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Dynamically distributed district heating for an existing system

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ABSTRACT

The study in hand introduces the concept of dynamically distributed district heating. The concept addresses the challenges related to transforming an existing 3rd generation district heating system into a 4th generation system, one area at a time. It enables a cost-efficient option for introducing low-temperature distribution and new distributed heat supply while preserving the advantages of an efficient, more centralised system. The concept includes new large-scale heat storage capacity in areas on the outskirts of the network or within otherwise suitable locations, charged during summer when low-cost heat is commonly available. These areas also have new distributed heat supply. The areas are run in an island-mode during the heating season, i.e. disconnected from the main system. The study presents a preliminary analysis of the concept using Helsinki district heating system as a case study based on open data on district heating demand, building stock data and optimisation modelling of the district heating system for assessing the heat supply costs.

1. Introduction

District heating (DH) sectors in developed DH countries such as Finland, Sweden and Denmark are undergoing a major transformation from 3rd generation (3GDH) to 4th generation (4GDH). 4GDH is also envisioned as an ideal design for new systems in developing DH countries. 3GDH is often based on fossil fuels and almost always on centralised heat supply. The 4GDH concept includes e.g. a more distributed heat supply based on renewable energy sources and/or excess heat, and it utilises low-temperature distribution [1]. Although thermal storages are already present in current DH systems, these new heat sources almost always benefit greatly from increased storage capacity. Also, the flexibility of the system is improved by increased storage capacity. This flexibility is anticipated to represent a major benefit for a renewable-based energy system with a considerable share of wind and solar power. The overall objective is the emission reductions, either directly within the heating sector or indirectly through the flexibility provided for the power system.

This study introduces the concept of dynamically distributed district heating. During the peak heating season, specific areas of the DH system are disconnected from the core system (i.e. the main DH system without the disconnected areas) and operated in an island-mode. The heat supply of these specific areas during this time is based on local distributed heat supply and by unloading a local, large-scale thermal energy storage. This heat storage is loaded during summer when low-cost heat is commonly available.

The main benefit of the concept is that it addresses a clear challenge in DH systems in transition, by enabling a cost-efficient way for introducing low-temperature distribution and new distributed heat supply and area at a time. This is one of the key issues related to transition within large, city-wide systems everywhere; it is almost impossible to make changes for the whole system at one. The concept also preserves the potential advantage of an efficient, more centralised heat supply. This can increase the utilisation rate of e.g. excess and renewable heat sources. Also, the concept allows the temperature levels within the small individual areas to be managed more efficiently due to shorter distribution distances. This can also enable the core system to be run at lower temperature levels. The demand profile of the core system is more favourable; the peak demands during winter-time are reduced, and the summer-time load is increased. The concept is applicable for new systems, existing systems or extensions of an existing one.

The concept of dynamically distributed district heating combines and builds on many already existing elements and concepts related to 4GDH and developing DH in general that have been widely studied. These include the use of seasonal heat storages and heat storages in general, maximising the use of low-cost heat abundantly available outside the heating season, designs with areas separated from the core system and using low distribution temperatures, distributed heat supply by heat pumps (HPs), and transition of 3GDH into 4GDH systems in overall.

Guelpa and Verda [2] present a comprehensive review on thermal

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Abbreviations

3GDH	3rd Generation District Heating
4GDH	4th Generation District Heating
CHP	Combined Heat and Power
DH	District Heating
HP	Heat pump
SMR	Small Modular Reactor

energy storage applications in DHC systems. In future energy systems combining different energy carriers and fluctuating renewable-based energy supply, thermal storages are seen as an affordable, stable and long-lived technology for providing high-efficiency energy storage capacity. The overall trend within the heating sector is electrification through power-to-heat technologies such as heat pumps. The flexibility required by e.g. increasing share of wind and solar based electricity production can potentially be provided thermal energy storages.

Seasonal heat storages in DH systems have been extensively studied and built as a solution to the mismatch between heating demand and available heat. According to IEA Solar heating and cooling report [3], the seasonal heat storage in Central Europe are built to store the heat produced by large collector fields during the summer months and deliver it through DH nets to heat the connected buildings in winter. The report notes other use cases for storages of big volumes that aim at increasing the use of biomass for electricity production, geothermal energy, waste heat from industry, dissociating electricity from heat production at combined heat and power (CHP) plants. Xu et al. [4] review technologies for seasonal thermal energy storages (sensible, latent, chemical) and conclude that sensible heat storage would remain dominant in large-scale applications in the short run. According to Gjoka et al. [5], seasonal heat storage is one of the main characteristics of the 4th and the 5th generation district heating and cooling. The distinction of the 5th generation systems is that they utilise a distribution temperature level that requires HPs to supply heat to connected buildings, while heat storages are used for smoothening out both heating and cooling peak heat demands. Several large-scale seasonal heat storages connected to district heating have been built in Europe, commonly in combination with solar collectors. Bauer et al. (2009) [6] summarize design, operation and monitoring of several types of seasonal heat storages implemented in Germany, and later Bauer et al. (2016) [7]) explore different characteristics of systems in Poland, Spain and Germany. Tian et al. [8] describes seasonal heat storages in Denmark and notes they may increase the share of solar heating and accommodate excess wind power (via HPs).

Penttinen [9] studied the sizing of a large cavern thermal energy storage for utilisation of heat from a waste incineration plant in summer. They concluded that in the most profitable case (90 GWh, 200 MW) the payback period is 14.5 years, the internal rate of return is 8.6 % and that the system emissions are reduced by more than 50 %.

Volkova et al. [10] studied the use of large-scale HPs in Baltic countries, concluding that heat storages play a significant role within future energy systems. Golmohamadi et al. [11] also identify heat storages as one of the most critical tools for increasing the flexibility of DH systems, both in short and long-term (seasonal) perspectives.

Vandermeulen et al. [12] define flexibility as the ability to speed up or delay the injection or extraction of energy into or from a system. In thermal networks this ability is related to thermal capacity, which may be found in heat carrier, thermal storage devices and thermal inertia of buildings.

Volkova et al. [13] studied a low-temperature sub-system connected to the return line of a larger DH system. The results of the study indicate that this type of connection enables increased utilisation of low-grade heat sources, reduced network losses and an increased energy generation efficiency, as well as enabling a part of the DH system to transition to 4GDH. Puschnigg et al. [14] reviewed low-temperature sub-networks in existing DH systems in Austria, Germany and the Nordic and the Baltic countries. The studied low-temperature systems were generally connected to the return line of the larger DH system. It was concluded that while solutions including low-temperature sub-networks have their limitations, they can enable an increased integration of renewable heat sources such as low-temperature waste heat, solar heat, geothermal heat.

Buffa [15] carried out a review of the 5th generation district heating and cooling systems. These systems are based on a neutral temperature (close to ambient temperature) network and DH substations with brine- or water source HPs. It is suggested that such networks can be considered alongside ground-source HP systems on a district scale. While customer substations become more complex and expensive, the benefits include low heat losses, lower pipeline insulation requirements, bi-directionality, and ability to recover low-temperature heat sources.

Hiltunen & Syri [16] show that significant carbon dioxide emission reductions and decrease of heat production costs are possible by utilisation of waste heat from data centres in district heating systems. The two-stage HPs are estimated to reach coefficients of performance of 5.5 due to high-temperature sources, which are exhaust cooling air (35 °C) and cooling liquid (50 °C) and supply temperature exceeding 90 °C 6.6 % of the time.

Jodeiri et al. [17] reviewed aspects related to the opportunities and challenges of integrating different renewable energy sources into DH systems in transition to 4GDH. One of the conclusions is, that the use of seasonal heat storage and lower distribution temperatures will be a necessary step to efficiently utilise renewable energy sources in a larger scale. Volkova et al. [18] discusses hurdles DHSs must overcome during transition into 4GDH and provides solutions how to overcome these problems. A methodology for evaluating the transition process to 4GDH is also presented by introducing six key performance indicators. These indicators are: 1) average DH supply and return temperature, 2) network average heat transmission coefficient, 3) the share of consumers covered by intelligent metering, 4) annual total renewable energy for heat generation, 5) CHP heat capacity and 6) the share of short-term thermal energy storages from CHP heat capacity.

The study in hand carries out a preliminary assessment of the viability of the dynamically distributed DH concept in the city of Helsinki and within its city-wide DH system. The city is divided into small areas with estimated heat demands based on the building stock data and the open-data total district heating demand provided by local DH company Helen. The objective of the study is to assess the impact of potentially suitable areas, to propose a design for a local large-scale heat storage and distributed heat supply, and to evaluate the overall cost-efficiency of the concept by modelling the heat supply costs using an optimisation model representing the DH systems within the metropolitan area of Finland. A secondary objective is to show and discuss how this concept would shape the operation of the main system.

2. Methodology

The assessment is carried out in seven steps as illustrated and summarised in Fig. 1, and elaborated below in more detail.

The first step in the process is the building stock data sampling carried out by Statistics Finland [19]. This data includes the total floor area for each small areas within the city of Helsinki, representing a higher spatial resolution than e.g. postal codes or districts within the city. The data is further grouped into total floor area built on a specific decade (decade of construction). The resulting values are then multiplied by an assumed average specific heat consumption (kWh/m^2) for buildings built on a specific decade to evaluate a yearly heat demand corresponding to each of the small district areas. Assumption (see Fig. 2) are based on updated datasets of the REMA model [20] by VTT Technical Research Centre of Finland.

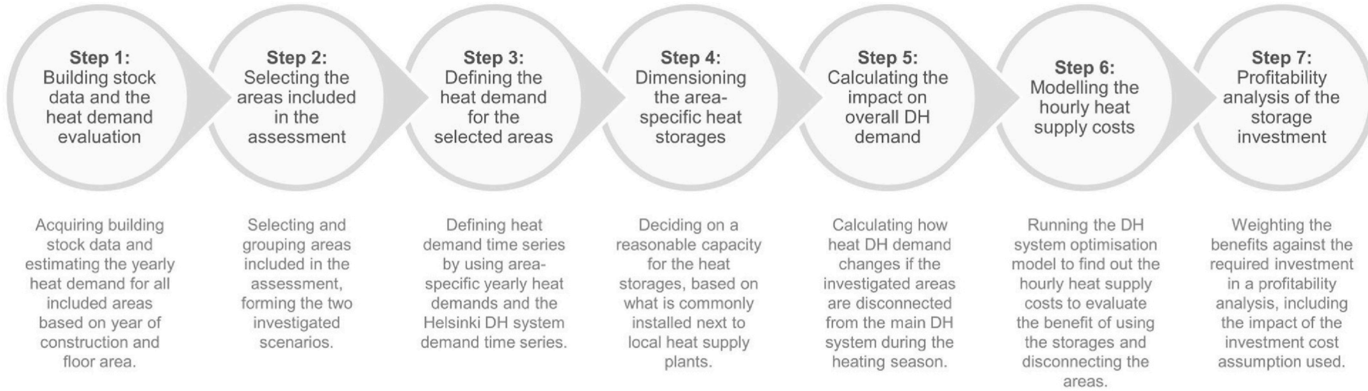

Fig. 1. An overview of the method used, described in seven steps.

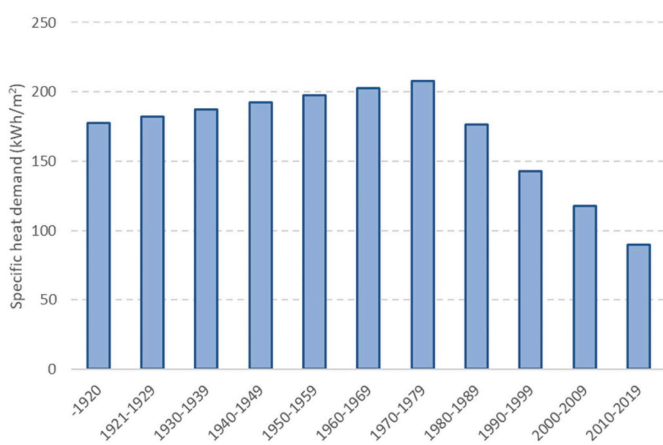

Fig. 2. Specific heat consumption assumptions for buildings built on a specific decade.

The second step includes the definition of the areas to include in the dynamically distributed district heating concept investigation. The areas are chosen from the outskirts of the DH system and the city, located away from the large-scale heat supply sites, i.e. the locations of the current CHP plant sites. They are also the most likely locations for future, large-scale energy supply units as they are defined as energy sites in city planning. At present, the site in the middle (marked with a dashed line circle), Hanasaari, has been decommissioned. However, a heat-only boiler plant exists. The two scenarios, "selected" and a larger area selection called "extended", have total yearly heat demands of 1.5 TWh and 2.8 TWh, respectively. Fig. 3 illustrates the areas selected, and the locations of the current CHP plants.

The third step consists of producing heat demand time series for each selected small area. This is carried out by utilising the open data made available by Helen [21] and by calculating the heat losses for each area. The heat loss evaluation is based on statistical data [22] between 2015 and 2020 (6.9 %). System level demand time series (open data by Helen) is then scaled to the resulting total demand and losses for each area, producing a set of area specific time series.

The fourth step is to assess the impact of a reasonably dimensioned seasonal heat storage for the demand time series; peak shaving during the heating season and increased base load outside this period. The heating season is defined to start at the middle of September and to end in middle of April. The storage capacity has been defined as 600 MWh (for each small area), which roughly corresponds to cylindrical accumulators commonly installed next to CHP plants, e.g. a storage of a similar size can be found within Salmisaari CHP plant site in the Western part of the Helsinki DH system. A storage of this capacity is large, but still something that could be implemented within urban surroundings. The total storage capacities in the two scenarios are 54 GWh and 90 GWh, respectively.

The fifth step is to use the area specific time series to find out how the system level DH demand looks with the storages included, and by disconnecting the areas from the core system during the heating season. The study assumes that there is enough distributed heat supply within each area; e.g. building-specific HPs or other local small-scale heat supply. These units have a total capacity of approximately 60 % of the peak demand. As the areas are compact and disconnected from the core system, the local distribution network within the small areas can be managed at lower temperature levels, thus improving the efficiency of local small-scale heat supply (if present and connected to the network).

The sixth step is to use the compiled system level demand as input for the Backbone optimisation model [23] for the specific case system to assess the hourly heat supply costs. The aim is a straightforward calculation of the benefits of using the low-cost heat available during the summer to charge the seasonal storages. This is how using the more expensive heat supply during the heating season is avoided, generating savings – and to pay back the heat storage investments. The analysis of the DH system utilises scenarios prepared for the Helsinki region DH modelling exercise concerning a small modular nuclear reactor (SMR) based DH system [24]. The hourly DH demand is varied according to energy storage modifications applied in this study and the electricity price is adjusted to the 2019 data. The DH production capacity within the Helsinki region is defined by including the existing capacity, and additional SMR based capacity (four SMR units of 200 MW each with 5 €/MWh production cost). An emission trading price of 100 €/ton is assumed. The electricity price time series is updated for the year 2019 and the natural gas price is set to 50 €/MWh. The hourly results from an annual optimisation are analysed in terms of three DH demand scenarios and calculating DH related production costs (in the case of gas-fired CHP unit, the gas consumption is calculated for DH by using energy-based allocation) for each modelling hour. In the Helsinki region, DH production can be basically divided into three categories: (1) SMR based production, (2) DH HP based-production, (3) biomass boiler-based production and (4) gas-fired unit based production. For simplicity reasons, import and export of DH to/from Espoo and Vantaa regions are ignored from the production cost calculations. SMRs are used here as the future baseload option, but they could be replaced by other low-cost alternatives such as large-scale utilisation of excess heat. In the case of Helsinki, this option could be the Kilpilahti refinery – at least if its main activity changes from oil refining into e.g. hydrogen and/or electrofuels production. The potential use for increased flexibility due to new heat storage capacity and the distributed HP based heat supply is not included in the optimisation.

In the seventh and final step of the approach, the benefit of utilising low-cost heat and seasonal storages is evaluated. This means that the value of the heat supply replaced by the use of storages is calculated, based on the modelling results. This value is used in a straightforward

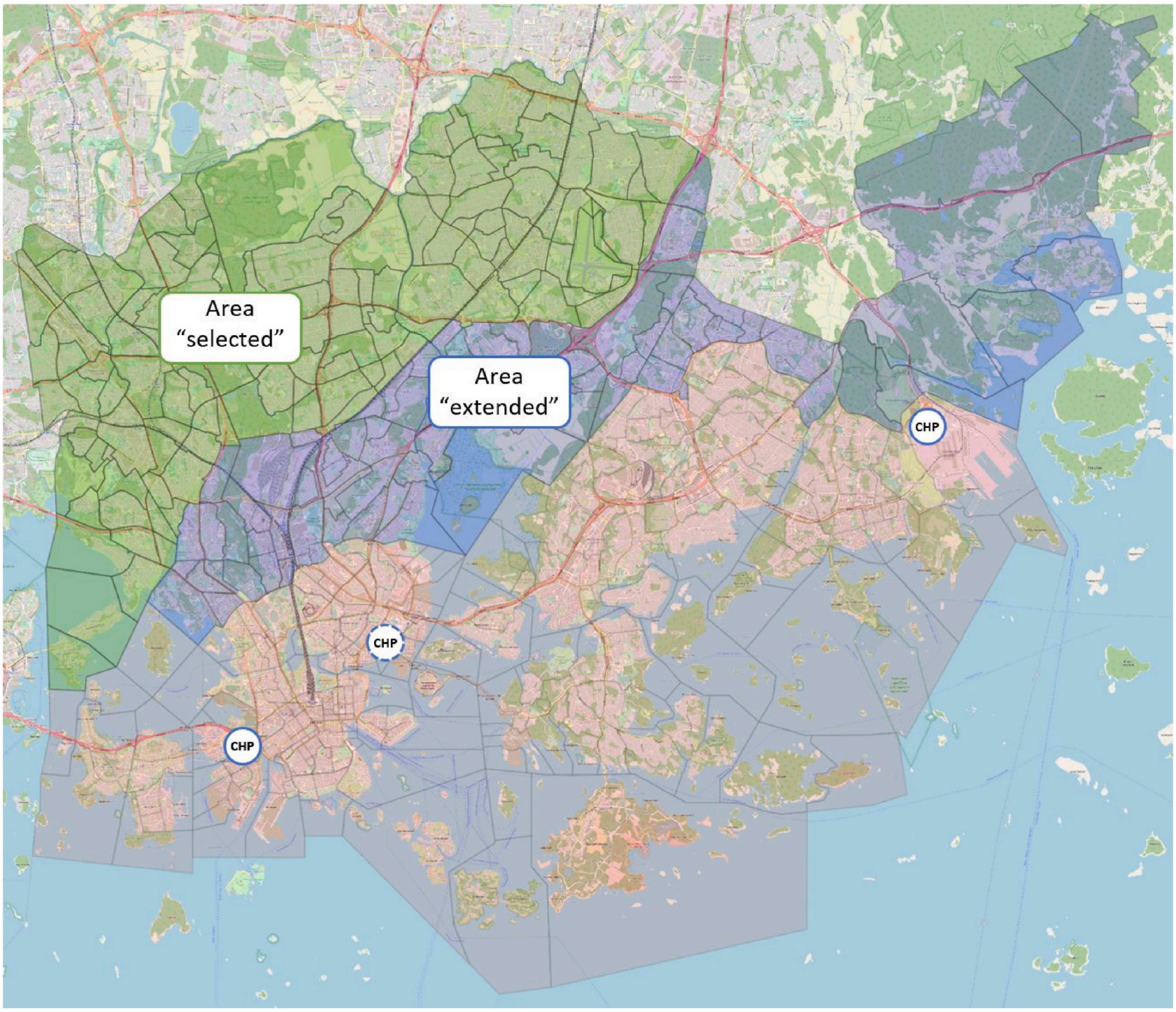

Fig. 3. Areas included in the assessment of dynamically distributed district heating concept (“selected” and “extended”) with major DH supply sites marked as small circles.

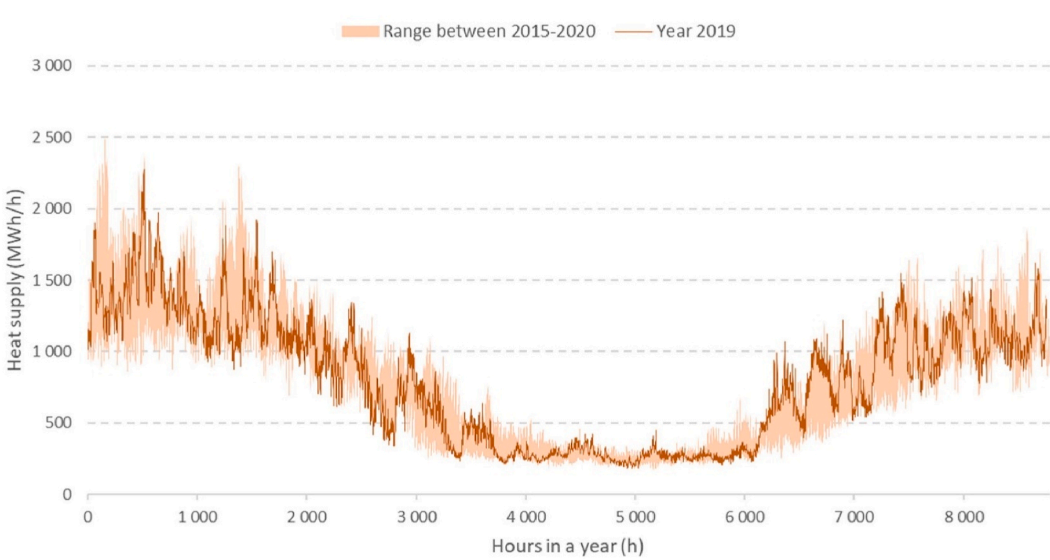

Fig. 4. District heating heat supply in Helsinki; range between 2015 and 2020 and the chosen example year 2019.

profitability analysis where a specific cost for the heat storage investment is assumed.

3. Case study description

The Helsinki DH system is the largest DH system in Finland with an annual heat demand of approximately 6–7 TWh. It also has a reasonably high linear heat density (4.7 MWh/m in 2019), making the system quite efficient in terms of heat losses (6.9 % in 2019) [22]. Fig. 4 illustrates the variation of the heat demand between 2015 and 2020, highlighting the year 2019 used in calculations of this study.

Although having one the largest HP facilities in the world (Katri-Vala HP plant [25], 126 MW heat and 80 MW cooling), the heat supply is still mostly based on fossil fuels, largely coal and natural gas (almost 90 %). Due to limited natural resources and/or large-scale excess heat, combined with the sheer scale of the system, the decarbonisation pathway is challenging. Also, many of the heat sources available are more abundant during summer, thus indicating a need for energy storage. Because of all this, the Helsinki DH system will in time have to become an archetype of a modern, sustainable DH system with a diverse set of heat supply options. This can also be the only option as there appears to be no single solution that can solve all challenges related to the decarbonisation effort. The recent innovation competition Helsinki Energy Challenge [26] highlighted this, as most of the entries introduced a complex set of heat sources to be utilised and a considerable heat storage capacity.

In this study, the focus is on one possible low-carbon scenario for the DH system that includes SMR-based capacity, HPs and limited biomass combustion as main heat supply options with natural gas as the source of peak heat supply. The SMRs are one particularly interesting solution for the reasons mentioned in the paragraph above. However, it is very similar to any large-scale excess heat source (low-cost heat, possible surplus production during summer-time), offering a perspective for generalisation of the results and ideas presented here.

Finally, the selections from the small districts and their corresponding heat demand are illustrated in Fig. 5. The colour-coding matches colours of the map in Fig. 3.

These three sets of small districts also form the scenarios investigated further in the results section.

4. Results

Fig. 6 shows the DH demand duration curves seen by the core system and the centralised heat supply units. The annual heat deliveries drop in "selected" and "extended" scenarios by 14 % and 27 %, respectively. Similarly, the peak heat demand drops by 18 % and 37 %.

The optimisation results (i.e. which type of units are in operation) corresponding to a system without introducing the dynamically distributed DH concept are illustrated in Fig. 7. The most interesting result from the two scenarios including the concept is the impact on full-load hours of the SMRs. These are 4416 h without the concept, 6741 h in the "selected" scenario and (interestingly) 6335 h in the "extended" scenario.

The heat supply specific costs of this optimisation run are used to calculate the value of the heat supply replaced by the distributed storages in scenarios "selected" and "extended", with the charging cost deducted (5 €/MWh; SMR-based heat supply during the summertime). These heat supply costs (€/MWh) are multiplied by the storage output (MWh/h) with results illustrated in Fig. 8 as cumulative monthly values (a) and (descending order) hourly values (b).

The total benefit of "selected" and "extended" scenarios are 2.2 M€ and 3.5 M€, respectively. Similarly, the relative values for the stored heat on average are 41.2 €/MWh and 39.1 €/MWh.

The resulting profit generated by utilising the heat storages is then evaluated in a profitability analysis with an assumption on investment costs. The investment costs are given as a range of possible costs with the average likely investment cost highlighted. The low, average and high investment costs assumed (based on [9,27,28] are 0.1 €/kWh, 0.7 €/kWh and 1.0 €/kWh, respectively. The highest investment costs (in the region of 10 €/kWh) are not considered here. A discount rate of 2 % is used, reflecting the role of the storages as long-term infrastructure components. The results are shown as cumulative investment curves in Fig. 9.

The payback times corresponding to the average investment cost assumption are 21 and 23 years for "selected" and "extended" scenarios, respectively.

5. Discussion

As expected, both the heat demand and the peak demand of the core system drop sharply when introducing the dynamically distributed DH concept; the demand profile for the system is simply flatter. This makes the core system more favourable for heat supply used for base-load. When looking at the optimisation results for the scenarios where the concept is introduced, the base load heat supply (SMRs) and its full-load hours are the highest in the "selected" scenario. In the "extended" scenario, the core system heat demand during the heating season drops

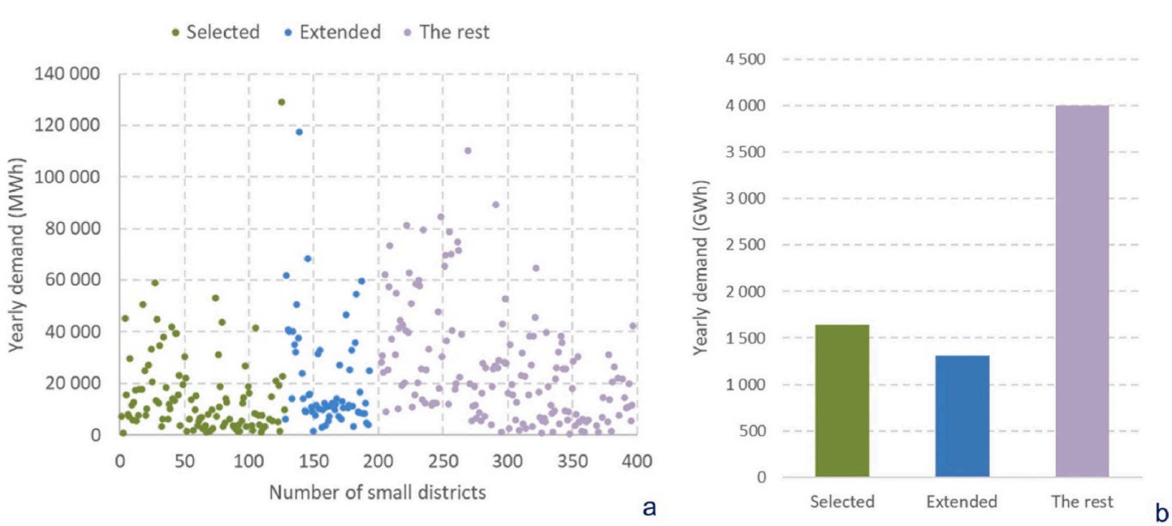

Fig. 5. Small districts and their specific heat demand for selected and extended scenarios, and the rest of the city. Left figure represents the district specific demands (a), and right figure the total demand for each group of districts (b).

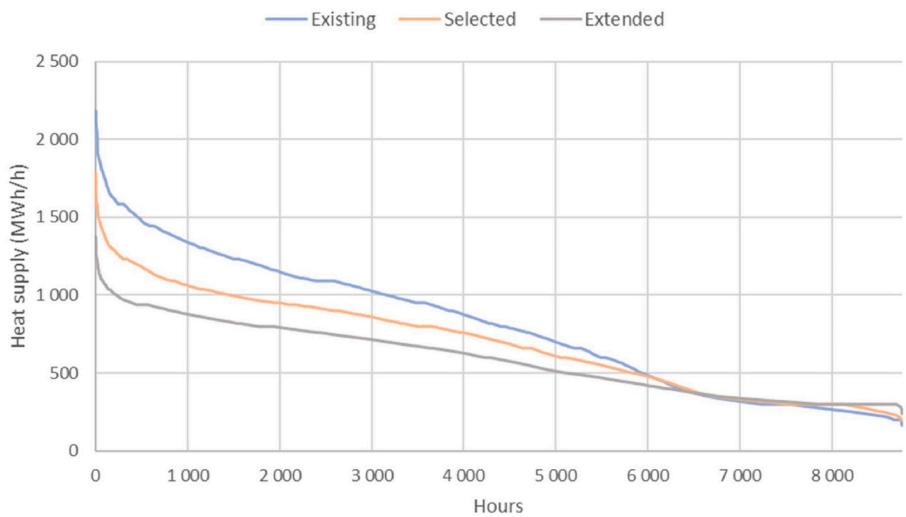

Fig. 6. Heat demand duration curves seen by the core DH system and the centralised heat supply units in different scenarios.

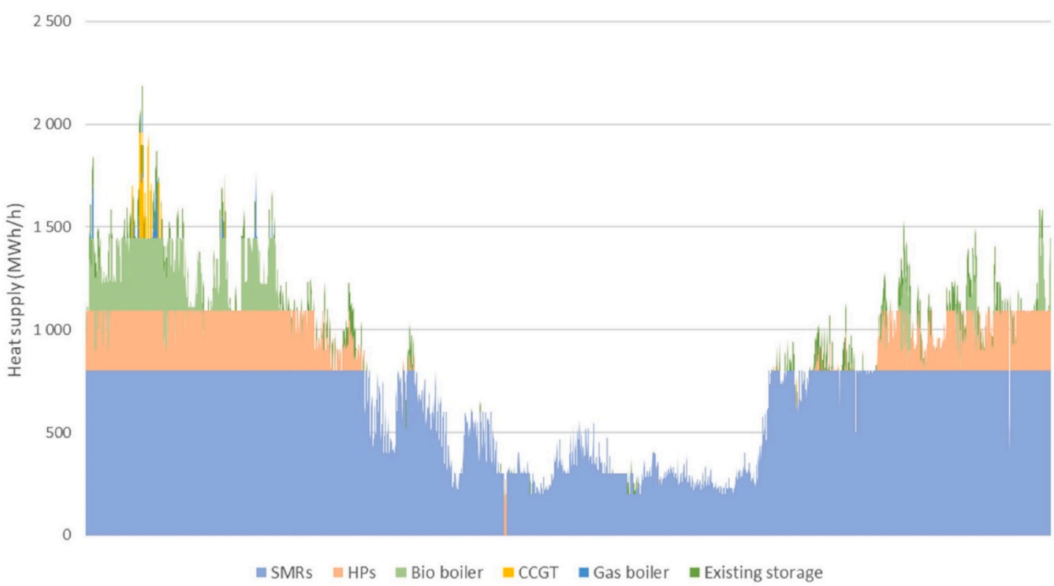

Fig. 7. Heat supply of the existing system with three SMR units as baseload corresponding to a reference scenario with no area specific heat storages included.

below the capacity of the SMR units from time to time. The full load hours still remain quite high (over 6000 h).

The benefit of the seasonal storages, i.e. the cost difference of heat supply when the storages are loaded and when they are unloaded, is considerable; around 40 €/MWh on average – in both of the studied scenarios. This provides a solid case for a seasonal heat storage. However, the investment cost is still a major factor – and even the estimated average investment costs result in payback times of around 20 years. Also, the analysis is carried out on a system level, i.e. summing up the use of storages in the calculation of the cost-savings they are generating – but individual small districts must be cost-efficient enough to justify the investment. Although the focus here is on seasonal heat storage application due to the assumed, very affordable (5 €/MWh) heat supply – there could also be a case for utilising the large storage capacity for flexibility purposes. This could enhance the profitability of the storage investment.

However, the concept as such is not envisioned to present a sole solution to decarbonise a large-scale system such as the Helsinki DH system studied here. It represents a moderately cost-efficient solution for transforming the system step by step into a one utilising 1) more low-carbon distributed heat supply and 2) low distribution temperatures. This is done in a way that makes the operation of the remaining core system more efficient as well. Firstly, the remaining demand profile is more favourable for the centralised heat supply. Secondly, the small districts on the outskirts of the system no longer set limits for the supply temperature from the centralised production. This means 1) lower heat losses and 2) improved efficiency of the heat supply, especially of HPs. SMRs considered here are not affected by the temperature level of the network, but e.g. a large-scale utilisation of excess heat from an industrial site would be.

The concept addresses one of the most significant barriers in developing large-scale DH systems, the inertia; meaningful changes in the systems take time and are difficult or impossible to implement for the whole system at once. Considering the DH system in smaller parts can enable faster transition to 4GDH, bringing immediate financial and emission reduction related benefits.

The main limitation of the study is related to the scale of the task. A full-scale analysis would include at least the following components: Accurate data on the network structure, analysis on locally available excess or renewable heat sources, simulation of the network thermal

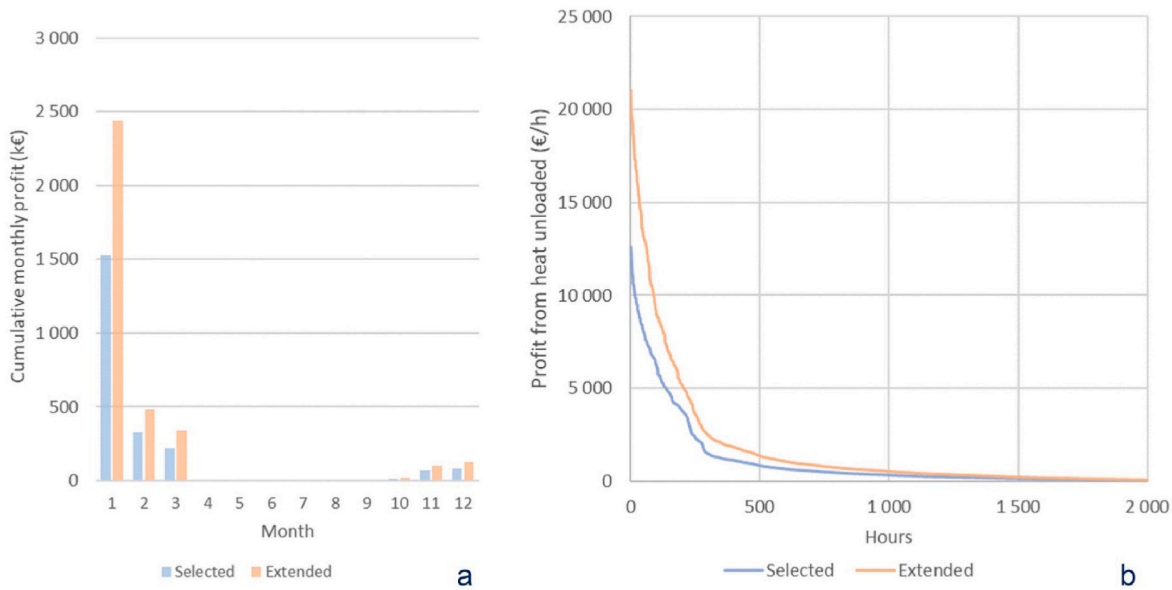

Fig. 8. Profit from utilising the stored heat in distributed storages for selected and extended scenarios as cumulate monthly values (a) and on an hourly level (b).

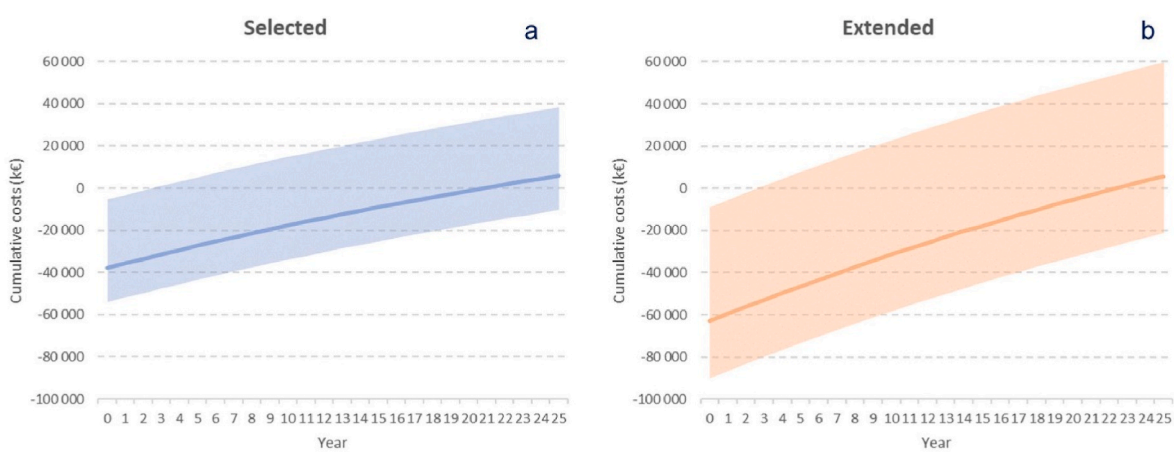

Fig. 9. Cumulative costs corresponding to the storage investment for selected (a) and extended (b) scenarios. Transparent area represents the range corresponding to low and high investment cost assumption while the line marks the assumed average cost.

dynamics within a system utilising the concept, measured or otherwise more accurate heat demands, more careful analysis on managing the distributed storages and the corresponding areas and parts of the DH network, design and implications of the method of disconnecting the areas in practice, and finally, a selection of the areas best suited for the concept. All this results in massive data requirements and need for several separate studies related to specific parts of the system and the concept. However, the study here lays the groundwork for planning such an undertaking and can help in identifying the most suitable systems for this type of work.

6. Conclusions

The study introduces the concept of dynamically distributed district heating and carries out a rough techno-economic evaluation of the concept in a large-scale DH system in Helsinki. The first results look mildly positive and point out a direction for further studies.

The results remain highly dependent on the difference in costs between the summer-time base load and the peak heat supply during the heating season, as well as the investment cost of the heat storage. The estimated average investment costs and the modelling results indicate that the concept could be techno-economically viable, although only barely, considering the payback times being a bit over 20 years. If the difference in costs is higher, and/or the investment costs lower, the payback time could be considerably shorter.

However, the main motivation behind the concept is that it could offer a cost-efficient way to transform a 3GDH system into a 4GDH, part by part. New distributed heat supply could be introduced into the partly disconnected districts and lower distribution temperatures could be introduced, further improving the efficiency of the new heat supply. The more such districts there are, the more favourable the total heat demand seen by the core system looks like, i.e. the utilisation rate of the affordable base load in total heat supply would grow. All this supports the transition into 4GDH systems that are based on renewables and utilisation of excess heat, and that are flexible and can thus operate in a future energy system with increasing wind and solar based electricity production.

It needs to be stated that the current evaluation does not consider the quite extensive addition of HP-based heat supply (the distributed heat supply within the districts) as an investment. However, it is very likely that HPs (in different applications) will play a major part in the decarbonisation of a system like Helsinki in any case. From this point of view, the presented concept merely provides a way of introducing the needed HP capacity in a highly efficient manner. It can be argued that the related investment would need to take place in any case and can be considered separately from the evaluation in this study. Also, the profitability of the HP investment or any investment in the system is also in practice paid back with revenues from the heat sales in general. The profitability assessment made within the scope of this work focuses on the storage investment and its direct impact only.

The topics for further research concerning the topic include more detailed evaluation of the individual districts, a more detailed technical design for the districts and the storage, identification of the most attractive areas (availability of heat sources, suitable location within the existing distribution network) and a more detailed impact assessment for the core system (including the distribution network and its temperatures). This would all contribute to an overall assessment that would indicate the true, realistic potential of the concept for a specific system and a defined operational environment.

Author contribution

Miika Rämä: Supervision, Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Esa Pursiheimo: Methodology, Formal analysis, Investigation, Writing – original draft. Dennis Sundell: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. Rinat Abdurafikov: Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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