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Introduction of new decentralised renewable heat supply in an existing district heating system

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ABSTRACT

The effects of new heat pump and solar collector capacity in an existing district heating system are investigated by using Helsinki as a case study. Existing heat supply consists of combined heat and power plants, boilers and large-scale heat pumps. Also, the potential benefit of low distribution temperatures is evaluated. Both an outdoor temperature dependent supply temperature between 80 and 110 °C and a constant supply temperature of 65 °C are considered for distribution.

EnergyPro modelling tool is utilised, providing information on optimal operation of heat supply. Changes in heat supply are studied with emissions of the system and techno-economic performance of the new heat sources evaluated.

Results indicate that CHP based heat production is set to decrease 68–73% by 2030. Heat pumps represent the most interesting option for heat supply with good performance on all economic, emissions and energy efficiency viewpoints. Low temperature distribution improves the performance of the system by 4% in both costs and as emission reductions compared to normal distribution temperatures.

1. Introduction

Heating and cooling related energy consumption within European Union (EU) had a share of 49% in total final energy use in 2012 with renewable energy sources (RES) providing 18% of the demand [1]. Reducing energy consumption and emissions of heating and cooling in buildings is one of the key issues if a low carbon energy system is to be achieved.

European Commission (EC) has already set a vision of decarbonising buildings sector. The actions to achieve this are renovation of old building stock, efforts on energy efficiency and renewable energy supported by decarbonised electricity production and district heating (DH). Waste incineration, CHP based heat production, replacement of fossil fuel consumption by renewable or excess heat sources used in DH or in building specific systems have been identified as technologies relevant for these actions [2].

DH as a technology for distributing heat generated in centralised or decentralised large-scale production plants can reach higher cost and energy efficiency than heat supply relying on building specific systems. On a European level, it has been shown that simply replacing building or apartment specific boilers burning coal, oil or natural gas and increasing the CHP based DH system can decrease total primary energy consumption by 3.7% or 7.0% with DH market shares of 30% or 50%, respectively [3].

DH supply is still mostly based on fossil fuels, 90% in the world and 70% within EU. The current generation of system design reflects this [4]. However, DH is currently experiencing development on both system and technology levels, moving towards implementation of the concept referred as 4th generation district heating (4GDH). 4GDH focuses on integrating district heating and cooling (DHC) systems with the surrounding energy system. Using DHC systems for balancing excess electricity production from renewable sources represents an untapped potential. Low distribution temperature with adequate cooling performance by the consumers is at the core of the concept as it enables low heat losses in distribution and, more significantly, efficient integration of renewable and excess heat sources. Combining energy supply design with long-term infrastructure planning processes such as city planning is also part of the concept [5].

In the EU Strategy on Heating and Cooling the member countries are encouraged to facilitate the increase of renewable energy and waste heat utilisation in DHC systems. The consumers are to be

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empowered to produce renewable heat locally and connect to an existing DHC system. The negative consequences on the revenue streams of the local DHC companies are recognised, but considered to be offset by positive social and environmental impacts. Also, the DH systems in general are considered as an enabling infrastructure for increasing the share of renewables in heating. Untapped potential of large-scale heat pumps (HPs) is recognised, and possibilities of utilising geothermal heat are noted. Existing systems are considered to be in need of development in terms of increasing renewable energy heat supply. This is to be accomplished by solving regulatory issues preventing e.g. fuel-switching to renewables and through increased opportunities for new renewable energy producers and consumers themselves. The consumers should be empowered to choose highest energy performance solution taking into account the future heating and cooling demand [1,6].

Proposal as a new directive on the promotion of the use of energy from renewable sources includes a dedicated section (Article 24) on DHC. The article states that end consumers are to be informed on the share of renewable energy in their heat supply and on overall efficiency of the system. If the DHC system is not efficient, users can disconnect in order to switch for a RES based option. A non-discriminatory access for RES and excess heat sources to the system should be granted, although the system operator, normally the DH company, can refuse if the heat supply is already based on high efficiency co-generation or on RES Disconnecting from a DH system can be made by an individual, a joint undertaking by a group of consumers or by a party acting on their behalf. Block of flats is treated as a single entity in this respect, i.e. a single apartment cannot disconnect on its own. New systems are exempted from granting the non-discriminatory access for a specified number of years if the system heat supply is based on renewable energy or utilisation of excess heat. A competent authority is to be assigned to evaluate on what grounds e.g. disconnecting from a system or granting access for new heat sources is refused, and adjudicate. In case of Finland, the systems are classified as efficient and most are also largely based on co-generation. As a consequence, much of the issues raised would not directly affect the Finnish DH industry. Interestingly, the Article 24 also states that electricity distribution system operators are to assess the potential of DHC in providing balancing and other system services such as demand side management and energy storages in cooperation with local DHC system operators [7].

In overall, the heating and cooling strategy and the Article 24 are ambiguous on some elements concerning the actual implementation of the future heating and cooling systems. However, DHC is clearly envisioned to play a role in a future energy system, the share of RES is to be increased and consumers are definitely on focus. The contents of the Article 24 could also be interpreted as a call for separating distribution system from heat supply, similarly to the electricity sector.

1.1. Scope and objective

Certain topics of research concerning DH have received more attention during past years. These include distribution network efficiency and especially low temperature solutions, utilisation of new heat sources, energy storages and different power-to-heat concepts. In addition, topics combining different facets of research such as building side actions enabling low distribution temperatures, power-to-heat and new heat sources and management of more complex systems with new heat sources, energy storage capacity and existing CHP units, and how all these systems work in a context of future cities and energy systems. These have all contributed to what is now known as 4GDH.

Low temperature distribution further enhances the efficiency of the heat sources and is an integral part of the 4GDH concept. Its implementation would be relevant both for the utilisation of RES and more conventional heat supply technologies [8]. Li and Svendsen [9] carry out an exergy and energy analysis of a Danish case system with low distribution temperatures, providing a number of design principles for reducing energy and exergy losses. Schmidt et al. [10] present options for implementing low temperature district heating demonstrating the benefits of the concept. Dalla Rosa and Christensen [11] investigate low temperature DH taking into account the effect of human behaviour on load patterns and compare DH and geothermal building-specific HPs for a low heat density area. They concluded that low temperature DH can be competitive with HPs. Yang and Svendsen [12] analysed different substation designs for domestic hot water supply with low temperature DH and evaluated their impact on the return temperatures for DH network.

Buildings and their heating systems are to be considered if low distribution temperatures are targeted. Østergaard and Svendsen [13] present practical steps towards lower return temperatures and thus, lower supply temperatures. The steps included identification of critical radiators and addressing the issue without compromising thermal comfort.

The main technologies for utilising renewable heat sources in DH are variety of different kinds of HP applications. In Ref. [14], Lund et al. discuss the socioeconomic potential of large scale HPs in context of the power-to-heat concept in Denmark, evaluating the potential to be 2–4 GW of thermal power. Østergaard and Andersen [15] study use of booster HPs in district heating with HPs also as the heat supply technology, finding out that use of booster HPs decrease the energy consumption and costs. Lund and Persson [16] introduce a mapping and quantification of heat sources for HPs stating that heat sources are widely available, larger heat sources are typically found in larger cities and concluding that sea water will have a substantial role as a heat source in future Danish energy system.

Some HP related applications utilise geothermal heat as a heat source. Østergaard and Lund [17] investigate the city of Frederikshavn and its objectives of having a fully renewable energy system. In the developed scenario, geothermal heat is used in combination with an absorption HP running on steam from a waste incineration plant. A very similar plan is studied by Østergaard et al. [18] for Aalborg municipality. Jensen et al. [19] present a heat supply by two absorption HPs connected in series to supply DH for Greater Copenhagen area.

Solar collectors (SCs) represent another widely studied source of renewable heat. Winterscheid et al. [20] consider a solar assisted district heating system where fossil based CHP unit is used as the main source of heat providing a methodology to avoid overdimensioning of solar systems and storage. They also propose that solar thermal systems work well with CHP based production in future energy systems with electricity price variations due increased production of electricity by solar panels. Soloha et al. [21] present a case study in Latvia with SCs and a thermal storage that can reach a solar fraction up to 78%. With energy efficiency measures included, a fraction of 95% can be reached in the studied case. Both Winterscheid and Soloha show that SCs paired with thermal energy storages are a viable solution for reducing emissions in DH systems with a fossil fuel based heat supply [20,21]. Rämä and Mohammadi [22] compare distributed and centralised SCs with the same total investment in a small-scale district heating system, concluding that a centralised SC plant connected to district heating clearly outperforms the distributed systems.

Although heat recovery from excess heat sources is more of an energy efficiency measure, it is often also categorised as renewable. For example, data centre waste heat has been suggested as a

potential solution for a stable source for DH [23]. All of the technologies listed are mature with abundant examples of their feasibility.

Although biomass combustion and waste incineration could be seen as more conventional options for renewable heat sources, they are present in many of the aforementioned studies such as Danish case studies [17,18]. Also, waste incineration and district heating have synergies as noted by Persson and Münster [24] who argue correctly that the conversion efficiencies of both existing and future waste incineration plants would be significantly higher if heat output of the plants could be utilised.

However, the implementation of the aforementioned technologies and concepts in an existing system requires a detailed examination. This is especially true for a DH system with efficient, back-pressure CHP production as the main heat supply. This type of DH system is typical in Finland, where 73.4% of DH was produced by CHP plants in 2015 [25]. The new heat sources can potentially reduce the heat load of the CHP unit to a level where economic operation of the co-generation is in doubt. This in turn can lead to a higher share of boiler based heat production, potentially increasing emissions and reducing the overall efficiency.

Although distributed heat production is a current topic of research, large-scale centralised applications supplying heat using DH should be competitive – especially in systems with lower distribution temperature. In comparison between building specific SC system and a solar assisted DH system, the same amount of investment enabled up to five times more renewable heat into system [22]. As building specific solar heating system is a commercialised and mature product, it can be expected that the conclusion is likely to be the same for other heat supply technologies as well.

A need for energy storages has been identified as one of major components in future energy systems [26]. Sensible thermal energy storages (STES) are already a mature technology that can provide a cost-efficient solution for addressing the need for flexibility due to variable renewable energy used in electricity generation. As a comparison, the cost (€/kWh) of Li-ion based battery, although rapidly decreasing, was 50 times higher than STES in 2012 [27,28].

In Ref. [29], Rinne and Syri investigate the operation of CHP units and thermal storages in a future energy system of Finland with high shares of wind power. They found out that the thermal storages could greatly benefit the operation of the CHP units. The current thermal storage capacity should be increased from 0.3% of DH consumption to 30% if high shares of wind power production are realised.

Böttger et al. [30] focus on the power-to-heat concept as balancing power in Germany by using electric boilers in DH. This offers an alternative for must-run power plants based on fossil fuels the current provide these system services, and presents a cost-efficient solution for reducing CO_2 emissions. Schweiger et al. [31] discuss the potential of power-to-heat in the Swedish system, estimating it to be 0.2–8.6 TWh. Additional heat storage capacity and high shares of wind and solar power increased the potential while available excess heat sources decreased the feasibility of power-to-heat.

With the objective of decarbonising the energy system, understanding of dynamics related to possible changes is very relevant in order to achieve the most cost-effective solutions for integrating renewable energy into DH systems. Not only for selecting the most reasonable option for developing the system, but for sharing the benefits of increased efficiency and creating transparency in a system with e.g. multiple suppliers of heat. As DH systems always include significant local characteristics related to heat supply, heat demand and technologies used, the case studies provide very useful information. These characteristics have been examined in several papers. Åberg et al. studied the sensitivity of heat demand reduction and electricity price variations for a DH system in Uppsala [32], showing that primary energy consumption decreased more than heat demand while low electricity prices during winter significantly increased the utilisation of heat pumps. Back et al. analysed HP competitiveness in Greater Copenhagen area [33], concluding that HPs reached 3500 in full load hours (FLH) in distribution network with lower temperature level while remaining 1000 h lower in the transmission network that connects the large-scale centralised units in the system. Levihn studied a combination of CHPs and heat pumps to balance renewable electricity production within the Stockholm DH system [34] based on empirical data of a real, existing system. Vesterlund et al. investigated the DH system in Kiruna [35] with multiple sources of heat by running an optimisation of model including the distribution network and the location of the supply units. The study concluded that while the most efficient units were used regardless of the location, they could help in maintaining lowest possible temperature level within the network needed by the consumers.

Helsinki DH system represents a city-wide system with very efficient, but mainly fossil fuel based heat supply. This makes it a challenging and an interesting case example as an attempt to integrate more renewable energy based heat sources into the system. In this paper, HPs and SCs are studied as new sources of heat, both as separate and together in the Helsinki DH system. The analysis is carried out both for currently used and low temperature distribution temperatures. The input assumptions are linked to planned development of the system and the results are compared against the targets set for the share of renewable energy in heat supply.

The aim of the paper is to study how existing system in Helsinki reacts to these two selected new heat sources complementing the studies [32–35] for different systems. The paper also evaluates the performance of the heat sources from system point of view and carries out a techno-economic analysis concerning their feasibility as investments.

The chapter on methods describes the starting point, the approach and the tools used in the study. This is followed by a description of the case system of Helsinki with information on the input assumptions provided. Results of the study are presented in a separate chapter, followed by related discussion. A chapter on conclusions that summarises the content of the study and the main outcomes finishes the paper.

2. Methods

As the literature review suggests, introducing low marginal cost decentralised renewables will affect utilisation of other heat production units in DH network. There are ambitious plans to increase the share of renewable heat in Helsinki, but the extent of integration and specific solutions have not been decided nor studied in detail. Thus analysing the effects of HPs and SCs on techno-economic terms in Helsinki DH network is interesting. Data was compiled on the investment costs of new renewable capacity, existing plants in Helsinki DH system and future plans on development of DH capacity. Operation of DH production units was simulated on an hourly level between 2014 and 2035 based on the variable costs for heat production, including fuel costs, Finnish taxation and variable operational and maintenance costs. DH demand and weather data for 2014 were used in formulation of the baseline and in the future scenarios utilised forecasted development of all fuel costs, electricity prices and DH demand.

Simulations of DH production were carried out in a number of scenarios with different capacities for RES based heat. Annual DH production, electricity production and total operational costs of the system were the main simulation outputs which were further used

in analysing the changes in shares of available heat production technologies, i.e. CHPs, boilers, HPs and SCs, and to calculate CO_2 emissions of DH production. Further simulations and analysis were conducted on sensitivity of electricity prices in order to study the role of electricity in a case with high CHP and HP capacity.

The simulations were carried out by EnergyPRO software [36]. EnergyPRO is an input-output model accounting both electricity and heat markets. EnergyPRO calculates optimal operation of heat production units based on operational costs of plants with different technologies and fuels. Total operational costs included variable operating and maintenance costs, fuel costs and taxes. Profit from heat sales was excluded in the optimisation, but later added in the calculation of net present values. Income from sold electricity generated by CHP plants were deducted from total operational costs. Investment costs of existing and new plants were excluded from the analysis but the profitability of new renewable heat investments was calculated separately.

Simulations were carried out for 4 milestone years, i.e. 2014, 2018, 2024 and 2030, decided according Helen's future plans for heat supply in the near future. To analyse different renewable heat supply setups, 4 different scenarios were simulated: business as usual (BAU), additional HP capacity (HP), additional SC capacity (SOL) and addition of both HPs and solar thermal (SHP). In order to analyse the effect of LTDH networks, all of the scenarios were simulated also with lower temperature levels, resulting in a total number of eight scenarios. The output of the simulations included total operational costs of heat production, share of different technologies in heat supply, electricity produced by CHP units and fuel consumption of individual units.

The addition of renewable heat capacity was determined by the average DH load during June–August. Additional HPs were sized to match the average DH demand in summertime, i.e. 140 MW in addition to existing capacity of 112 MW in 2018. To analyse and compare the benefits of different technologies, the investment costs were estimated to be approximately 90 MEUR in all of the simulated scenarios, corresponding to the investment cost of the aforementioned 140 MW in HP capacity. Investments in new renewable heat capacity were assumed to take place in two phases, 2018 and 2024, in all scenarios.

The effects of introducing HPs and SCs were evaluated both on economic and environmental indicators. Economic indicators included total operational costs of heat production and profits from electricity sales. Environmental indicators were share of renewable heat in total heat supply and total emissions of heat production. Distribution constraints and bottlenecks inside Helen DH network were excluded from the simulations as well as heat trade with neighboring DH systems. Input assumptions concerning operational environment are presented in the following section.

3. Case Helsinki

DHC system in the city of Helsinki is operated by Helen, one of the largest energy companies in Finland. The company is fully owned by the city of Helsinki. In 2015, Helen supplied 5984 GWh and 125 GWh of DHC, respectively. The system is characterised by a high share of co-generation in heat supply (88%) and an extensive (1351 km) and efficient distribution network with yearly heat losses 6.5%. The co-generation plants produced 4659 GWh of electricity indicating a very high power to heat ratio of 0.82 [25].

The efficiency of the Helsinki energy system has been recognised globally with Helen having won the Global District Energy Climate Award 2013 in the category of municipal schemes serving more than 10 000 citizens. Helen was awarded for its solution for combining co-generation, DHC in the most energy efficient way in the world [37].

Although being very efficient, the present combined heat and power production is mostly based on fossil fuels, mainly coal and natural gas. Helen has set a goal of decreasing its carbon dioxide emissions by 20% by 2020. Ultimately, Helsinki is envisioned to be 100% carbon neutral by 2050. This will be accomplished by increasing the share of renewable energy, improving energy efficiency, developing new emission-reducing products and services and by investing in a smart energy system where distributed production and excess heat sources are integrated into the existing system [38].

In 2015, Helen made major investment decisions which will affect the DH production capacity in Helsinki in the near future [39]. First, Helen has already shut down 92 MW heavy fuel oil (HFO) boiler in Salmisaari and decided to replace it with pellet based heat only boiler (HOB) of the same capacity by 2018. Secondly, Helen is investing in new heating and cooling plant which is expected to begin producing both heat (22 MW) and cooling (15 MW) in Spring 2018 [40]. Thirdly and most importantly, Helen has decided to shut down 420 MW Hanasaari coal CHP plant by the end of 2024 due to several reasons; targets set for reducing CO_2 emissions in Helsinki, low expected electricity prices and investment required for flue gas purification. To replace the missing heat production capacity, Helen is planning to build a 150–250 MW HOB fueled with wood chips or pellets in Vuosaari. Capacity of the proposed plant depends on future development of DH demand and extent of energy saving measures in Helsinki. In addition, Helen has plans to invest in yet unidentified, decentralised renewable heat production. The potential for HP and SC based heat supply studied in this paper correspond to this option.

An hourly heat load time series of the system studied in this paper was evaluated based on statistical data on heat consumption [25] and weather data [41] for the year 2014.

The heat losses in the distribution network were evaluated by using a steady state heat loss calculation method [42], using assumptions on supply and return temperatures at the points of supply combined with statistical data on heat losses on yearly level [25] and an assumption of a constant undisturbed soil temperature of 5 °C. The distribution network was considered as a single effective supply and return pipe element that matched the heat losses in statistics by using the outdoor temperature related supply and return temperatures. The resulting heat loss coefficients were used in evaluating heat losses for low distribution temperature system.

The heat load of 2014 was used as basis for calculating the heat demand for milestone years of 2018, 2024 and 2030. The assumption on this projected development is based on Nordic Energy Perspectives 2016 report [43]. The resulting heat demand is presented in Fig. 1.

The heat supply in Helsinki DH network consists of several CHP units, boiler plants, two heat storages and a large-scale HP facility. The existing system configuration is given in Table 1.

Just recently Helen announced [44] plans for a new heat storage of 260 000 m^3 located in an old underground heavy fuel oil storage. This new capacity, still in planning stages, is not taken into account in the simulations.

The coefficient of performance (COP) of the heat pump was modelled in EnergyPro based on design values of Katri-Vala heat pump plant [45], as well as on the inlet and outlet temperatures for both the heat source and the district heating system.

Inlet temperature for the heat source as well as both supply and return temperatures for the district heating system were given as time series. According to [45] the Katri-Vala heat pumps in winter mode supplies DH at 62 °C, but in this paper the supply temperature was assumed to be the DH supply temperature or at maximum 88 °C (supply temperature in summer mode). The assumption was made to have larger shares of HP based heat supply technically

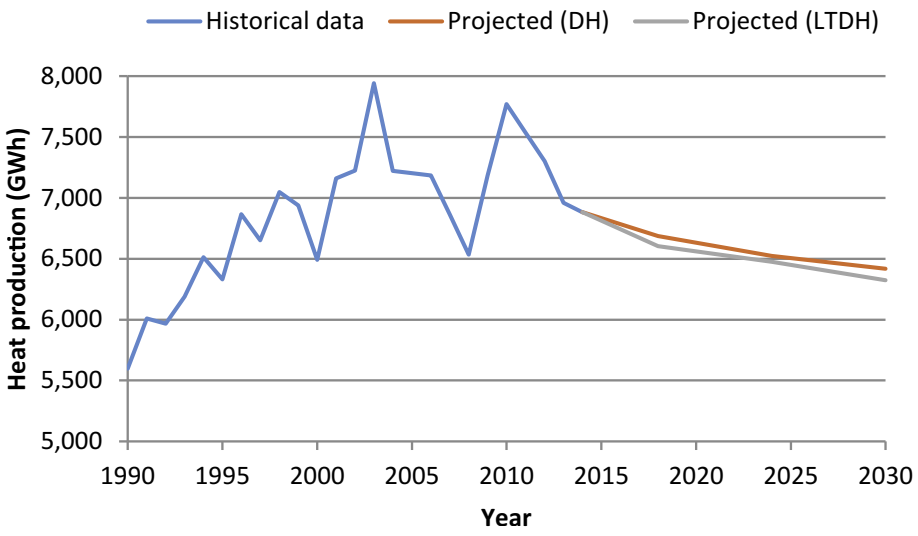

Fig. 1. Statistical and projected heat demand for current and low distribution temperatures.

Table 1
Heat supply in the Helsinki DH system.

Plant	Count	Total heat production capacity [MW]	Total electricity production capacity [MW]	Total efficiency (weighted average)
CHP - Coal	2	720	378	90%
CHP - Natural gas	2	580	630	86%
HOB - LFO	1	164	–	91%
HOB - HFO	6	917	–	92%
HOB - Natural gas	4	934	–	92%
HOB - Coal	1	180	–	97%
Heat pump	1	90	–	COP (calculated)
Heat storages	2	220 (45 000 m^3)	–	100%
Total	17	3585	1008	

feasible in normal distribution temperatures.

The heat source inlet temperature varied between 10 °C and 20 °C, depending whether the primary heat source was sewage water (winter, from November to March) or district cooling (summer, from May to August). During the spring and autumn, the temperature was assumed to change gradually from 10 °C to 20 °C or vice versa. Outlet temperature for the heat source was assumed constant (4 °C). Resulting COPs range from 2.8 to 3.6 with normal distribution temperatures and from 3.4 to 4.0 with low distribution temperatures.

The investigated scenarios included increased HP capacity, centralised SC plant or a combination of these two with comparisons to the existing system. All the scenarios and the business as usual reference scenario are described in Table 2.

The four scenarios are investigated with two alternative distribution temperature levels; an outdoor temperature dependent supply temperature varying roughly between 80 and 110 °C or a constant supply and return temperatures of 65 °C and 30 °C. These alternatives represent a normal Finnish practice and a minimum temperature level still allowing domestic hot water supply without additional heating at consumer substations, respectively.

Changes in heat supply are described in Table 3. The whole studied period is from 2015 to 2035, but changes in heat supply only take place at 2018 and 2024.

Heat sources for additional HP capacity are not considered in this paper as a thorough mapping similar to would be needed. However, the potential sources such industrial excess heat, supermarket cooling systems, waste water, drinking water and natural bodies of water as are likely to have similar temperature levels and thus enabling roughly similar COPs [46].

The economic parameters considered in this study were current investment costs and projected development of fuel and electricity prices [43] taking into account the current taxation regime in Finland.

A values of 650 €/kW and 440 €/m^2 were used as investment costs for HPs and SCs, respectively [47].

Finnish fuel taxation is based on energy content and specific CO_2 emission of the fuel in question. The tax also includes a security of supply levy. The taxation for CHP units is calculated by the heat output of the plant multiplied by 0.9. The CO_2 component of the tax halved for CHP based production. Boiler plants are taxed by their fuel consumption.

The resulting effective fuel costs for coal, natural gas, light fuel

Table 2
Description of the investigated scenarios.

Scenario	Short name	Description
Business as usual	BAU	Represents the existing system based on current setup of CHP units, boiler plants and a large-scale HP facility.
Heat pumps	HP	Existing system with increased HP capacity. The resulting increased HP capacity corresponds to the average summertime heat demand in June, July and August.
Solar collectors	SOL	Existing system with added solar collector based heat supply. The capacity increase is calculated by matching the investment costs with the HP scenario.
Heat pump and solar collectors	SHP	Existing system with both increased HP capacity and added SCs. The capacities for each technology are half of the values used in HP and SOL scenarios.

Table 3
Changes in heat supply for all scenarios.

	2018	2024
BAU	Wood pellet boiler (92 MW) added	Wood chip boiler (150 MW) added
	Heat pumps (22 MW) added	*Coal CHP (420 MW) removed*
HP	Heat pumps (70 MW) added	Heat pumps (70 MW) added
SOL	Solar collectors (103 409 m^2) added	Solar collectors (103 409 m^2) added
SHP	Solar collectors (103 409 m^2) added	Heat pumps (70 MW) added

oil (LFO) and HFO are presented in Fig. 2.

In calculation of the costs of HP based heat production and the changes in revenues from electricity production, hourly variation of electricity market price during a sample year [48] and projected price development [43] were considered. 2014 Spot prices in Nordic electricity market and projected price development for milestone years is presented in Fig. 3.

In addition to the electricity prices, electricity taxes in Finland (22.53 EUR/MWh) were taken into account for the HP based heat production while the distribution tariffs were partly omitted as the distribution grid is owned by Helen. However, the consumption based fee for grid services set by national transmission system operator (TSO) are part of the distribution tariffs and were taken into account. This fee is 2.7 EUR/MWh except during daytime (7:00–22:00) between December and February when it is 9.0 EUR/MWh.

The assumptions used in the modelling represent the case system reasonably well, but a few shortcomings or inaccuracies should be noted. As seen in Fig. 1, years can be very different in terms of heat demand. Only a single representative year was used as

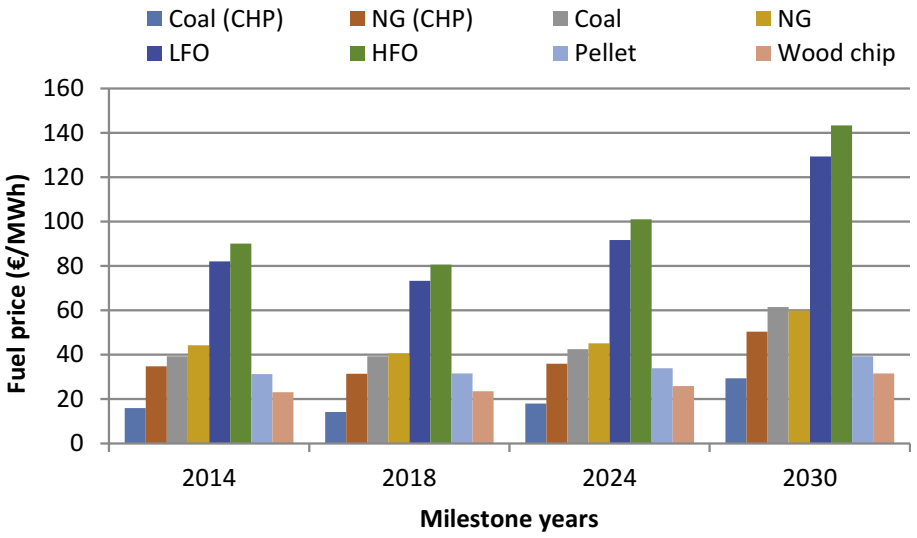

Fig. 2. Total fuel prices for CHPs (indicated in legend) and boilers.

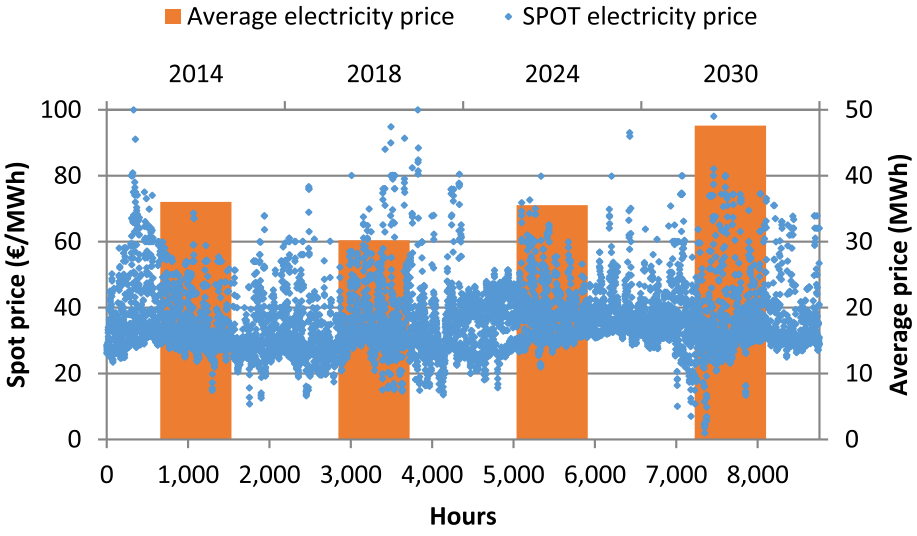

Fig. 3. Average electricity price in milestone years and spot electricity price time series.

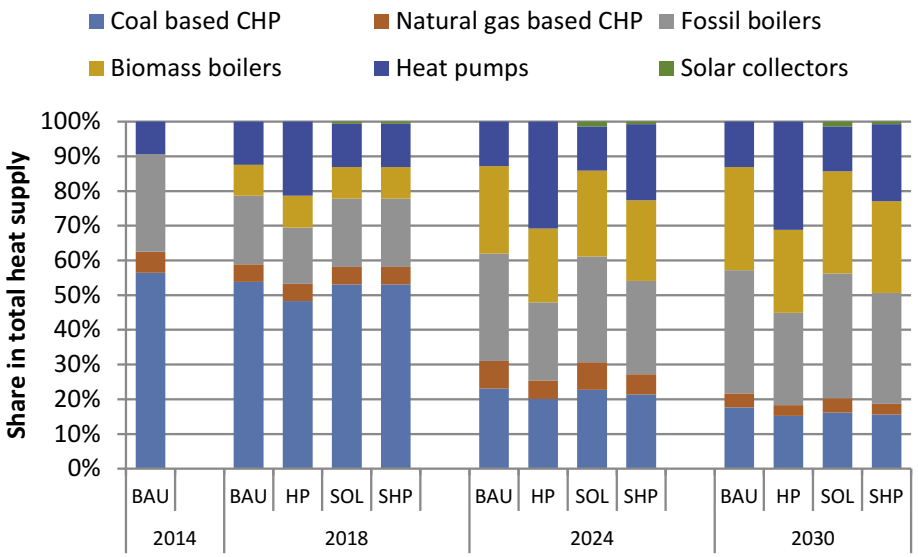

Fig. 4. Share of each heat source in heat supply with current distribution temperatures.

modelling input, although the projected future decrease in heat demand was taken into account. The heat demand was also calculated by using weather data and not real measured demand. The CHP plants were not modelled with full accuracy as only public sources of information were used in the definition of the model. The resulting CHPs were assumedly less flexible in operation than the real plants. Also, the existing CHPs and boilers did not take into account the effects of lower distribution temperatures; this was only done for studied new sources of heat. In terms of the distribution network, any transport capacity restrictions were not considered due to lack of information.

4. Results

Fig. 4 presents the share of each source of heat for all scenarios with current distribution temperature levels for calculated milestone years.

Fig. 5 shows the results of a sensitivity analysis on electricity price by illustrating the effect of increasing electricity price with 25% steps from normal reference price level. Milestone year of 2024 is used as the point of comparison.

Fig. 6 represents the changes of heat production by different types of heat sources for each scenario compared to BAU scenario of the corresponding milestone year.

Fig. 7 illustrates the relative difference heat output by available heat sources between current and low distribution temperature levels for each scenario in year 2030.

Fig. 8 further breaks down the effect of distribution temperatures for SCs by representing collector output (GWh) and solar fraction[1] (%) as monthly values.

Table 4 presents the share of RES with current and low distribution temperature level compared to RES target set by Helen. The current share (2016) is 10% and 20% is expected to be reached in 2020 when Hanasaari plant is replaced by a renewable heat source and the long term target is to be carbon neutral by 2050, which is assumed here as a RES share of 100% [38]. The target values for milestone years have been interpolated.

Fig. 9 presents comparisons of net present values (NPV) after 20 years of operation between BAU scenario with current distribution temperatures to all other scenarios. Discount rate of 6% is used in the calculation. Current average DH price of 64.9 €/MWh with a yearly increase of 2% is assumed.

Fig. 10 presents the carbon dioxide emissions of all scenarios with current distribution temperatures. The emissions of electricity were calculated using the newest published [49] specific emission value (175.1 gCO_2/kWh) and by the assumption emissions in Finland from heat and power production will reach zero by 2045 [43].

5. Discussion

The results show the impact of the planned new production capacity and the studied optional new heat sources of heat pumps and solar collectors. Although the share of renewable heat sources increased, the same applies to separate production of heat by fossil boilers. Based on the results, the decline of CHP based production seems unavoidable. Heat pump based production seems the most reasonable option. Especially if low distribution temperatures could be used, there should be potential for additional HP capacity.

The modelling results in Fig. 4 show low shares of CHP based heat production, e.g. 63% in BAU scenario in reference year 2014. This is considerably less than production reported in the Finnish DH statistics (88%). This is due assumed fuel prices that might differ from real values, modelling assumptions on start-up costs (2500 €/start-up) that are defined for CHPs but not boilers, the minimum operational hours per start-up (168 h) for CHPs and constant high efficiency defined for the HPs. At the milestone year of 2030, the share of CHP based heat production is 18–22% depending on the scenario.

Fig. 6 shows effects on production by different types of heat sources for all scenarios compared to BAU scenario. In this comparison, the studied new heat sources replace mainly boiler based production and to some extent, CHP based heat production. When looking at the results in Fig. 4 the new heat sources, decommissioning of one coal based CHP plant in 2024 and planned pellet and wood chip boilers lead to unsurprising reduction in CHP based heat production.

Although the calculated share of CHP based heat output is different from statistical values, the situation itself is not

[1] Solar collector output divided by total heat supply.

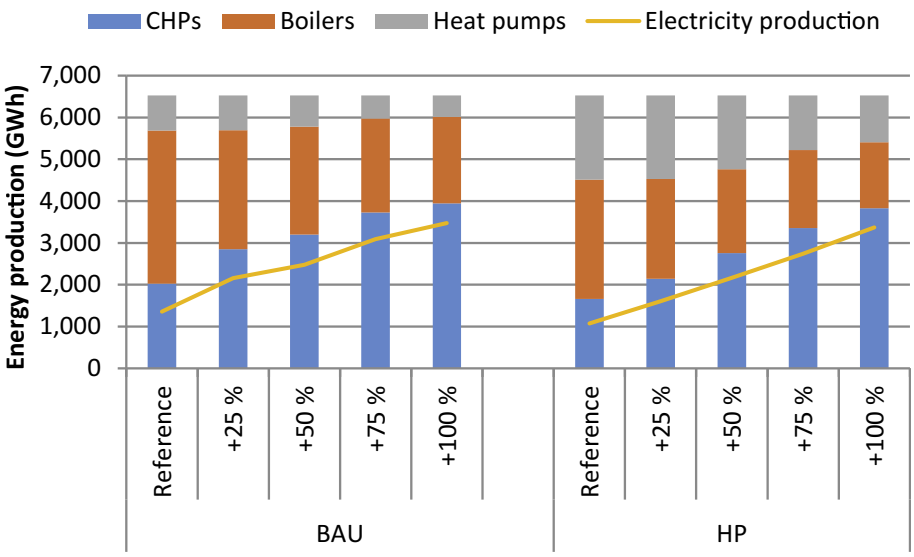

Fig. 5. Electricity price sensitivity on heat and electricity production for BAU and HP scenarios in 2024.

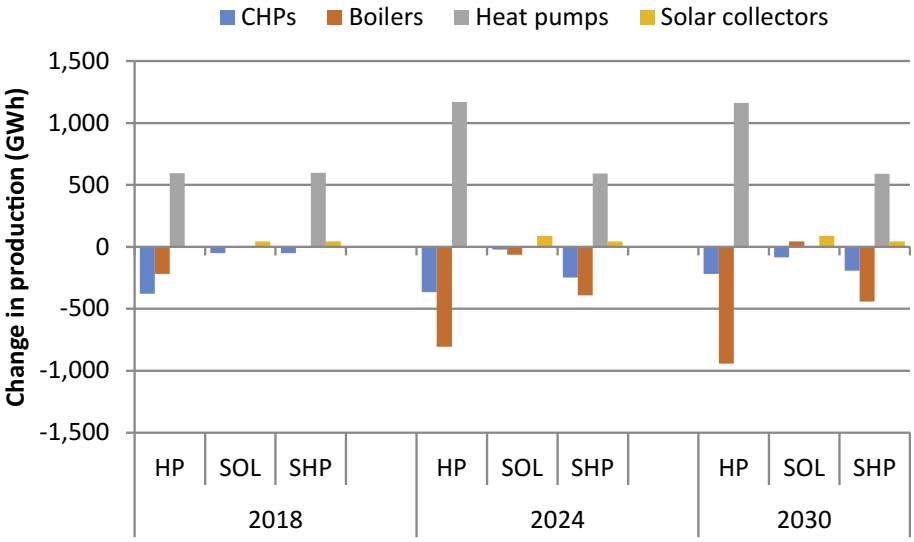

Fig. 6. Changes in production by different heat sources with current distribution temperatures.

unexpected. The current difficult operational environment for back-pressure CHPs in general has been noted in Finland [50]. The discussion is partly because CHP based electricity production in plants servicing a city level DH network is 19% of total domestic electricity production [51] and thus important for electricity supply.

This situation is heavily influenced by the electricity price as illustrated in Fig. 5. In BAU scenario at milestone year 2024, doubling the electricity price increased CHP based heat production by 94% while decreasing HOB and HP production by 44% and 39%, respectively. In the HP scenario, the relative increase in CHP heat production was even more; 131%. HOB and HP production decreased by 45% and 44%, respectively.

HPs are clearly outperforming the SCs in the calculated scenarios. SCs are producing the expected amount (436–513 kWh/m^2) of heat, but the total heat output is insignificant compared to output of HPs. Considering the same investment costs were allocated for both options, HPs represent a more economic option with the input assumptions of this study. The solar irradiation would be significantly higher in Central or Southern Europe; e.g. Paris and Rome have 29% and 79% higher horizontal irradiation levels than Helsinki, respectively [52]. This would naturally have an impact on the results concerning the performance of the SCs.

Although SC contribution in heat supply can only be considered minor on yearly level, on monthly basis the effect can already be observed. Fig. 8 shows that the solar fraction of the district heating system can reach 10% during summer.

The low temperature distribution reduced heat losses by 22%, but since the relative heat losses were low already (5.6%) the effect is not very pronounced. However, low temperature distribution did affect the heat supply; as seen in Fig. 7, HP and SC based heat production is increased by 5–10% and 19%, respectively. CHP and boiler based heat production is decreased 0–6% at the same time. Low distribution temperature also increases the efficiency of CHP and boiler based production, especially biomass based boilers due to flue gas condensation. However, the effect is less significant compared to increased efficiency of the new heat sources.

The share of renewable energy in heat supply set targets very well as seen in Table 4. The low distribution temperatures enabled

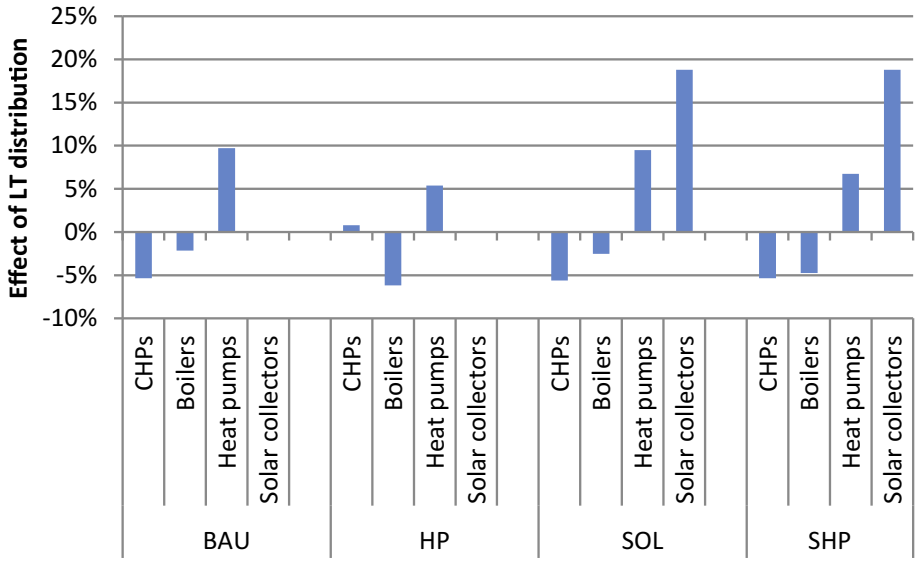

Fig. 7. Effects of low temperature (LT) distribution to heat output by specific sources of heat in 2030.

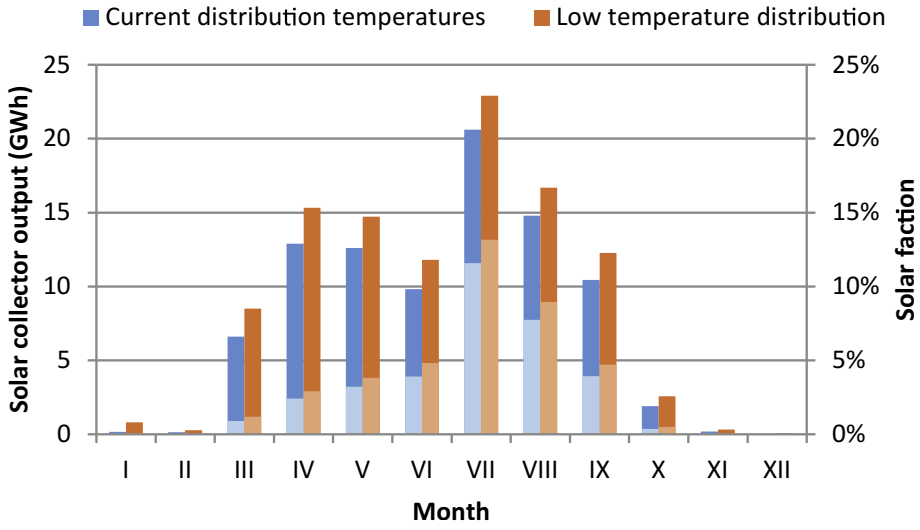

Fig. 8. Monthly solar collector output and solar fraction (light colour) for SOL scenario at year 2024.

Table 4
RES shares with current and low distribution temperature levels and the Helen target share.

Milestone	Scenario	DH	LTDH	Target
2014	BAU	6%	8%	
2018	BAU	17%	19%	15%
	HP	23%	25%	
	SOL	18%	20%	
	SHP	22%	20%	
2024	BAU	34%	36%	31%
	HP	42%	45%	
	SOL	35%	37%	
	SHP	39%	44%	
2030	BAU	38%	40%	47%
	HP	45%	48%	
	SOL	39%	41%	
	SHP	42%	44%	

up to 5 %-units more renewable heat supply.

In economic analysis the NPV after 20 years were calculated and results presented in Fig. 9. It shows comparisons between all scenarios and the BAU scenario with current distribution temperatures. Only scenarios with solar collectors present (SOL and SHP) with current distribution temperatures showed negative impact. The economic benefit of reduced distribution temperatures is clearly visible. The most attractive scenario with increased HP capacity and low temperature distribution resulted in 7.3% higher NPV. This value should be more than the effect of the likely investment needed to enable low temperature distribution. In monetary terms this 7.3% would be 200 M€ over the studied 20 years.

As the electricity production is decarbonised on an energy system level, specific emissions of electricity production will continue to decrease. The benefits the HP based heat production as seen in Fig. 10. Coal will remain the main source of CO_2 emission in Helsinki

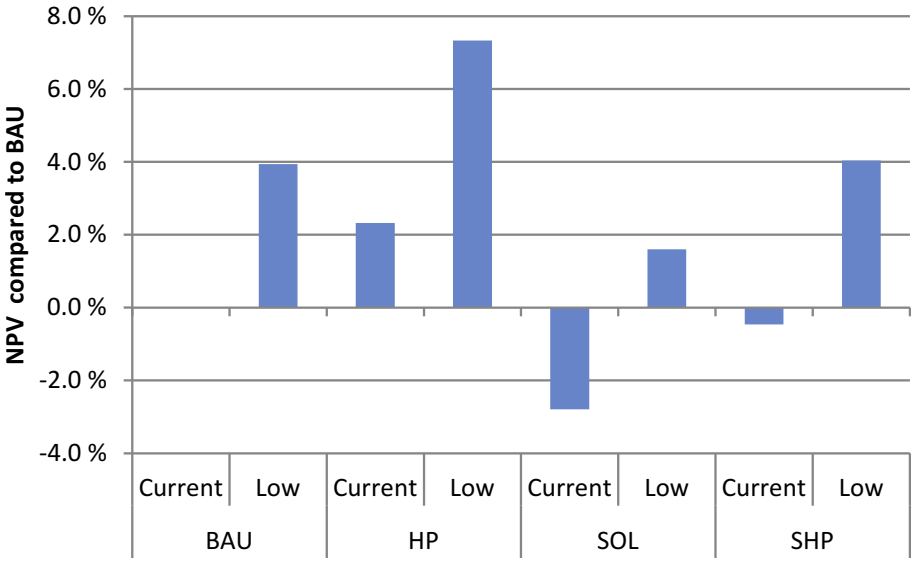

Fig. 9. NPV after 20 years compared to BAU scenario with current distribution temperatures.

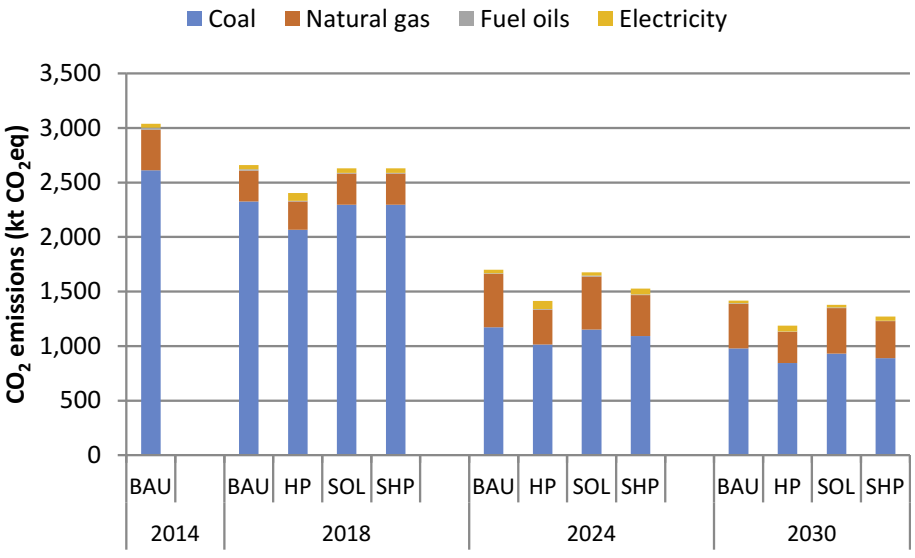

Fig. 10. Carbon dioxide emissions for all scenarios with current distribution temperatures.

system for the foreseeable future. Low temperature distribution reduces the emissions from 2% to 5%, depending on the scenario and milestone year investigated. At the milestone year of 2030 the highest reductions were attained in SOL and HP scenarios (4.1% and 4.0%, respectively) with low distribution temperatures where the system benefits from low specific emissions of electricity, higher output by HPs and the zero emission output of solar collectors.

6. Conclusions

Helsinki DH system was used as a case example in studying effects of adding new renewable heat sources in form of HPs and SCs into an existing district heating system with considerable CHP based heat production capacity.

Results indicate that HPs are clearly the better option both in terms of cost-efficiency and emission savings. Solar thermal does not seem profitable investment on current temperature levels, but results suggest that investments could be profitable if low temperature DH networks could be exploited. In overall, low temperature distribution clearly improved the performance of any system; including the BAU scenario representing current plans for developing the system.

At the current price levels CHP plants cannot benefit from electricity production and thus, the utilisation of CHP plants decreases. Furthermore, low electricity prices benefit HP production. The currently planned new biomass boilers further reduce the output from CHP plants. Although the emissions of the system are decreased, the share of fossil fuel based HOBs is increasing.

Further research on costs and measures of implementing low temperature DH networks for specific systems is required. Also, the potential for locally-available heat sources should be systematically mapped and evaluated due to the attractiveness of HP based heat production indicated in this paper.

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Nomenclature

4GDH	4th generation district heating
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
DHC	District heating and cooling
EC	European Commission
EU	European Union
FLH	Full load hours
HFO	Heavy fuel oil
HOB	Heat only boiler
HP	Heat pump
LFO	Light fuel oil
NPV	Net present value
RES	Renewable energy sources
SC	Solar Collector
STES	Sensible thermal energy storage
TSO	Transmission system operator

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