for the city of Milano. Energy Rep, Bd 2021;7:449–57.
[60] Monie SW, Åberg M. „Power balancing capacity and biomass demand from flexible district heating production to balance variable renewable power generation. Smart Energy, Bd 2021;4(Nr):100051.
[61] Gjoka K, Crawford R, Rismanchi B. A comparative life cycle assessment of fifth-generation district heating and cooling systems. Energy Build, Bd 2024;323: 114776. Nr.
[62] Van Oevelen T, Neven T, Brès A, Schmidt RR, Vanhoudt D. „Testing and evaluation of a smart controller for reducing peak loads and return temperatures in district heating networks. Smart Energy 2023:100105. Nr.
[63] Aymar F. „Decarbonization in district heating sector: strategies to reduce environmental impact with cost-effective solutions,“ Politecnico di Torino. 2022.
[64] Schweiger G, Kuttin F, Posch A. „District heating systems: an analysis of strengths, weaknesses, opportunities, and threats of the 4GDH. Energies 2019;Bd. 12. Nr. 24.
[65] Lund H, Østergaard PA, Nielsen TB, Werner S, Thorsen JE, Gudmundsson O. „Perspectives on fourth and fifth generation district heating. Energy 2021;Bd. 227:120520. Nr.
[66] Bartolozzi I, Rizzi F, Frey M. „Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy. Renew Sustain Energy Rev, Bd 2017;80:408–20.
[67] Siddique MB, Nielsen PS, Rosendal MB, Jensen IG, Keles D. Impacts of earlier natural gas phase-out & heat-saving policies on district heating and the energy system. Energy Policy 2023;174:113441.
[68] Fritz M, Savin M, Aydemir A. „Usage of excess heat for district heating-Analysis of enabling factors and barriers. J Clean Prod 2022;Bd. 363(Nr):132370.
[69] Schmitt S, Zeh R, Stockinger V. „Quantification of heat losses and gains of 5th generation district heating and cooling networks compared to conventional heating networks. 2022. p. 337–43.
[70] Buffa S, Cozzini M, D'antoni M, Baratieri M, Fedrizzi R. „5th generation district heating and cooling systems: a review of existing cases in Europe. Renew Sustain Energy Rev, Bd 2019;104:504–22.
[71] Volkova A, Pakere I, Murauskaite L, Huang P, Lepiksaar K, Zhang X. „5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems. Energy Reports, Bd 2022;8: 10037–47.
[72] BAFA. „Liste der Wärmepumpen mit Prüf-/Effizienznachweis. Bundesamt für Wirtschaft und Ausfuhrkontrolle. 2020.
[73] Siddiqui S, Macadam J, Barrett M. „The operation of district heating with heat pumps and thermal energy storage in a zero-emission scenario. Energy Reports, Bd 2021;7:176–83.
[74] Zwickl-Bernhard S, Huppmann D, Golab A, Auer H. „Disclosing the heat density of district heating in Austria in 2050 under the remaining European CO2 budget of the 1.5° C climate target. Sustainable Energy, Grids and Networks 2022;Bd (31).
[75] Jadwiszczak P. „Heat pumps as a way to Low or Zero Emission district heating systems. In: E3S web of conferences, bd. 17, nr. EDP Sciences; 2017. p. 32.
[76] Toleikyte A, Roca Reina J, Volt J, Carlsson J, Lyons L, Gasparella A, Koolen D, De Felice M, Tarvydas D, Czako V, Koukoufikis G, Koukkanen A, Letout S. The heat pump wave: Opportunities and challenges (JRC134045). Luxembourg: Publications Office of the European Union; 2023.
[77] Javanshir N, Syri S, Teräsvirta A, Olkkonen V. „Abandoning peat in a city district heat system with wind power, heat pumps, and heat storage. Energy Reports, Bd. 2022;8:3051–62.
[78] Ochs F, Magni M, Dermentzis G. „Heat pumps and renewables in district heating–evaluation of central and decentral approaches. In: CLIMA 2022 conference; 2022.
[79] Ochs F, Magni M, Dermentzis G. „Integration of heat pumps in buildings and district heating systems—evaluation on a building and energy system level. Energies 2022;Bd. 15(11). Nr. 3889.
[80] Beiron J, Normann F, Johnsson F. A techno-economic assessment of CO2 capture in biomass and waste-fired combined heat and power plants–A Swedish case study. Int J Greenh Gas Control 2022;Bd. 118(Nr):103684.
[81] Chalendar JD, Glynn PW, Stagner J, Benson SM. „Decarbonization of campus energy systems and optimization of grid-friendly electrified district heating and cooling with thermal storage. CIGRE US national committee 2017 grid of the future symposium. 2017.
[82] Morvaj B, Evins R, Carmeliet J. Decarbonizing the electricity grid: the impact on urban energy systems, distribution grids and district heating potential. Applied Energy, Bd 2017;191:125–40.
[83] Su Y, Hiltunen P, Syri S, Khatiwada D. Decarbonization strategies of Helsinki metropolitan area district heat companies. Renew Sustain Energy Rev, Nr 2022: 112274. 160.
[84] Umwelthilfe Deutsche. Promoting renewable district heating. Seven policy recommendations,“ deutsche umwelthilfe. 2021.
[85] Sorknæs P, Østergaard PA, Thellufsen JZ, Lund H, Nielsen S, Djørup S, Sperling K. „The benefits of 4th generation district heating in a 100% renewable energy system. Energy 2020;Bd. 213. Nr. 119030.
[86] Sulzer M, Werner S, Mennel und S, Wetter M. „Vocabulary for the fourth generation of district heating and cooling. Smart Energy 2021;Bd. 1(Nr):100003.
[87] Cunha JM, Faria AS, Soares T, Mourão Z, Nereu J. „Decarbonization potential of integrating industrial excess heat in a district heating network: the Portuguese case. Cleaner Energy Syst, Bd. 1, Nr. 2022:100005.
[88] Thiel GP, Stark AK. „To decarbonize industry, we must decarbonize heat. Joule, Bd 2021;5(3):531–50.
[89] Innovativ Bayern. Hybrid storage officially in operation in Bremen. https://www.bayern-innovativ.de/en/page/hybrid-storage-officially-in-operation-in-bremen; 2019 [Zugriff am 06 01 2024].
[90] Aste N, Caputo P, Del Pero C, Ferla G, Huerto-Cardenas H, Leonforte F, Miglioli A. A renewable energy scenario for a new low carbon settlement in northern Italy: biomass district heating coupled with heat pump and solar photovoltaic system. Energy, Nr. 2020:118091. 206.
[91] Pieper H, Kirs T, Krupenski I, Ledvanov A, Lepiksaar K, Volkova A. „Efficient use of heat from CHP distributed by district heating system in district cooling networks. Energy Reports, Bd 2021;7:47–54.
[92] Ómasson ÓS. Life cycle assessment of a district heating system that utilizes waste heat recovery from alcoa aluminum production. Reykjavik; 2022.
[93] Pratiwi AS, Ravier G, Genter A. Life-cycle climate-change impact assessment of enhanced geothermal system plants in the Upper Rhine Valley. Geothermics 2018;75:26–39.
[94] Gkousis S, Harcouët-Menou V, Damen L, Welkenhuysen K, Laenen B, Compernolle T. Life cycle assessment of geothermal plants targeting the lower carboniferous limestone reservoir in northern Belgium. J Clean Prod 2022;376: 134142.
[95] Karlsson J, Brunzell L, Venkatesh G. Material-flow analysis, energy analysis, and partial environmental-LCA of a district-heating combined heat and power plant in Sweden. Energy 2018;144:31–40.
[96] Douziech M, Tosti L, Ferrara Nicola, Parisi M, Pérez-López P, Ravier G. Applying harmonised geothermal life cycle assessment guidelines to the rittershoffen geothermal heat plant. Energies 2021;14(13):3820.
[97] Welsch B, Göllner-Völker L, Schulte D, Bär K, Sass I. „Environmental and economic assessment of borehole thermal energy storage in district heating systems. Applied Energy, Bd 2018;216:73–90.

[98] Kimming M, Sundberg C, Nordberg Å, Hansson P. Vertical integration of local fuel producers into rural district heating systems – climate impact and production costs. Energy Policy 2015;78:51–61.
[99] Björnsson L, Pettersson M, Börjesson P, Ottosson P, Gustavsson C. Integrating bio-oil production from wood fuels to an existing heat and power plant - evaluation of energy and greenhouse gas performance in a Swedish case study. Sustain Energy Technol Assessments 2021;48:101648.
[100] Livingstone D, Smyth B, Lyons Gary A, Foley A, Murray ST, Johnston C. Life cycle assessment of a short-rotation coppice willow riparian buffer strip for farm nutrient mitigation and renewable energy production. Renew Sustain Energy Rev 2022;158:112154.
[101] Brattebø H, Reenaas M. Comparing CO2 and NOX emissions from a district heating system with mass-burn waste incineration versus likely alternative solutions – city of Trondheim, 1986–2009. Resources 2012;60:147–58.
[102] Ghafghazi S, Sowlati T, Sokhansanj S, et al. Life cycle assessment of base–load heat sources for district heating system options. Int J Life Cycle Assess. Int J Life Cycle Assess 2011;16:212–23.
[103] Guillén-Lambea S, Carvalho M, Delgado M. Sustainable enhancement of district heating and cooling configurations by combining thermal energy storage and life cycle assessment. Clean Technol Environ Policy 2021;23:857–67.
[104] Lausselet C, Cherubini F, del Alamo Serrano Gonzalo, Becidan M, Strømman A. Life-cycle assessment of a Waste-to-Energy plant in central Norway: current situation and effects of changes in waste fraction composition. Waste Manag 2016;58:191–201.
[105] Nitkiewicz A, Sekret R. Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. Energy Convers Manag 2014;87:647–52.
[106] Bonamente E, Aquino A. Life-cycle assessment of an innovative ground-source heat pump system with upstream thermal storage. Energies 2017;10(11):1854.
[107] Santagata R, Maione A, Massarotti N, Vanoli L. Environmental assessment of a heating, cooling and electric energy grid from a geothermal source in Southern Italy. J Clean Prod 2022;375:134198.
[108] Jeandaux C, Videau J-B, Prieur-Vernat A. Life cycle assessment of district heating systems in Europe: case study and recommendations. Sustainability 2021;13(20):11256.
[109] Welsch B, Göllner-Völker L, Schulte D, Bär K, Sass I, Schebek L. Environmental and economic assessment of borehole thermal energy storage in district heating systems. Appl Energy 2018;216:73–90.
[110] Harter H, Willenborg B, Lang W, Kolbe TH. Climate-neutral municipal building stock - life cycle assessment of large residential building stocks based on semantic 3D city models. Energy Build 2023;292:113141.
[111] Mahon C, Mediboyina MK, Gartland D, et al. Life cycle assessment of Irish district heating systems: a comparison of waste heat pump, biomass-based and conventional gas boiler. Clean Technol Environ Policy 2022;24:1437–51.
[112] Pratiwi AS, Trutnevyte E. Life cycle assessment of shallow to medium-depth geothermal heating and cooling networks in the State of Geneva. Geothermics 2021;90:101988.
[113] Wu X. *Life cycle assessment of solar district heating with borehole thermal energy storage in Nunavik; Doktorarbeit.,* Montreal: Diss. Concordia University; 2021., 2021.
[114] Formhals J, Feike F, Hemmatabady H, Welsch B. Strategies for a transition towards a solar district heating grid with integrated seasonal geothermal energy storage. Energy 2021;228:120662.
[115] Wang H, Bi X, Clift R. Utilization of forestry waste materials in British Columbia: options and strategies. Renew Sustain Energy Rev 2021;150:111480.
[116] Nie Y, Zhang S, Liu RE, Roda-Stuart D, Ravikumar AP, Bradley A, Masnadi MS, Brandt AR, Bergerson JA, Bi XT. Greenhouse-gas emissions of Canadian liquefied natural gas for use in China: comparison and synthesis of three independent life cycle assessments. J Clean Prod 2020;258:120701.
[117] Kotagodahetti R, Hewage K, Karunathilake H, Prabatha T, Krishnan H, Kasumu AS, Bryant T, Sadiq R. Liquefied natural gas exports from Canada to China: an analysis of internationally transferred mitigation outcomes (ITMO). J Clean Prod 2022;347:1311291.
[118] Rehl JMT. CO2 abatement costs of greenhouse gas (GHG) mitigation by different biogas conversion pathways. J Environ Manag 2013;114:13–25.
[119] Bartolozzi I, Rizzi F, Frey M. Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy. Renew Sustain Energy Rev 2017;80:408–20.
[120] Bonamente E, Aquino A. Life-cycle assessment of an innovative ground-source heat pump system with upstream thermal storage. Energies 2017;10:1854.
[121] Diaz F, Pakere I, Romagnoli F. Life cycle assessment of low temperature heating system in Gulbene Rgion. Environ Clim Technol, Bd. 2020;24(2):285–99. Nr.
[122] Famiglietti J, Gerevini L, Spirito G, Pozzi M, Dénarié A. Environmental Life Cycle Assessment scenarios for a district heating network. An Italian case study. Energy Rep 2021;7(4):368–79.
[123] Greening B, Azapagic A. Domestic heat pumps: life cycle environmental impacts and potential implications for the UK. Energy 2012;39(1):205–2017.
[124] Karlsdottir MR, Lew JB, Palsson HP, Palsson OP. Geothermal district heating system in Iceland: a life cycle. In: The 14th international symposium on district heating and cooling, Stockholm, Sweden; 2014.
[125] Martin N, Thellufsen J, Chang M, Talens-Peiró L, Madrid-López C. „The many faces of heating transitions. Deeper understanding of future systems in Sweden and beyond. Energy, Bd 2024;290:130264.
[126] McCay AT, Feliks MEJ, Roberts JJ. Life cycle assessment of the carbon intensity of deep geothermal heat systems: a case study from Scotland. Sci Total Environ 2019;685:208–19.
[127] Murphy M, Allen A, Henze G, Long N. „Optimal environmental and economic performance trade-offs for fifth generation district heating and cooling network topologies with waste heat recovery. Energy Conv Manag, Bd 2024;309:118322.
[128] Neirotti F, Noussan M, Simonetti M. Evaluating the emissions of the heat supplied by district heating networks through A life cycle perspective. Clean Technologies, Bd. 2020;2:392–405.
[129] Olsson N. LCA of low-temperature district heating network components. Reykjavik: Lund University; 2021.
[130] Pa A, Bi XT, Sokhansanj S. A life cycle evaluation of wood pellet gasification for district heating in British Columbia. Bioresour Technol 2011;102:6167–77.
[131] Pieratti E, Paletto A, Atena A, Bernardi S, Palm M, Patzelt D, Romagnoli M, Teston F, Voglar GE, Grebenc T, Krajnc N, Schnabel T. „Environmental and climate change impacts of eighteen biomass-based plants in the alpine region: a comparative analysis. J Clean Prod, Bd 2020;242:118449.
[132] Raluy RG, Serra LM, Guadalfajara M, Lozano MA. Life cycle assessment of central solar heating plants with seasonal storage. Energy Proc 5 5 2014;48:966–76.
[133] Raluy R, Guillén-Lambea S, Serra L, Guadalfajara M, Lozano M. „Environmental assessment of central solar heating plants with seasonal storage located in Spain. J Clean Prod, Bd 2021;314:128078.
[134] Wirtz M, Kivilip L, Remmen P, Müller D. 5th Generation District Heating: a novel design approach based on mathematical optimization. Appl Energy, Bd 2020;260:114158.