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Exploring the location and use of baseload district heating supply. What can current heat sources tell us about future opportunities?

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ABSTRACT

The decentralization of energy production and recovery of excess heat (EH) to reach climate targets is essential for renewable and fully decarbonized heating systems. This paper identifies current and potential industrial EH sources providing baseload capacity for district heating (DH) systems. These sources are evaluated by sector and process for supplying baseload capacities explored for current 3rd generation district heating (3GDH) and 4th generation district heating (4GDH) systems with lower grid temperatures and losses, with and without expansions. The method combines geographical analysis and available baseload capacity estimations for 360 Danish DH systems scenario-making and an additional sensitivity analysis evaluating baseload capacity full-load hours. It is found that 80 % of Danish DH systems have an unmet baseload capacity of 50 % or higher. Half of the systems have geothermal capacity available and up to 20 % of industrial EH baseload capacity potential, which sums up to 5 PJ of EH potential within a 2 km distance. The findings also suggest that there is an additional opportunity for the placement of future energy infrastructure able to supply EH, which is highly contextual and strategic in heat planning, particularly considering the future development of sustainable and energy-efficient DH systems.

1. Introduction

Global greenhouse gas (GHG) emissions are unprecedentedly speeding up global warming processes and independently affecting different geographical scales [1]. According to the latest IPCC report on Climate Change, a call must be made for urgent and faster climate action to mitigate the earth's temperature adaption and limit global warming to 1.5 °C above pre-industrial levels [2]. Amongst the efforts towards climate action are climate agendas that push for faster and targeted carbon emission reductions [3]. Energy systems are spotted as having great emission reduction potentials [4], since the production of energy is responsible for around 87 % of global GHG emissions [5]. Significant climate actions require ambitious energy transitions that explore suitable energy technology pathways supporting systems' objectives. Energy transitions involve phasing out and ultimately replacing fossil-fuelled technologies, which require new, unused, and underused alternative renewable energy sources (RES) [6]. Low-cost and energy-efficient integration of RES must be understood as an integration across all energy sectors, the so-called Smart energy systems (SES) approach [7]. Typically, the SES approach considers integrating RES technologies and cross-sectoral connections between the electricity, heating, industry, and transport sectors [7,8]. A main focus has been the heating sector since it has demonstrated low-cost solutions for RES integration and several potentials for renewable heat generation. EU-wide alternatives and strategies for local heat supply assessments have been investigated in the Heat Roadmap Europe projects [9–12], arguing that new heating strategies can reduce approximately 15 % of the costs by increasing efficiency and integrating heating systems. According to Connolly et al. [13], heating strategies integrate District Heating (DH) systems and energy efficiency in buildings as well-established technologies offering increased efficiency and flexibility while supporting the decarbonization of the other system components, such as the electricity sector. DH systems provide heat produced centrally and distribute it to users through a distribution grid to cover the heating demand in buildings, mainly space heating and domestic hot water (DHW). This study focuses on Denmark, where traditionally designed DH systems have evolved throughout the last

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Nomenclature

GHG	Greenhouse gas
DH	District Heating
EE	Energy efficiency
EH	Excess heat
3GDH	3rd generation DH
4GDH	4th generation DH
GIS	Geographic Information Systems
DHW	Domestic Hot Water
RES	Renewable Energy Source
EU	European Union
FLH	Full-load hours
BL	Baseload
CHP	Combined Heat and Power
HD	Heat demand

century. This development has been triggered by fossil resource scarcity and its characteristic deficiency; the already developed DH systems started transitioning their supply from coal and oil combustion only to fossil-based Combined Heat and Power (CHP) plants [14]. Natural gas has partly replaced oil and coal for Danish DH systems as a transitory fuel that reduced emissions relative to the fossil fuel replaced. As renewable integration penetrated the system, fossil dependency decreased, and DH technologies moved accordingly to reach a more sustainable heat supply. By incorporating solar, geothermal, biomass, and biogas resources, fossil fuels accounted for 16 % of the total fuel consumption for Danish DH systems in 2021, which shows a reduction in the reliance on fossil fuels by about 50 % compared to the numbers shown for 1990 [15] in Fig. 1.

By 2021, of the approximately 400 DH networks in Denmark 70 % are renewable based and classified into small, decentralized, and centralized systems according to their connections and the number of dwellings they supply. Altogether, these systems covered over 50 % of the national heat market in 2019 and 66 % of Danish households [15]. Specific features have marked this development in Danish DH systems, such as large-scale heat planning, specific mandatory connections, and non-profit principles, as highlighted by Johansen and Werner [16]. In the coming years, these numbers are foreseen to increase due to the government's ambition to increase energy efficiency in buildings and DH expansion to transition individual heating systems away from fossil fuels, e.g., a government instrument policy that targets 200,000 new connections to DH systems within a 2023–2028 timeframe [17,18]. Additionally, to meet a national carbon neutrality target, the DH Association in Denmark has established a CO_2-neutral DH system for 2030, highlighting potentials from renewable fuels such as geothermal, excess heat from industry, and data centres, amongst others [19].

Regarding the efficiency and flexibility of heating systems, old and current DH systems have improved by integrating solar thermal, geothermal, or energy conversion technologies such as power-to-heat technologies [20,21]. This DH evolution and increased energy sector integration are defined as a generational development by Lund et al. [22], which defines current 3rd generation DH (3GDH) and future 4th generation DH (4GDH) systems. The future generation of DH systems incorporates extra RES by allowing lower supply and return temperatures [23] within the systems; these are around 80–100/45 °C in 3GDH, compared to 50–60/25 °C in 4GDH [24,25]. Literature supports that lower temperatures reduce fuel consumption and carbon footprint [26], which means that 4GDH scales down systems' costs and allows additional renewable integration while working as conventional hybrid-fuelled systems. Danish research has already marked the gradual expansion of DH as strategic for reaching Denmark's 100 % renewable energy targets [27,28]. Sorknæs et al. [29] point out efficiency measures in both the heat demand and the heat supply side as fundamental to reaching new generations of low-temperature DH systems. Nielsen et al. [30] simulate scenarios of potential DH expansion considering both measures in The Northern Region of Denmark. Both authors highlight the utilisation of industrial waste heat sources and the utter dependency of their usage potential on the specific geographical dimension of the analysis. These discoveries are also taken to specific targets in the IDA Climate Response 2045 where a gradual conversion of 3GDH to 4GDH, 50 % for 2030, and 100 % by 2045 is targeted [31].

4GDH systems allow for a lower cost utilisation of unused or underused heat sources, such as waste heat or excess by-product heat from industrial and commercial processes. Danish unconventional sources such as data centres, wastewater treatment, metro stations, and service sector excess heat are already targeted and could significantly support low-temperature DH systems [32]. Sustainable heat sources have certain advantages and disadvantages, including renewable energy sources and excess heat in pathways for future decarbonized DH systems. Systematically, excess heat from industry and commercial activities offers increased efficiency in energy utilisation and yearly availability while

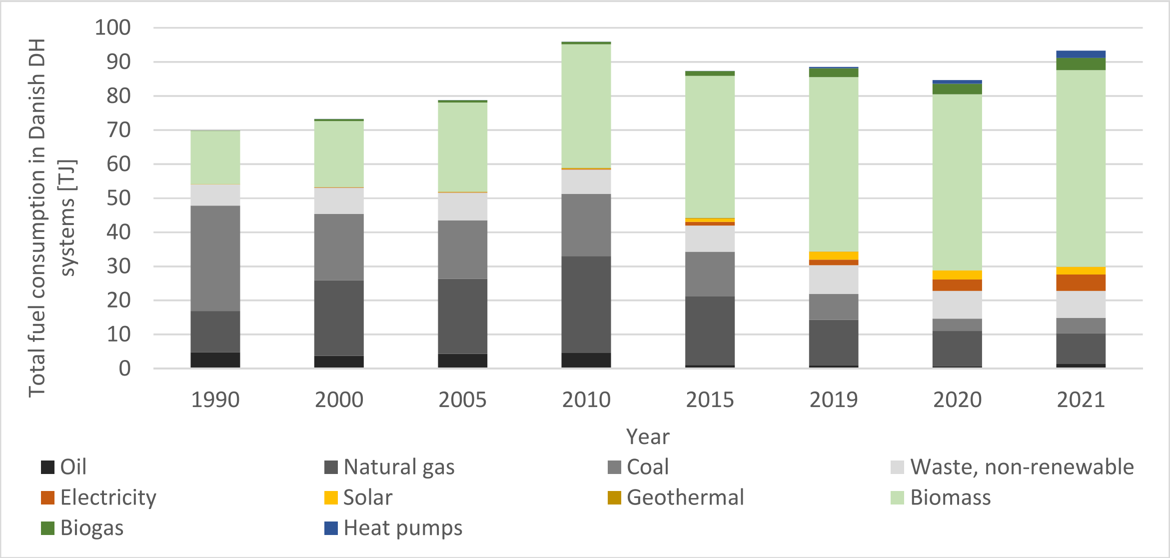

Fig. 1. Development of total annual fuel consumption in Danish DH systems [TJ] with data from Ref. [15].

simultaneously representing challenges due to geographical location limitations [33]. At the operational level, there are still several challenges related to new DH systems due to concerns related to the environment, the safety of lower temperatures in water circulation systems, and building infrastructure readiness for such temperature transition [34]. Overall, it is necessary to promoting the understanding of these sources as excess heat producers to exploitable renewable heat resources through research, as expressed by Werner [35].

International studies also support these statements, such as the mapping of DH jointly with hybrid energy system analysis, which shows that excess heat contributes significantly to the energy supply of the DH system at a province level in Turkey [36]. Or the societal waste heat accounting model developed in China to map excess heat, highlighting the largest potential in the industrial sector. The Chinese study states that excess heat represents 42 % of total primary energy input and a theoretical 26 % of energy savings through excess heat [37]. At a European level, studies suggest that industrial excess heat could potentially supply around 17 % of the building heat demand in Europe [38] and about 78 % of an estimated 71 % DH coverage potential for the 14 European Union member states [39]. Other studies that specifically consider urban low-temperature excess heat sources quantify up to 1.2 EJ/y of heat potential, including heat recovery demonstration sites throughout Europe [40]. Researchers investigating heat recovery from large industrial facilities at a small scale suggest that smaller heat sources should be considered and that detection with spatial planning is fundamental [41]. At the same time, according to Bühler et al. [42], Danish energy-intensive industries could meet 5.1 % of the national annual heat demand. In energy systems studies, these excess heat sources have effectively covered different DH demand shares in system scenarios, concluding positive economic feasibility [43,44].

The literature cited substantiates further validation for broadening the analysis scope regarding RES baseload for DH systems. With expected growth and generational changes in DH technologies, non-traditional heat sources will gain relevance because they will penetrate the system, competing with existing DH baseload facilities. To facilitate this transition, it is crucial to understand the role of the geographical dimension within DH ecosystems to optimize the usage of this resource.

2. Scope

Excess heat (EH) is surplus or waste heat generated as a by-product from industrial facilities that are typically released into the environment or dissipated by cooling systems. Given today's climate, energy quantification instruments are crucial for assessing current and future renewable heating systems. Much of the cited literature and studies include EH as a renewable heat input when modeling energy systems. While these studies address potential EH, they compromise their analysis accuracy by simplifying and omitting geographical dimensions, using top-down approaches, or filtering out potential heat sources by solely focusing on energy-intensive and high-temperature industrial processes. These limitations become relevant locally as DH systems are geographically unique and highly contextual, as is the availability of surrounding heat sources. In the initial hypothesis, the authors propose that there is untapped potential for renewable heat supply in the wide range of industrial or commercial facilities and geographically identified geothermal energy sources, particularly considering 4GDH systems, spatial infrastructure expansion, and the availability of new heat sources. The hypothesis is explored by focusing on the location of the heat demand (HD) of current and future Danish DH systems, and heat supply potentials, i.e., industrial EH and geothermal energy. HD estimates in DH systems include end-use EE savings and system losses for both types of systems, 3GDH and 4GDH. Industrial branches, processes, and temperatures are factored in the EH quantification which materializes in the study as potential supply of baseload (BL) heat capacity to the local DH system. The methodology covers the geographical dimension using location and proximity of both HD and heat supply in DH systems which are assessed through geographic information systems (GIS). The outcomes from the method are used to discuss the unfulfilled BL capacity in current and future DH systems. While the location of unserved BL capacity implies an opportunity for emerging heat sources involving exothermic processes, i.e., data centres or Power-to-X facilities, the outputs show a large diversity in what Danish DH systems need in the future. The study focuses on energy, not economic or environmental assessments of infrastructure expansion or the incorporation of heat sources into the systems. The estimated EH potential in this research disregards the usage of additional heat pumps in the systems, which is anticipated to favour the EH potentials presented if included. An additional constraint of the study is the omission of potential advancements in industrial technology, such as processes electrification or energy efficiency measures at a facility level, which can impact the estimations made. Consequently, the paper showcases a novel bottom-up geographical methodology for assessing the location of EH potential for the energy supply in current and future DH systems, using Denmark as the geographical scope for the analysis.

3. Methods

This section describes the methodology for assessing the potential RES BL capacity in Danish DH systems. The methodology starts by creating an overview of the geographical location of current DH areas and the network expansion potential, as well as mapping heat sources to supply for 3GDH and 4GDH systems. Secondly, it elaborates on the methodology pursued to assess the potentiality of RES to supply the systems. Thirdly, a sensitivity analysis is conducted to discuss the identified potential. The methodology includes mapping and technical estimation methods as a starting point for such local and specific assessments. A visualization of the methodology is illustrated in Fig. 2, where the connection and feed from the methodological parts are shown.

This study presents the potential contribution of each RES to the national aggregated DH demand. This is reached by categorizing RES heat into temperature levels to supply different generations of DH systems and performing a BL capacity estimation. Results are also presented for several regions in Denmark to show the high dependency of potentials on the particular location.

3.1. Mapping heat demand and supply

GIS methods are used for the identification of the location and further spatial analysis of current systems, their heat supply, and heat source facilities near demand sites. The software used for the spatial analysis is ArcGIS Pro 3.1.0 [45]. In the analysis, DH networks and their expansions are polygon features where heat demand from buildings is aggregated into total demands within each polygon. The excess heat sources are point features, and included in this assessment are current waste incineration and current and potential industrial EH. Furthermore, the geothermal potential is shown as a polygon feature covering larger areas that are expected to have a geothermal potential. The analysis is performed at a DH network level, and a near analysis is performed using a buffer radius from DH networks. The buffer distance responds to a desirable closeness for potential network connection, given the costs of installing and maintaining the distribution of the heat network effectively and efficiently. Depending on the size of the heat source and potential heat pump additions, the connection to the DH system might become feasible at further distances. Hyper-local urban studies have considered distances ranging from 250 to 500 m [41], while other city-level studies have used 2 km distances from excess heat point

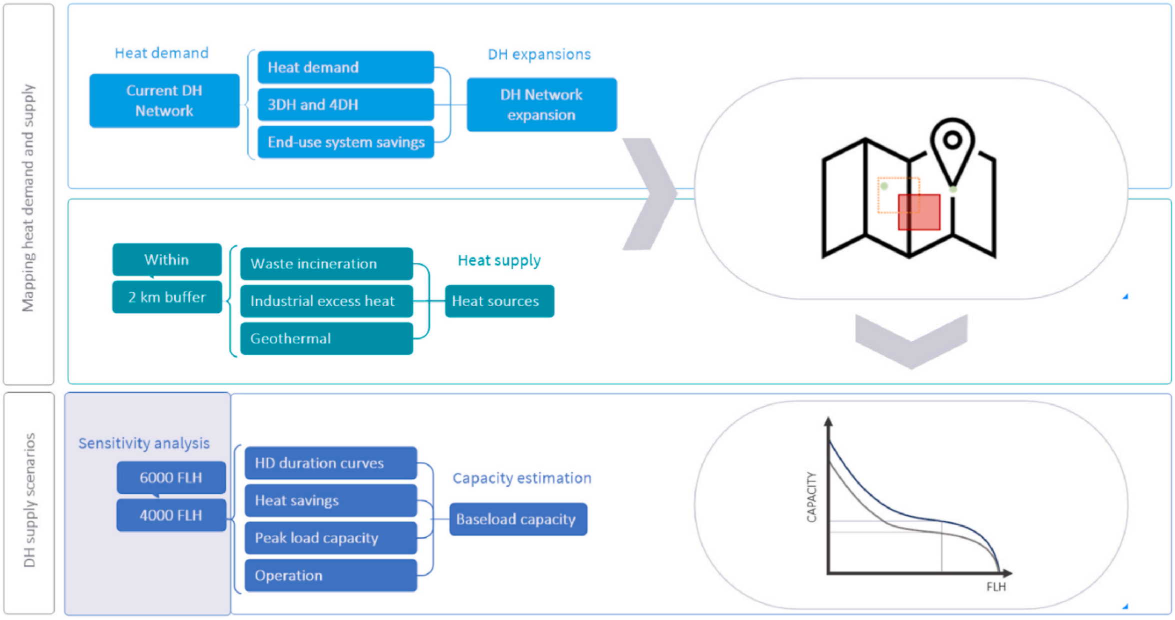

Fig. 2. Methodological framework for the analysis. In the figure reads full-load hours (FLH), Heat demand (HD), and District Heating (DH).

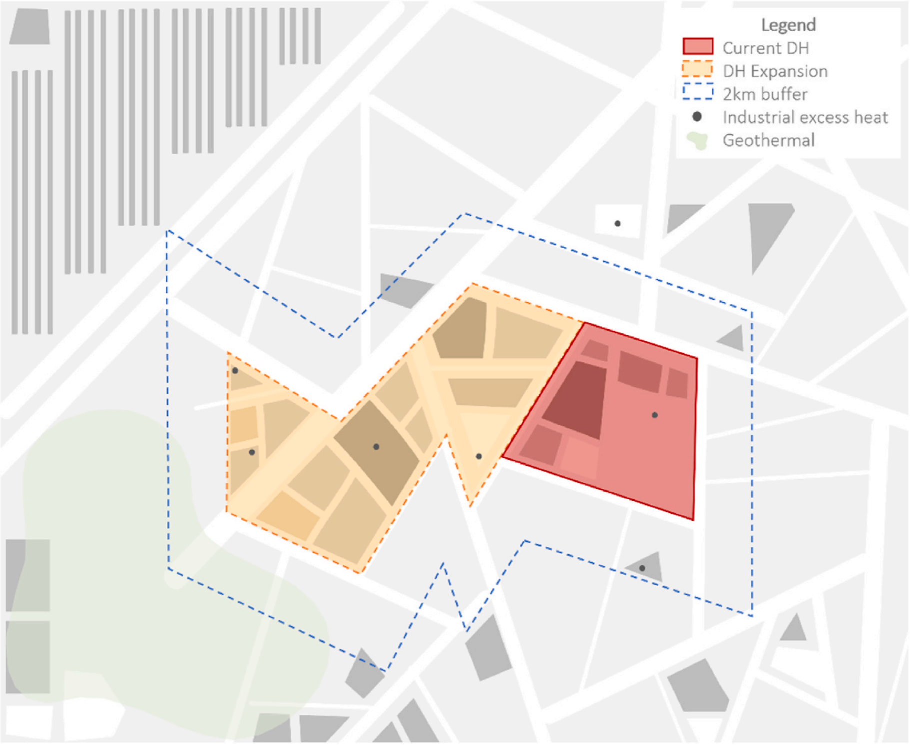

Fig. 3. Illustration of the mapping method. Heat sources considered are located within DH areas, their expansions or intersecting the dotted 2 km buffer.

sources [46]. Local investment feasibility is highly contextual, and the 2 km buffer distance is deemed appropriate as an average distance connection feasibility for this study. The visualization of this mapping is illustrated in Fig. 3 and the mapping methods are subdivided to be further explained in the following subsections.

3.1.1. *Heat demand mapping*

The heat demand of Danish buildings is estimated in the Danish Heat Atlas, which has been continuously developed since 2008 [47,48]. The Danish Heat Atlas combines register data from the Danish building register with heat demand estimates for different building types. From the Danish building register, the Danish Heat Atlas uses information on floor-area size, building usage, construction age, geographic co-ordinates, and heat supply of the building. The heat demand model used in the Danish Heat Atlas is based on a statistical analysis of heat sales from heat supply companies and is related to the usage and construction age of the building described in Ref. [49]. Furthermore, the Danish Heat Atlas has been used to assess the socio-economic feasibility of EE measures in all the buildings, where an average reduction of 32.6 % of the total heat demand was deemed feasible [50]. DH scenarios supplying HD with EE and without EE measures are included in this report; these are detailed in section 3.2 and the results are discussed in 4.1.

3.1.2. DH expansions mapping

In terms of DH development, Sorknæs et al. [50] have assessed the impacts of 3-4GDH and DH expansions. Here, the conclusions were that a level of 63–70 % DH expansions and 4GDH is the most feasible solution. The same assumption is applied in this article; however, an updated methodology is used for the DH expansions. In Ref. [50] the DH expansion scenarios were based on different heat densities, evaluating which heat densities are sufficient for DH expansions at a national level. The methodology did not make a connection between the expansions and specific DH areas; thus, it has been developed further to include this aspect. The same heat density minimum a threshold of 10 kWh/m^2 has been applied. In addition, an analysis of the distance to existing DH areas has been used to identify likely connections and select feasible areas only. As the methodology must be applied nationally, a simple near analysis is used to estimate the distance to existing DH areas, resulting in a straight-line distance. A DH transmission line would typically follow the road network layout, so the near distance is a simplification. The distance is then combined with the estimated heat demand for the potential DH area to assess the investment costs of the transmission line. Here, the function from Fig. 4 has been used to estimate the feasible distance in relation to the heat demand of the potential area. The function basically ensures that areas with large heat demands can connect further away from existing DH than areas with smaller demands. As DH expansion to new areas often makes other areas more attractive, five iterations of the assessment have been performed, ensuring that areas close to other expansions are included since they were not feasible on their own. This methodology gives a subset of the potential in Ref. [50] with a connection to specific existing DH areas. It should be noted that the areas that were filtered out in this process could have potential for developing smaller new DH areas, which is outside the scope of this article.

3.1.3. EH source mapping

The focal point of this article is mapping BL heat production and its impact on the availability of new BL heat production units. The design of this method has been inspired by studies assessing RES heat sources as BL capacity, evaluating available EH at a geographical level [39] and sub-sector based EH estimates [51,52]. The BL sources are split into existing EH units and potential ones based on existing industries not currently providing heat to the DH systems. The focus is on the industry potential since existing units are registered, and the location of geothermal potential areas that are mapped in previous studies. For the existing BL, the sources considered are waste incineration plants and industrial EH. The current energy units supplying heat to DH networks are listed in the Energy Producer Census from 2019 [53]. Up to 2019, there is a total installed capacity of 1314 MW of waste incineration and 400 MW of industrial excess heat in Danish DH systems.

Table 1
Cut-off criteria for EH potential estimation.

Criteria type	Number of units	Cut-off description
All	122,236	Units included in selected branches
Geographical	118,868	Units with valid geographic coordinate attributes
Sizing	9263	Units with more than 20 employees
Potentiality	9235	Units excluding existing excess heat producers

This procedure quantifies potential excess heat from industrial and commercial facilities in Denmark for all industries independent of their energy intensity. This means that the spectrum of current research on EH is broadened. The workflow starts with collecting facilities with publicly available data from the Danish Central Business Registry (Det Centrale Virksomheds Register – CVR) [54]. Data retrieval uses a Python script that makes a SQL search and retrieves data from the registry. The query includes all facilities registered until 2020 from the 46 selected industrial branches shown in Table A1. Each industrial branch refers to sectors of interest for EH, with a specific economic sectorial classification for closely related raw materials, goods, or services. The data available on facilities include location, branch code, branch name, and the range of number of employees. The Danish industrial branch codes are aligned to the *Nomenclature statistique des activités économiques dans la Communauté européenne* (NACE2) codes. The cut-off criteria are shown in Table 1, implying that only around 7 % of the facilities in the CVR database are considered suitable for further analysis after a central filter

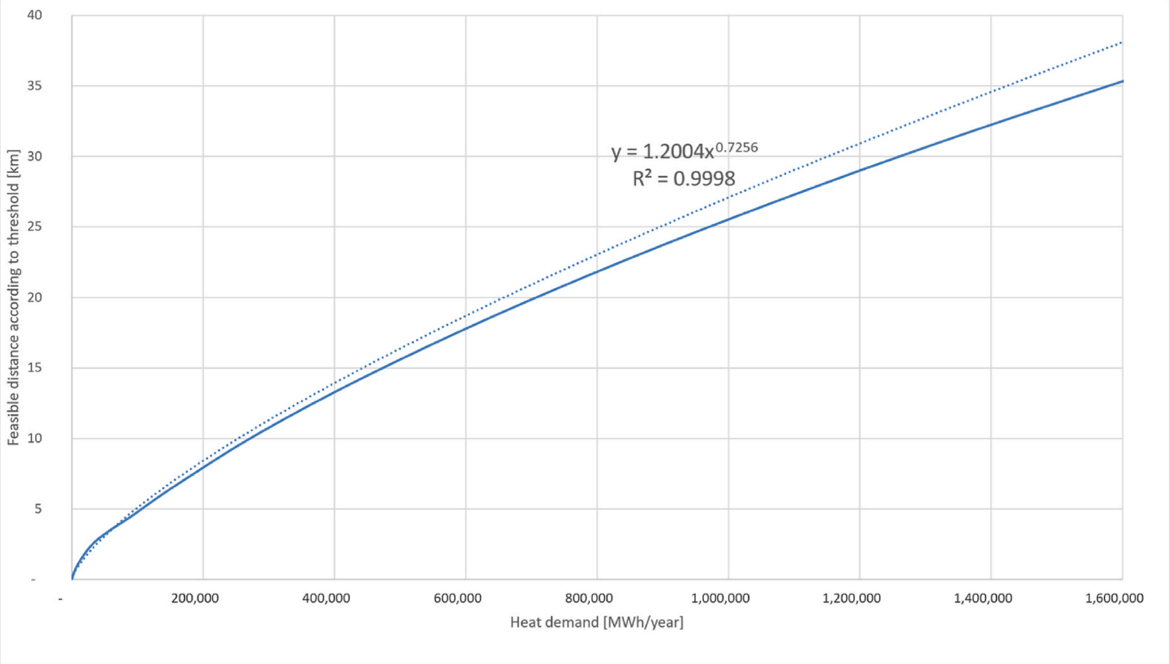

Fig. 4. Feasible expansion distance for potential DH areas given a 107 EUR/MWh threshold for the transmission line based on costs from Ref. [50].

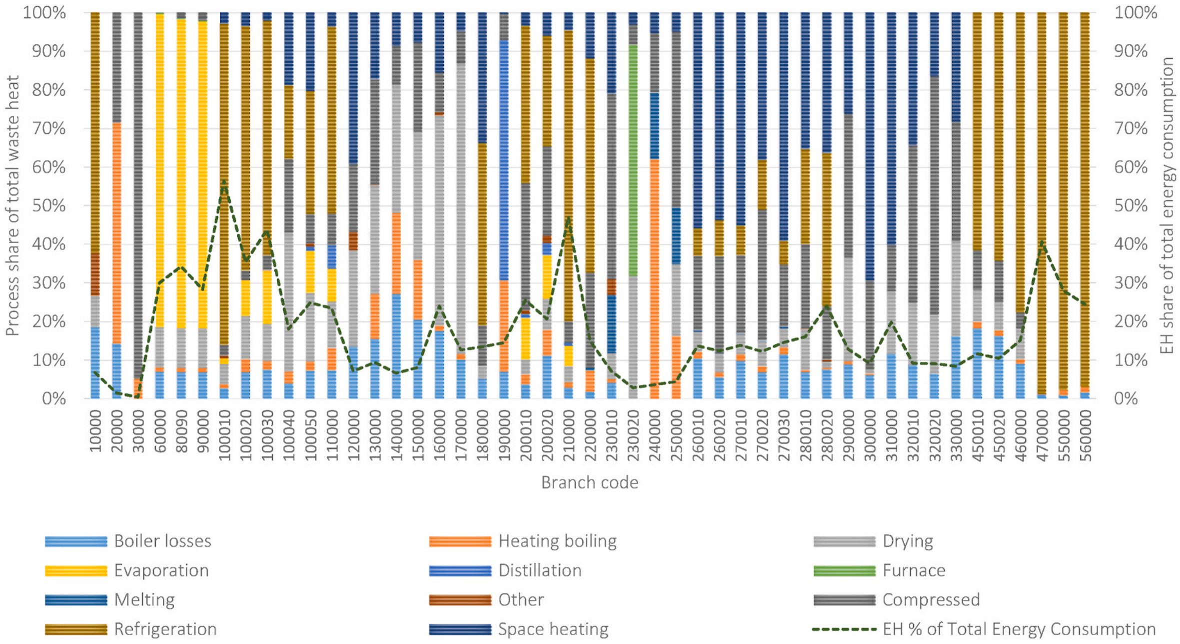

Fig. 5. EH shares in Danish industrial processes. The symbology reads as follows: the stacked bars use the left vertical axis to represent the process share of total EH. The dotted line uses the right vertical axis to show the EH share of total energy consumption. The horizontal axis represents industrial branch codes as defined in Table A1.

is applied to discard small facilities with less than twenty employees.

After the facilities are located and filtered, facility sizing takes place. This classification is needed to size the quantity of EH later in the process. Other methodologies could have developed using the industrial building footprint as an indicator for industrial dimensioning. However, the authors disregard this alternative due to uncertainty about CVR and the potential misleading locations of industrial processes. This study uses the number of employees as a proxy for industrial facility sizing in the lack of other finer indicators e.g., the energy consumption of each industry would have been a better indicator, yet it is not available. The classification is carried out progressively, dividing the facilities into groups based on the number of employees. The categories include ranges such as 20–50, 50–100, 100–200, 200–500, 500–1000, and those with 1000 or more employees.

In tandem, the industrial branch energy identification takes a departure from previous studies done on Danish industry [55], such as EH mapping from industrial and commercial energy consumption [56], and the assessment of EH shares on the overall production [57]. Assembling these inputs, a matrix is developed on the distribution of EH over total energy consumption by industrial process and industrial branch for the Danish industrial sector. At the branch level, significant potentials are noticeable in the meat, dairy, pharmaceutical, and retail industries. The complete matrix is plotted in Fig. 5.

Data is gathered from the cited industrial energy mapping to characterize the EH potential for 3-4GDH by industrial process type. Given that the EH temperature is determined by the technology and efficiency used in the specific process, the following numbers approximate the temperatures accessible through industrial processes to track and characterize their potential. As shown in Fig. 5 and Table 2, industrial processes exhibit variations in quantity and temperature that can be exploited. In the context of this research, the process's temperature range is averaged to simplify calculations, and the calculated EH potentials consider requirements for 3-4GDH where the criteria of temperatures >80 °C and >60 °C are met, respectively. Lower temperature EH is calculated but omitted in the potentials, as the inclusion of heat pumps is not factored in the analysis.

The EH potential of the facility is thus determined by the parameters output above as the EH potential related to energy consumption, processes, and temperatures associated with a concrete industrial branch. Each facility is categorized following these parameters, and their EH is estimated. This is accomplished by applying a top-down methodology that utilises statistical data per industrial branch and extends it to individual units based on their size category. Each industrial branch size is given weights, and data from the 2018 ENE3H database obtained from Statistics Denmark (Danmarks Statistik) [58] is allocated accordingly.

Table 2
EH estimated potential by temperature range.

Process	Highest EH potential	Temperature range [°C]
Melting	Metal, glass, ceramics, and concrete industries	300–400
Furnaces	Cement, brick industry	200–250
Boiler losses	Refineries, food, and beverages industries	160–250
Other heating	Hardening, annealing, and singeing	150–200
Drying	Food, paper, chemical, concrete, and brick industry	80–100
Heating/boiling	Oil refineries, food, beverage, textile, chemical, concrete, and metal industries	70–90
Compression air	Food, chemical, pharmaceuticals, refinery, plastic, glass, and machinery	60–80
Distillation	Oil refinery, food, and chemical	40–60
Evaporation	Food, beverages, pharmaceutical, and chemical industries	35–50
Cooling and refrigeration	Food, beverages, pharmaceutical, and chemical industries	20–40
Space heating	Manufacturing sector	20–30

3.2. DH BL capacity estimation and scenario-making

A combination of baseload units and peak and reserve units produces heating in DH systems. A BL demand refers to the minimum constant amount of heat demand through a period, meaning the minimum demand that the system must meet, and it is highly dependent on the full-load hours (FLH) of its production units. FLH are hours in which a unit operates at full capacity, compared to full-load operation hours, that are hours in which the unit runs, including partial and full hours. BL units typically run all year and must operate at least 6000 FLH to be feasible. However, a reduced FLH can be feasible if the heat source represents a lower investment than other sources i.e., industrial EH. Scenarios for DH BL are used to assess how much industrial EH can cover the BL demand in DH systems to a maximum extent, and whether the remaining portion of the BL can be fulfilled with geothermal energy when geographically available. The capacity thresholds for the system demand are calculated using two duration curves output by previous Danish DH studies for 3-4GDH [59]. The demand thresholds for determined FLH and supply capacities are conducted for the BL. The threshold estimations serve as benchmarks to measure the aggregated BL supply that meets the BL demand capacity.

The duration curves plot the distribution of heat demand before and after heat savings for a DH system with an initial annual heat demand of 125,000 MWh, and 87,500 MWh when 50 % savings in space heat demand are applied. No savings have been accounted for DHW, and the savings in space heating average a 32.6 % of total heat demand reduction [50] which aligns to what has been proposed in Heat Plan Denmark 2021 [59]. Using Eq. (1), the equivalent total FLH for the system are calculated by dividing the annual heat demand by the peak load capacity in each curve.

$$FLH = \frac{Heat\ demand\ [MWh]}{Peak\ capacity\ [MW]} \tag{1}$$

For a demand without heat savings, this results in an estimated 3129 FLH and 3542 FLH when heat savings are included. The hours are then used in Eq. (2) to identify the peak capacity of the individual system, its BL capacity share, which is a fraction of the prior, and ultimately the baseload capacity threshold given a system demand. A plot of this methodology is shown in Fig. 6 where the baseload capacity share approximations are marked by blue and green coloured lines.

Table 3
DH BL scenario parameters. DH coverage relates to the heat demand calculated for each scenario. Each scenario builds into the subsequent, adding to existing DH demand end-user savings, DH expansions, and from 3GDH to 4GDH.

Scenario Parameter	Existing DH demand	EE Savings + 4GDH	DH Expansions
EE savings	None	32.6 %	32.6 %
DH generation	3GDH	4GDH	4GDH
DH coverage	Existing	Existing	Existing + expansions

$$BL_{threshold} = \frac{Heat\ demand\ [MWh]}{FLH\ [h]} x\ BL\ capacity\ share \tag{2}$$

The HD mapping methodologies in Sections 3.1.1 and 3.1.2 output the HD dimensioning before and after DH expansion. According to the method, the parameters described in Table 3 are calculated at a DH system level for 3GDH and 4GDH, respectively. Using FLH, peak BL capacity share, and heat demand with and without EE savings, BL capacity thresholds are calculated. A sensitivity analysis with a lower FLH threshold is added in Section 4.4 to show the potential variation of RES capacities under system changes. The estimated BL capacities are explained in Eq. (3), as follows:

$$BL_{available} = BL_{threshold} - BL_{existing} \tag{3}$$

Where the $BL_{available}$ is the capacity left from subtracting the calculated BL capacity threshold and the existing capacities supplying to the DH. The $BL_{available}$ capacity is to assess industrial EH, geothermal, and other potential sources in Danish SH systems.

For the potential supply side, each of the 9235 facilities assessed in Section 3.1.3 is taken as a potential heat source, and their capacity is assumed to be a BL unit that runs 8000 h a year, assuming a steady industrial and commercial operation throughout the year. Geographical aggregations for potential BL supply from these heat sources are performed using a budder proximity within 0 km and a 2 km from DH areas and their expansions.

The parameters described are used for the scenario formulation.

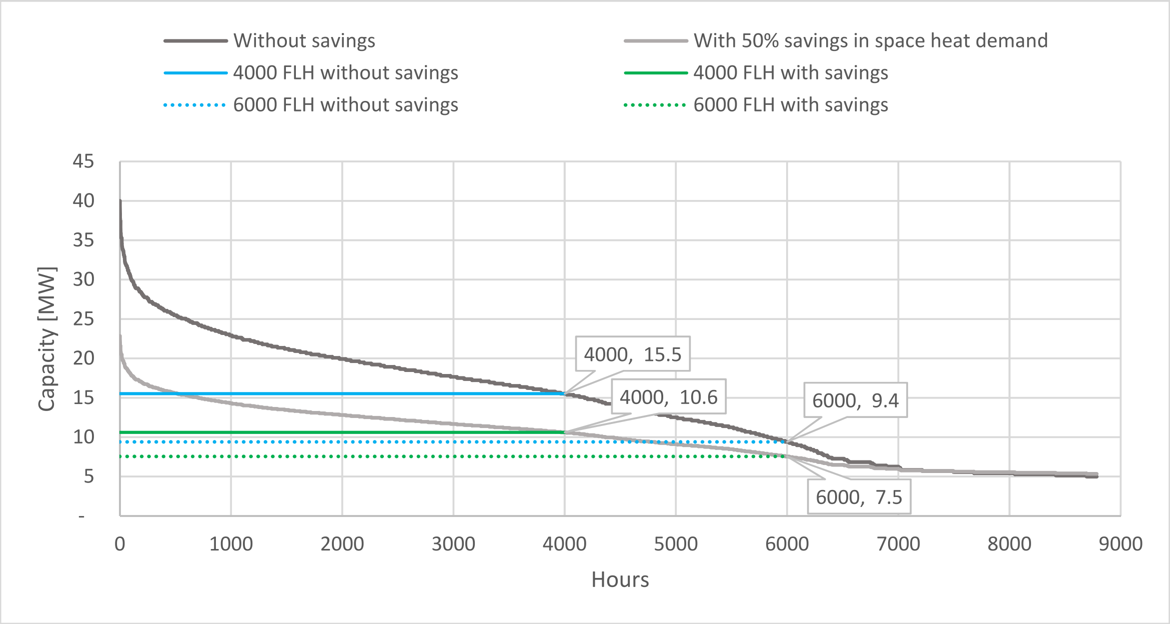

Fig. 6. BL threshold capacity estimation in Danish DH systems using 3GDH and 4GDH systems, with and without heat savings. In the symbology: Coloured lines show the proportional capacity corresponding to 4000 and 6000 FLH.

Table 4
DH BL supply scenario variables for 3GDH and 4GDH.

Variables	3GDH	4GDH
Existent BL capacities*	Waste incineration; Industrial excess heat	
EH temperature potential capacities*	>80 °C	>60 °C
Geographic proximity from DH	0 km; 2 km	0 km; 2 km

*Calculated based on 8000 FLH

There are three base scenarios in the analysis of this paper, for which parameters are listed in Table 3.

Existing BL capacities are included in all scenarios without alteration for the systems supplying BL. Potential BL capacities supplying DH are subdivided into temperature levels and geographic proximity to the demand site. The supply scenario variables are listed in Table 4, and the subsequent section presents the results and discussions.

4. Results and discussions

The results are first shown for the heat demand, DH expansion, and heat sources assessment and later for the baseload study.

4.1. Heat demand, DH expansion, and heat sources

A visualization of the mapping method result described in Section 3.1 is illustrated in Fig. 7. Here, a Close-up of the Danish DH infrastructure assessed can be seen for the Viborg and Løgstrup area. The map shows current and potential expansions of DH areas and quantified and categorized industrial heat sources. Heating demand areas not meeting the cost-distance parameters to be considered for DH expansion potential are symbolized in grey, and the 2 km buffer used to assess the available heat sources at proximity distance from DH systems is visualized in dotted blue polygons. The method was applied for all DH systems in Denmark, which vary in size and proximity to heat sources.

Geographically located heat demand estimations from 360 DH areas are aggregated nationally for each scenario detailed in Section 3.2. To facilitate the visualization and analysis, the DH systems are categorized based on their annual heat demand: small systems with a range of 0–100 GWh/y, medium systems with a range of 100–1000 GWh/y, and large systems exceeding 1000 GWh/y, see Fig. 8.

Categorizing DH systems enable more precise identification of the modelled national heat demand development across different scenarios. While the figure may not provide specific geographic information about these systems, it is worth noting that the largest DH systems are typically associated with densely populated areas in the country. These areas demonstrate significant potential for reducing heat demand through reduced system losses in 4GDH and EE measures in buildings. In contrast, small and medium DH systems exhibit a larger total potential for expansion than the larger systems. On average, DH systems in Denmark have a potential to reduce the annual demand by 35 % through heat savings in buildings and reduced grid loss via the 4GDH temperature levels. Considering 4GDH, and system savings, the expansion potential increases the heat demand by 14 %. Notably, these numbers deviate from one DH system to another, as especially the heat savings potentials and potential for DH expansions vary according to their system configuration.

Additionally, these results are the output from the methodological approach used to simulate current Danish DH systems, and this expansion would be subjected to various aspects in the specific DH planning. For example, the feasibility of expansion in the model is based on the distance cost described in Section 3.1.2, which uses straight Euclidean distances. The distance feasibility of the network will depend on road network connectivity, urban planning, availability of land, geological conditions, and construction permits, amongst other parameters which model does not consider.

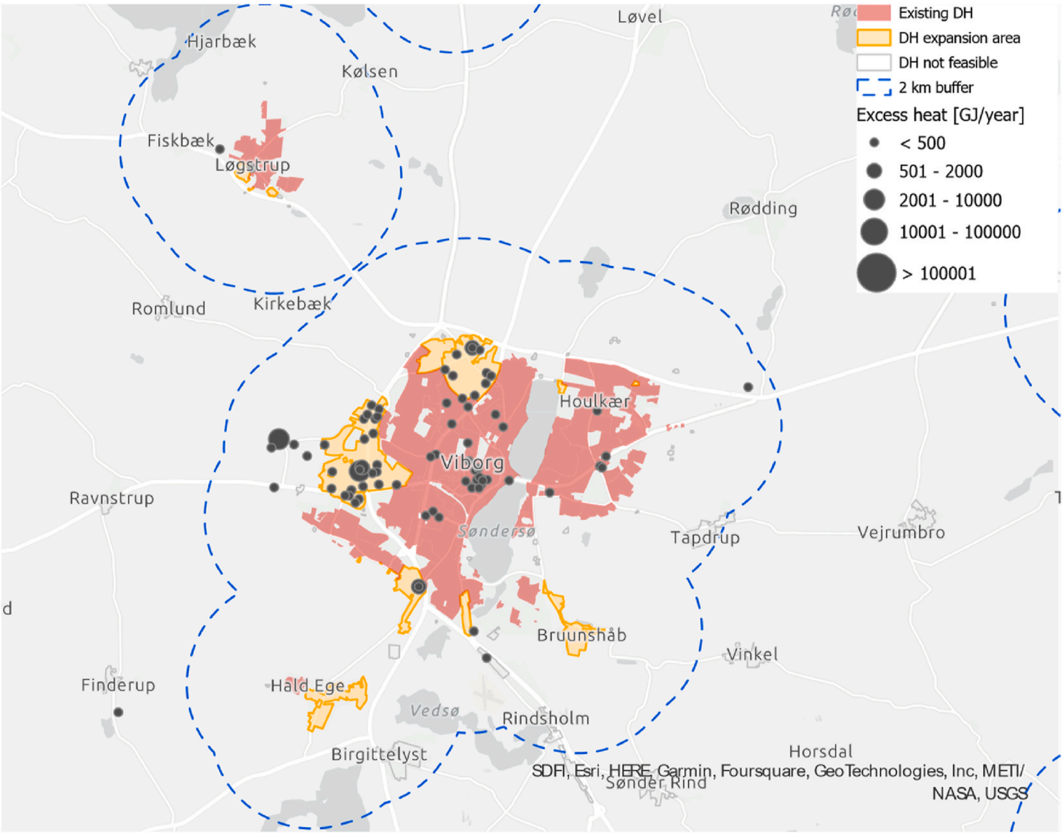

Fig. 7. Mapping heat demand and supply results.

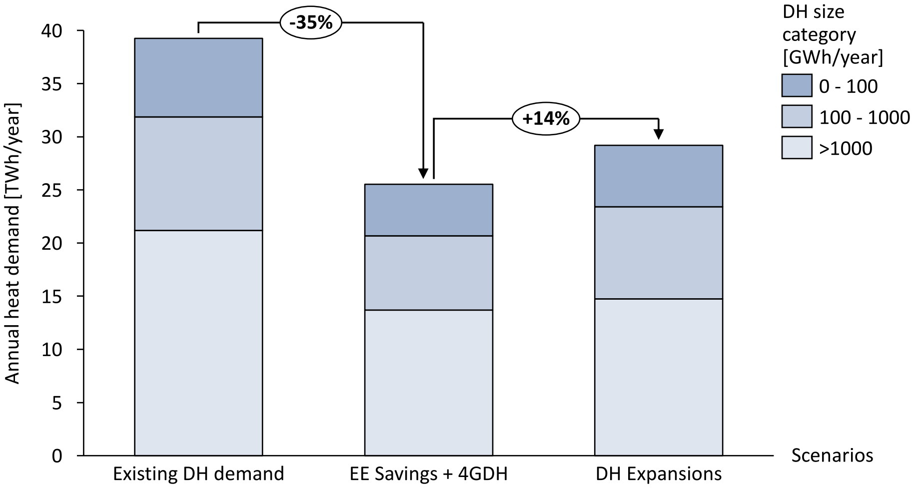

Fig. 8. National modelled heat demand development.

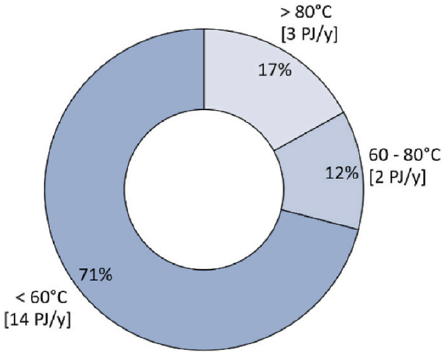

Fig. 9. EH estimated potentials by temperature.

4.2. EH potential

Municipalities such as Kalundborg and Aarhus, characterized by their concentration of industries and commercial activities, exhibit noteworthy EH potentials, making them key contributors to the overall supply side of DH systems. A total of 19.8 PJ of EH is estimated from the 9235 facilities in 46 Danish industrial branches. Out of the full potential, 17 % of the potential responds to high temperature (>80 °C), 12 % to medium temperature (60–80 °C), and 71 % to low temperature (<60 °C) EH, as seen in Fig. 9. In terms of industrial sectors, significant potentials are observed in the dairy, meat, retail, and pharmaceutical industries, refer to Figure A1. When compared to other available Danish EH estimations, the output potential compares to 9.54 PJ [44], 12.4 PJ [60,61], and 12.3 PJ [42], respectively. These variations can be attributed to differences in temperature level considerations and the exclusion of certain industrial branches based on energy consumption or data availability.

The research adopts a conservative approach by utilising potential EH from temperatures above 60 °C, corresponding to different DH system generations. Subsequently, by geographically analysing these heat sources in conjunction with the existing infrastructure of 360 DH systems and future DH infrastructure, and employing a 2 km buffer distance analysis, an estimated total potential of approximately 3 PJ and 5 PJ is identified for 3GDH and 4GDH systems, respectively. These EH potentials found for the different generations of DH are delimited by their temperature, whereas it can be argued that the utilisation of heat pumps can significantly expand the overall EH potential. While this approach ensures that the estimated EH potential for BL is on the conservative side, it also emphasizes the broader potential of low-temperature sources for future DH systems.

For the heat sources, the EH potential method utilised in this paper faces several significant limitations that need to be addressed. Firstly, one major drawback is the limited availability and accessibility of data required for input and validation purposes i.e., industrial facility level data for methodological design and/or validation. This lack of accessible data further complicates the process of accurately assessing the method reliability and precision. The challenge that arises with the latter is the reliance on employee numbers for sizing facilities, which oversimplifies the complex dynamics of industrial processes and EH generation. This simplification fails to consider the variations in heat delivery capabilities among units of the same size, which greatly depend on the specific industrial unit or branch involved. Furthermore, the technical feasibility and economic profitability of incorporating industrial excess heat into networks pose additional concerns. It becomes crucial to evaluate whether it is more cost-effective for industries to sell the excess heat or utilise it for their own purposes, such as employing absorption technology to produce chilled water in district cooling plants or electric usage that can represent energy recovery and CO_2 emission reduction for the facility itself. Factors such as infrastructure requirements, market demand, and the overall profitability of such integration must be carefully analysed to ensure a viable and sustainable solution. While comprehensive approaches should consider the specific characteristics of industrial units, and thorough economic analysis, the method provides a novel screening approach for quantifying and mapping the potential of EH in Danish DH systems. The authors refer to such novelty from the relationship between the process-based industrial characterization of the EH supply and the proposed spatial aspect of energy planning.

4.2.1. Validation of EH method

Despite lacking specific datasets for validating the EH methodology output, the coefficients used for assessing the industrial EH potential in Denmark have been compared to the ones used for a European city scale study available in the literature [41]. Fig. 10 shows such a comparison for the industrial branches for which data is available; the percentages relate to the share of EH potential, taking the total energy consumption as the reference unit. The plot shows that the method underestimates the potential of EH in up to 7% points in industries related to the manufacture of paints, machinery, and printing. At the same time, an overestimation of up to 28% points is seen in the rest of the validated branches, particularly and more extensively in industries manufacturing plastics, chemicals, and dairy products. The difference could be explained by divergences in the industrial processes and temperature levels included in the EH potential quantification, as well as assumptions

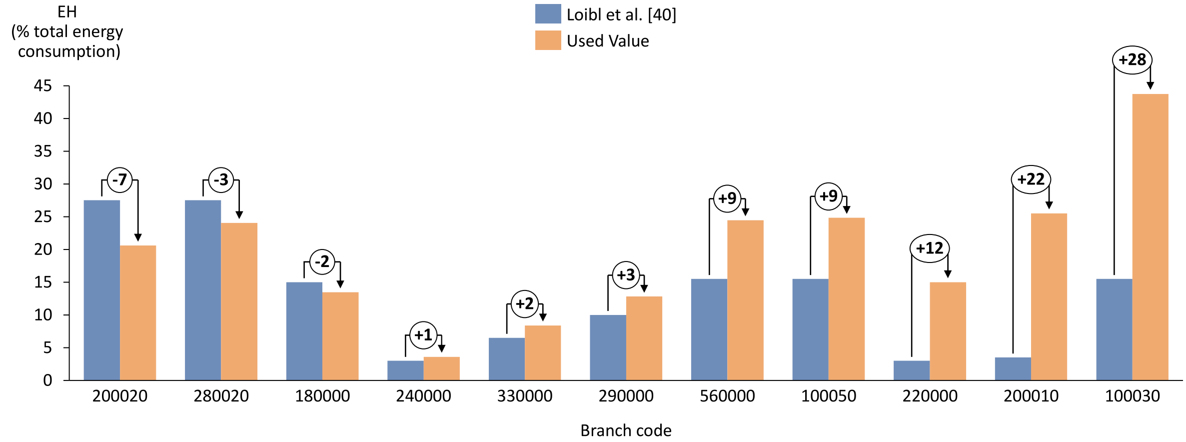

Fig. 10. Validation of EH potential. The horizontal axis represents industrial branch codes as defined in Table A1.

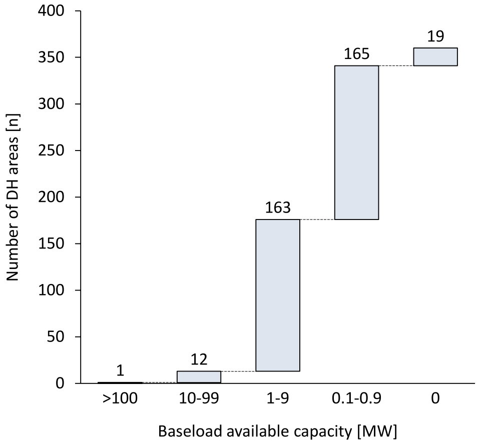

Fig. 11. Number of DH areas grouped by $BL_{available}$ capacity.

made regarding the number of employees, which in both methods serves as a proxy for industrial sizing and scale. However, it should be noted that this validation is performed for 11 out of 46 industrial branches included in this study, underscoring the necessity for additional research to investigate the underlying reasons for these differences.

4.3. DH systems BL capacity

As per the method outlined in Section 3.2, scenarios are created to assess the potential for additional RES heat sources, including EH and geothermal energy, to meet the heat demand of the BL in Danish DH systems. Fig. 11 shows the results obtained from Eq. (3) for the DH Expansions scenario, considering 6000 FLH, and utilising 2 km buffer distance from DH systems to determine the EH potential. DH areas are categorized based on their $BL_{available}$ capacity, revealing that more than 90 % of the evaluated DH areas have $BL_{available}$ capacities ranging from 0,1–9 MW. However, it is noteworthy that in 19 localized DH areas, the BL capacity is already fully supplied by existing production facilities.

To show the geographical assessment of DH systems and provide a visual representation of the diversification of the output $BL_{available}$, a detailed map is included in Fig. 12, focusing on a specific area in Denmark, including the regions of Zealand, Central, and Southern Jutland. The presented part of Denmark covers approximately 70 % of the total land area of Denmark. The map visualization employs pie charts to symbolize the share of BL capacity showed in Fig. 13, with each pie chart representing a distinct DH system. The size of the pie chart represents the total capacity required for the DH BL. Geothermal potentials are geographically identified, showing the capability to supply maximum baseload capacities, when available. The existing industrial EH capacities are noticeable in punctual areas of the region, whereas industrial potential capacities are also distinguishably around the Mid-Jutland and West-Zealand region. At the same time, non-RES existing BL capacities seem crucial (>50 % BL), particularly for the large DH systems such as Copenhagen, Aarhus, and Odense, which represent some of Denmark's most populous cities; ergo largest heat demands of the country. Looking further into the map, the potential for other RES heat sources around North and South Jutland is shown. Based on the findings, these locations appear attractive for the strategic location of new EH sources, such as data centres or PtX facilities that favour the decarbonization of DH systems. The availability of these sources to provide BL capacity to DH systems is regarded as an additional benefit. Hence, it should be noted that specific geographical analysis including required additional parameters such as proximity to CO_2 sources or electricity grids should be included. Altogether, the geographic visuals of the findings aim to foster discussions about the placement and location of general transition roadmaps, which are necessary to fully leverage the resource potential. The results claim that the design of future DH systems infrastructure is highly dependent on the geographically proximity to current infrastructure and RES EH sources.

Moreover, at an individual system level, the BL capacity shows the distribution of the $BL_{available}$ and its potential diversification. For this, all 360 DH systems are plotted, each utilising a stacked bar graph in Fig. 13, symbolizing 100 % of the total baseload capacity. In the graph, DH areas are arranged in ascending order based on their $BL_{available}$ capacity, ranging from none to 100 %, left to right. This means that DH systems covering 100 % of their BL capacity with both existing and potential EH capacities are located at the left of the graph, and systems with remaining available potential towards the right. Existing BL capacities are represented in darker tones, and the calculated EH potential is shown in green with varying temperatures, aiming to depict the share of BL capacity that they can supply. The blue line shows the $BL_{available}$ in DH systems. The analysis reveals that around 5 % of the systems can meet a total of their BL capacity with the calculated EH capacities, and up to 20 % of the systems can meet about 50 %. The green bars show that more than 70 % of the areas may benefit from the EH potential to some degree. Plus, potentials for high and low temperatures appear complementary, reaching higher shares of baseload capacity as the systems allow for lower temperatures. However, this potential in 80 % of the total areas ranges from none to 20 % of the total BL capacity. While this visualization does not provide information about the size of the DH system, it does indicate the degree of variation of $BL_{available}$ on each system and puts into perspective, an approximate 80 % of systems requiring >50 % baseload capacity to be fulfilled. The latter suggests once again that there is a need for these systems to be geographically identified and planned alongside current and future DH infrastructure.

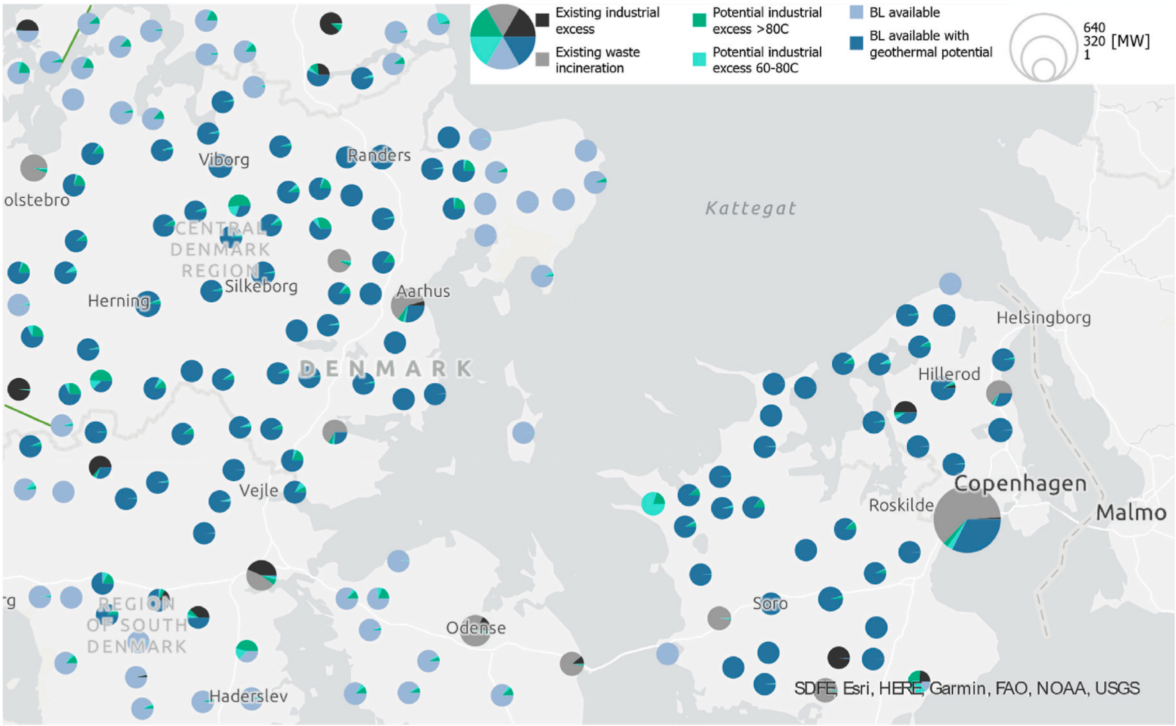

Fig. 12. Close-up of Danish DH systems under the DH Expansions scenario.

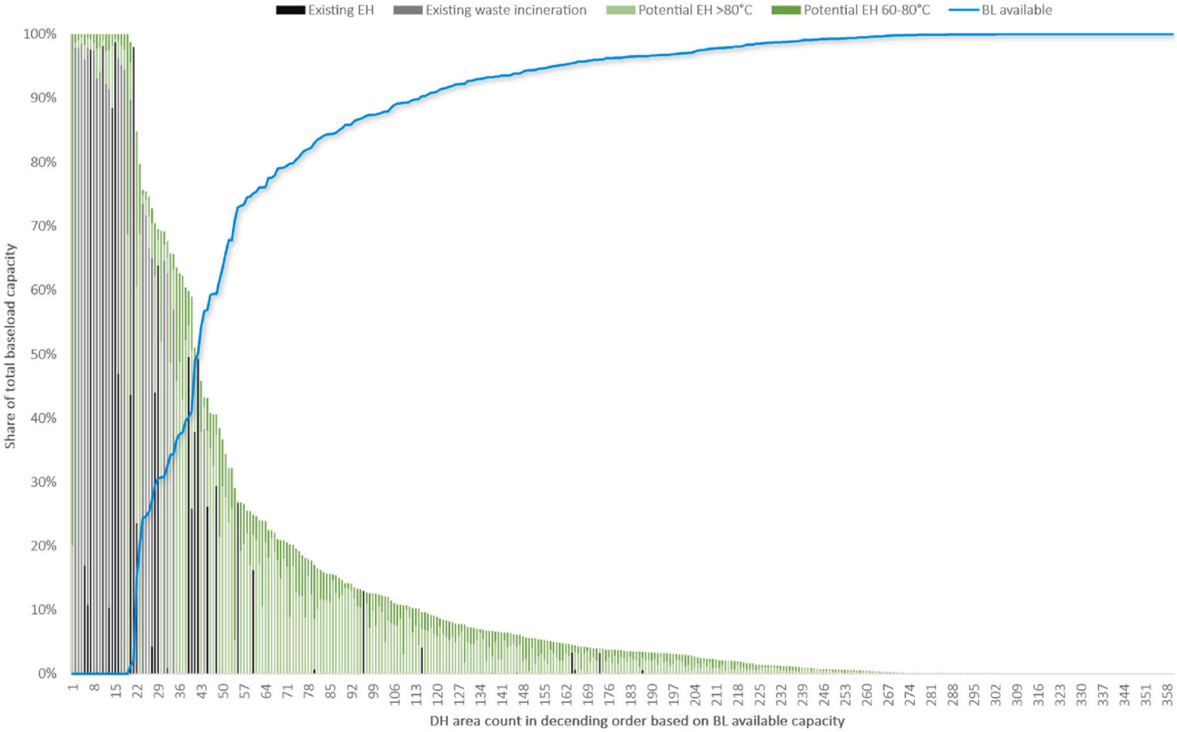

Fig. 13. Share of BL capacity by DH system.

4.4. *Sensitivity analysis with lower FLH threshold*

A sensitivity analysis is performed utilising 6000 and 4000 FLH to assess the impact of variations of FLH in the calculations of BL capacity, given that EH capacities have been calculated assuming 8000 FLH, see Table 4. In all scenarios of Fig. 14, $BL_{available}$ capacities are increased due to the reduction of FLH assumed in the systems. When examining the *Existing DH demand* scenario without EE measures or expansion, the system demonstrates twice the amount of $BL_{available}$ heat compared to the scenario with 6000 FLH. As the system incorporates EE saving measures, updates generation technologies, and expands, this requirement increases to approximately 2.5 times the base scenario. An interesting observation here is that the system capacity reaches the same level of $BL_{available}$ heat as the *Existing DH demand* scenario with 6000 FLH, as well

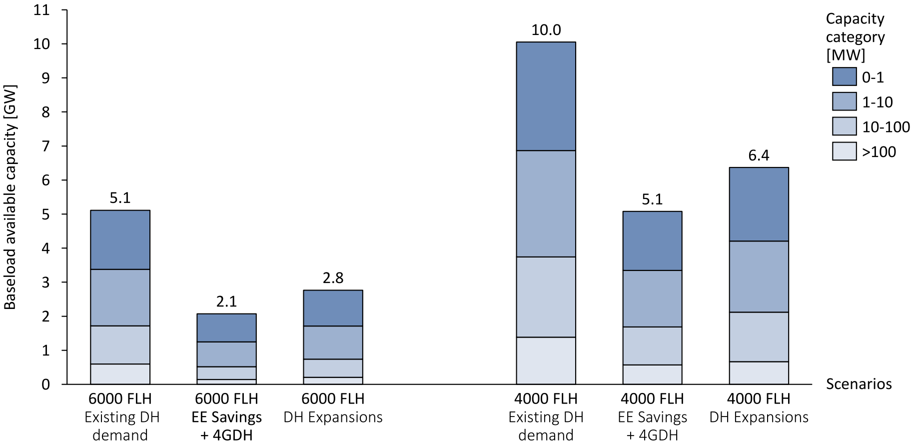

Fig. 14. Sensitivity analysis on $BL_{available}$ capacity with varying FLH.

as the *EE savings* + *4GDH* scenario with 4000 FLH. This compensation in FLH variation is achieved by implementing EE savings and configuring a 4GDH system. In perspective, a reduction in FLH influences the amount of heat that can be sold to DH systems, reducing the revenue and making the implementation and investment of the heat recovery riskier and less attractive due to reduced heat sale income. This fact also depends on the EH source operation, i.e., data centres differ from industrial facilities in delivering heat for supplying BL capacity to DH systems. These parameters hold significant importance and must be carefully considered, especially at a more localized level.

While the study developed provides important insights, the potential for advancements in future heat sources that could impact these findings is acknowledged. These advancements may come as a decline in the use of waste incineration as a heat source for Danish DH systems, or the electrification of industrial processes leading to a shift away from combustion-based systems. Consequently, these factors could potentially reduce the estimated EH potential not only in terms of quantity but also in exploitable temperature. It can also be argued that the calculations on FLH and capacity estimation are based solely on the heat demand duration curve in Section 3.2. If heat storages were implemented, this could potentially increment the FLH used for the BL capacity calculations, hence the 6000 FLH sensitivity analysis.

Additionally, the limitations discussed in Section 4.2 should be considered regarding the quantification methodology for assessing the influence of the EH potential to the BL capacity estimation, regardless of the FLH taken. The methodology relying on employee numbers as a proxy for facility size can lead to an overestimation of the EH potential in facilities with larger organizational sizes or an underestimation of the EH potential in heavily industrialized facilities. As shown in the validation included in Section 4.2.1, it is evident that factors related to the type of industrial processes and their associated temperature levels included in the assessment significantly impact the total potential estimation. Employee-based estimates are usually more fitting for a financial and business assessment instead of an energy potential assessment. However, this study intends to show that the industrial process mapping with combined geographical dimension factoring of current and future infrastructure located close to industrial facilities elevates the research to a thorough extent. Lastly, the present assessment did not encompass other technologies capable of different forms of energy recovery. Hence, there is room for further exploring and incorporating these alternative technologies to enhance the overall EH recovery potential.

5. Conclusion

Renewable baseload capacity can be supplied to Danish DH systems by recovering the EH from industrial and commercial activities. As DH systems move towards 4GDH, they allow for lower temperatures, more connections, and better integration with other energy sectors. At the same time, heat recovery not only commits the industrial sector to more sustainable pathways and joins efforts towards the energy transition, it potentially contributes to the facility's management through economic benefits, reduced energy costs, and increased overall efficiency. However, the proximity of the EH and HD depends on the surrounding context, which adds an essential geographical dimension to the requirement.

This research locates 9235 industrial facilities in 46 Danish industrial branches and 360 Danish DH systems, each of which is individually assessed for potential EH supply in proximity. Current DH BL capacity supplied from industrial EH and waste incineration sources are factored, and additional BL capacity supply sources are evaluated for future DH systems, i.e., unused industrial EH and geothermal heat. At a DH local level and for each of the scenarios used, unmet BL capacity is mapped.

It is estimated that 19.8 PJ of industrial EH can supply heat to 3-4GDH and that 25 % (5 PJ) of this potential is located within a 2 km buffer distance from Danish DH systems. The potential is deemed conservative as heat pumps are excluded and EH temperature lower than 60 °C is disregarded, which limits the connections to the grid. The potentials found vary within the country; Aarhus and Kalundborg municipalities have the most industrial EH potential, and the Zealand and Mid-Jutland regions have the most geothermal energy available. The geographic tools in this research explain the estimated symbiosis between DH expansions and BL capacity supply potential, particularly in large DH systems such as Copenhagen or Aarhus's municipalities, where larger shares of BL capacities are needed. When aggregated, available BL capacities account for 2.1–5 GW and are primarily located on small to medium-sized systems across the DH scenarios.

This study explores the location and use of existing EH sources in current and future DH systems, and it also hints at locations for new heat sources that can provide BL capacity in Denmark. Yet, the findings have broader implications that go beyond the scope of this research. It provides an understanding for the location opportunities for future heat sources not explicitly addressed in this research but quantified as a whole, such as data centres or Power-to-X facilities that produce e-fuels. These implications hold significance to the fundamentals of any strategic heating plan as they increase the circularity and efficiency of production and consumption of resources in heating systems. Heat recovery potential can be more significant to DH systems in more industrialized contexts or where RES heat sources are more limited. Finally, the authors acknowledge that the methods designed for this study respond to the data availability and that facility-level data could help improve the EH estimation in further analysis. The last statement calls for more data availability and accessibility for a more comprehensive understanding and modelling of RES heat sources.

Author contribution

Diana Moreno: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. Steffen Nielsen: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. Peter Sorknæs: Conceptualization, Formal analysis, Writing – review & editing. Henrik Lund: Conceptualization, Funding acquisition. Jakob Zinck Thellufsen: Conceptualization, Supervision. Brian Vad Mathiesen: Conceptualization, Funding acquisition.

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.

Acknowledgement

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Appendix A

Table A.1
Detailed industrial branch names and codes

Branch Code	Branch Name
10000	Agriculture and horticulture
20000	Forestry
30000	Fishing
80090	Extraction of gravel and stone
90000	Mining support service activities
100010	Production of meat and meat products
100020	Processing and preserving of fish
100030	Manufacture of dairy products
100040	Manufacture of grain mill and bakery products
100050	Other manufacture of food products
110000	Manufacture of beverages
120000	Manufacture of tobacco products
130000	Manufacture of textiles
140000	Manufacture of wearing apparel
150000	Manufacture of leather and footwear
160000	Manufacture of wood and wood products
170000	Manufacture of paper and paper products
180000	Printing etc.
190000	Oil refinery etc.
200010	Manufacture of basic chemicals
200020	Manufacture of paints and soap etc.
210000	Pharmaceuticals
220000	Manufacture of rubber and plastic products
230010	Manufacture of glass and ceramic products
230020	Manufacture of concrete and bricks
240000	Manufacture of basic metals
250000	Manufacture of fabricated metal products
260010	Manufacture of computers and communication equipment etc.
260020	Manufacture of other electronic products
270010	Manufacture of electric motors, etc.
270020	Manufacture of wires and cables
270030	Manufacture of household appliances, lamps, etc.
280010	Manufacture of engines, windmills and pumps
280020	Manufacture of other machinery
290000	Manufacture of motor vehicles and related parts
300000	Manufacture of ships and other transport equipment
310000	Manufacture of furniture
320010	Manufacture of medical instruments, etc.
320020	Manufacture of toys and other manufacturing
330000	Repair and installation of machinery and equipment
450010	Sale of motor vehicles
450020	Repair and maintenance of motor vehicles etc.
460000	Wholesale
470000	Retail sale
550000	Hotels and similar accommodation
560000	Restaurants

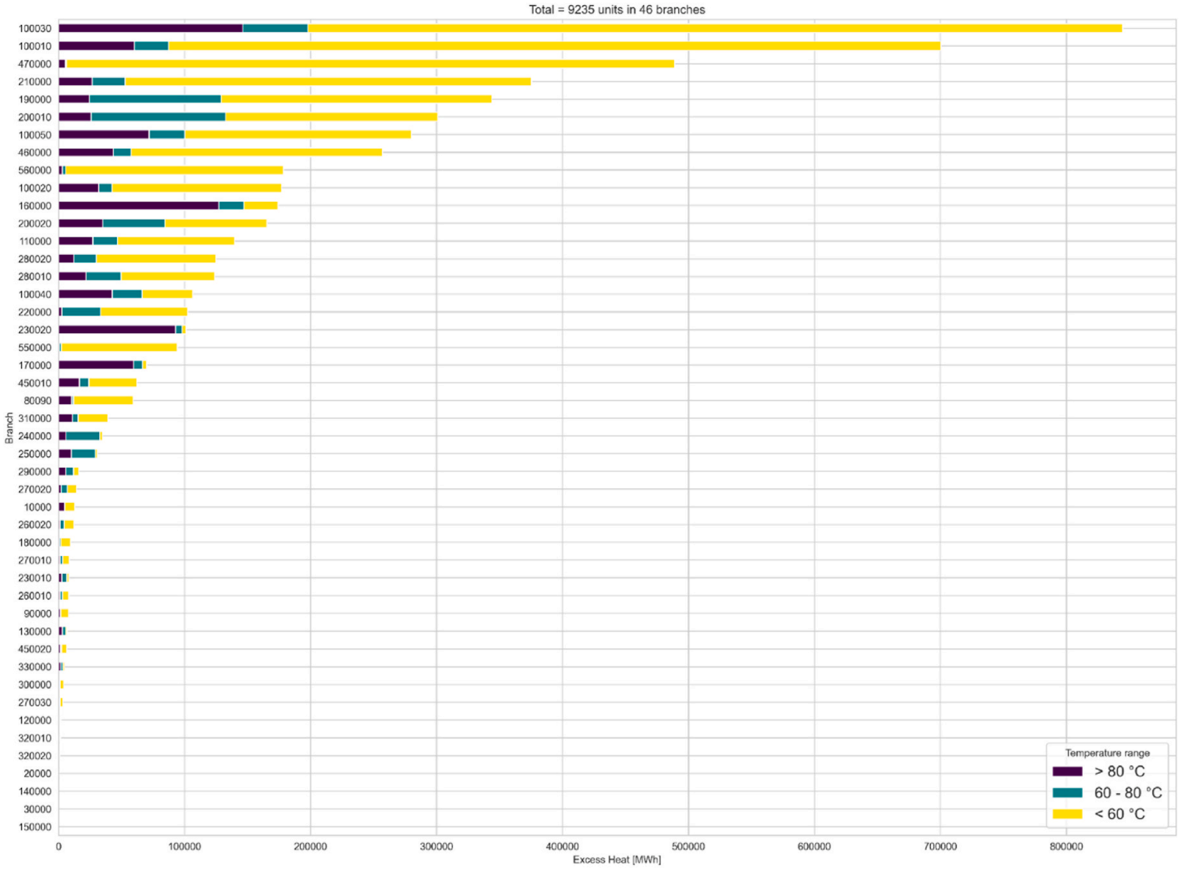

Fig. A.1. EH potential estimated per branch and temperature level.

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