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Combining techno-economic modeling and spatial analysis for heat planning in rural regions: A case study of the Holbæk municipality in Denmark

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ABSTRACT

This study examines the opportunities and challenges related to heat decarbonization in rural municipalities by applying a spatial analysis in combination with techno-economic modeling using TIMES. While the transition to low-carbon heating technologies is progressing in urban areas, this shift is happening more slowly in rural areas, reflecting a difference in decarbonization rate between urban and rural contexts. This study takes the Holbæk Municipality in Denmark as a case to investigate the potential for rural heating systems considering local fuels, excess heat, and investments in different energy infrastructures. The technology options investigated include both individual heating technologies, such as domestic boilers and heat pumps, and district heating. The modeling results demonstrate that use of excess heat from the municipal wastewater treatment plant and the neighboring industrial site for district heating competes with individual heating systems that have heat pumps and biogas-fueled boilers, where the mix depends on the conditions assumed for each technology and the heat demand density. The extent of district heating expansion differs between districts in the municipality, ranging from 14% to 100% depending on the heat demand density and proximity to the current district heating network. The different possibilities for the transition of the heating sector revealed in this work indicate that a successful transition will require both a clear policy for the heating sector and an explicit decarbonization strategy for the industries that can provide excess heat for district heating.

1. Introduction

Heating is an essential component of daily life in terms of maintaining comfort and well-being, as well as an important part of many industrial processes. Heating for buildings accounts for around half of the final energy consumption in the European Union (EU), and 57% of this is supplied by burning fossil fuels [1]. The European carbon footprint linked to heating and cooling is large because it uses natural gas (42%), oil and coal (12%), and to a lesser extent electricity (12%) [2], making its decarbonization critical to achieving European climate mitigation targets [3].

A cross-referenced reading of the scientific literature reveals that the main options for low-carbon-emissions heating are electricity from renewables, encompassing stand-alone heat pumps (HPs), and HPs in district heating (DH) systems. Waste heat recovery from industrial processes is also discussed as one of the priority options [4–6]. Geothermal [7], and biomass energy [8], also have roles to play, albeit on a smaller scale given their limitations, i.e., being location-specific [9] and with strong competition effects across sectors [10], respectively. Solar thermal DH with and without heat storage also shows potential [11–13], although the technology is currently marginal and shows weak market uptake [14,15].

Yet, when the above options are discussed, it is usually concerning applications to large, densely populated cities, and it is not clear how they can be applied to rural areas, including small towns[1] [16]. Rural municipalities, including towns and small cities, account for 25% of the EU's population [17]. Several authors have pointed out that there is a misalignment between overarching national policies for the energy transition and their implementation in the heating sector [18–20], due

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[1] We refer to the classification of [81] for small towns/cities: i.e., municipalities of fewer than 50,000 inhabitants in a city center.

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Nomenclature

CHP	Combined heat and power
CityH	Holbæk city center with high demand density
CityL	Holbæk city center with low demand density
CTDH	Close to the existing district heating network
DH	District heating
EH	Excess heat
EU	European Union
FFDH	Far from the existing district heating network
HP	Heat pump
KIS	Kalundborg Industrial Symbiosis
NG	Natural gas
PTES	Pit thermal energy storage
RES	Renewable energy sources
SA	Sensitivity analysis
WWTP	Wastewater treatment plant

to that the latter has intrinsic local spatial features in terms of heating conditions which is not addressed in national policies [21]. Batel and Devine-Wright [22] have further shown the existence of a “local-national gap”, whereby national energy policies show a commitment to sustainable and low-carbon solutions but with a considerable lag in their implementation, especially in local communities. Similarly, Vyver et al. [23] have argued that local authorities face challenges in executing local heat strategies, due to a lack of data and a lack of specific expertise among the involved actors. Vyver et al. [23] and Andersson et al. [24] have pointed out that the abilities of local authorities to implement local heat strategies are constrained by their governance capacities, as well as the lack of knowledge exchange and coordination among the actors.

In addition, we observe a difference between urban and rural areas, with the implementation of low carbon energy technologies in rural areas tend to lag behind compared to urban areas. This is especially visible when low carbon energy supply is associated with deployment of large infrastructure for which population density is the main driver for investment (such as for district heating and electric car charging stations). From a study of South Wales, the authors in Ref. [25] observed that rural communities tend to be trapped in a position of energy peripheralization, which is coined as “uneven energy transition”. They explained this phenomenon by weaker political capability in rural areas compared to urban areas. Zhao et al. [26] also revealed this trend among Chinese households. This imbalance in realizing decarbonization between urban and rural areas is evident also in the heating strategies presented by several European countries in response to the Energy Efficiency Directive (2012/27/EU) [27]. In Finland, the strategy shows ambitious decarbonization solutions that include waste heat recovery in DH systems, whereas there is no clear strategy for rural regions [28]. In Sweden, DH is widespread from small towns up to the large cities, while there has also been strong expansion of individual HPs in regions where DH is not available [29]. District heating is also widespread in Denmark, although the current Danish plans for DH expansion [30] do not differentiate between urban and rural areas and may, therefore, ignore the challenges in rural areas. Several authors also pointed out that less attention has been given to energy transition research of rural areas and their potential to reduce carbon emissions [31,32].

The abovementioned factors seem to point to a lack of strategic heat planning at the local level and poor consideration of heating strategies that are tailored for more-rural regions. Usually, energy systems modeling studies that focus on heating adopt a national scope that overlooks the local conditions [33,34]. To take the local conditions into account to investigate how they affect heating strategies, there is a need to apply a spatial analysis to understand how the heating demand can be met with local heat resources. In addition, spatial considerations in energy transition strategies has received insufficient attention highlighting the necessity for integrated spatial and energy planning to effectively achieve energy transition goals [35]. This is essential because heating needs, as well as the use of fuels and potential waste heat sources, will differ across rural areas. This contrasts with large cities, where the population is concentrated so the precise locations of the available heat resources are less crucial, as they are typically integrated with or close to the areas that require the heat. Although there is a growing body of research that provides knowledge at a more de-aggregated energy planning level, this research is still largely restricted to urban areas and overlooks rural municipalities [36].

Among the heat decarbonization alternatives, rural areas can often benefit from energy resources that are locally available and easy-to-access, such as bioenergy resources in the form of residues from agriculture [37–39]. Biogas from the anaerobic digestion of agricultural waste can replace natural gas in a natural gas network. Biogas can be injected directly into the existing gas grid after it has been sufficiently cleaned and upgraded [40]. Thus, biogas can be an attractive fuel alternative, provided that the additional costs associated with biogas upgrading are low [41]. Collecting organic waste for biogas production and transporting it to the biogas plant require significant logistics and infrastructure, which makes it more suitable for areas in proximity to farmland. Excess heat (EH) is another heat source that is particularly suitable for rural areas, since industrial facilities are often located in peri-urban and rural areas [42,43]. EH is typically available all year around [43] low cost [44,45], and offers potentially substantial CO_2 emissions cuts when used as a substitute for carbon-based heating resources, provided that the industries generating the EH are also decarbonized. Yet, the DH business cases for using EH are highly dependent upon factors such as the level of heat output, temperature, and the distance to the DH installations [46]. Finally, heat decarbonization through electrification is currently a topic of discussion given the rapid uptake of electricity generation from RES [47,48]. While this includes increasing the deployment of HPs and electric boilers to meet the heating demand, it will also require additional electrical capacity to become available in the electrical network and it will need to be coupled to successful decarbonization of the electricity grid with RES [49]. To mitigate the challenge related to the variability of wind power and solar photovoltaics (PV), flexible control of HPs in combination with thermal energy storage is a possibility [34,50].

Rural and semi-rural[2] areas may have less well-developed gas and electricity grids, resulting in limited energy supply choices [51]. Instead, these areas may have available alternative heating solutions in the vicinity, such as biomass resources, which can contribute to self-sufficiency of the area. Rural areas typically have sparsely distributed heat consumption points represented by small villages and low heat demand density which require specific local evaluation of each area. For these reasons, DH systems face extra hurdles in rural settings, including lower building density and thereby the need for more pipe networks per heated floor area [52]. Thus, there is a need to include a spatial assessment of both the supply and demand sides when analyzing the development of heating systems in rural and semi-rural areas. This can be done by combining a spatial analysis of the heat demand with techno-economic modeling of the development of the heating system. Therefore, this study has the aim to combine energy systems modeling and spatial analysis of heating demand with focus on semi-rural areas to explore viable alternatives for decarbonizing heat supply. Energy systems optimization models can offer valuable insights into system development, making them useful tools for analyzing the transition of energy systems [for a review, see Ref. [53]].

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[2] In this study, semi-rural areas refer to the rural municipality where it has a city center with inhabitants fewer than 50,000 according to the classification in Ref. [81]. On the other hand, rural areas refer to rural municipalities without a city center.

The Holbæk municipality in Denmark is chosen as a case study because it is representative of rural areas that are primarily heated by gas, which is common in Denmark and many other rural regions in Europe. We aim to answer the following questions:

- To what extents can the utilization of locally available resources, i.e., fuels and infrastructure, in semi-rural areas contribute to achieving locally defined carbon emission targets for heating?
- What are the unique obstacles and potential advantages specific to heat decarbonization in semi-rural areas when the spatiality of local resources and rural areas are considered?

Through this work, we contribute to the current state-of-the-art by elucidating the challenges and opportunities related to heat decarbonization in semi-rural municipalities that include a smaller city center.

This paper is organized as follows: Section 2 outlines the methodology, presents the case study, the data and assumptions, and the scenarios developed based on the stakeholder dialogue and used as input to the modeling. Section 3 presents the modeling results, including the sensitivity analysis of the relevant parameters. The discussion of the results follows in Section 4, and conclusions are drawn in Section 5.

2. Methodology

For the spatial analysis, we use the Danish Central Register of Buildings and Dwellings (BBR) database integrated in QGIS 3.18.2. The obtained spatially distributed heat demand is then used as input to the TIMES energy systems optimization model. In this study, the heat demand only includes space heating excluding the domestic hot water demand.

2.1. Holbæk municipality in Denmark

Holbæk municipality is located in the eastern part of the Danish Island of Zealand. It covers an area of approximately 583 km^2 and had a population of around 72,000 people as of Year 2022. Holbæk has decided to reduce its greenhouse gas emissions to meet both the national and local climate goals, with a target of 70% reduction in CO$_2$ emissions reduction by Year 2030, as compared to Year 1990. This target corresponds to reducing by approximately half the current emissions from each sector, i.e., heating, electricity, transport and industry [54]. Holbæk is a semi-rural municipality in which a city center (Holbæk city center) and small villages are integrated. As shown in Fig. 1, natural gas (yellow areas) dominates the heat supply of the Holbæk municipality, including the smaller city center (Holbæk city center). Specifically, 77% of the heat demand is supplied by individual gas boilers. The DH infrastructure (blue areas) covers around 20% of the heat demand, with most of the heat being generated by natural gas combined heat and power (CHP). Holbæk therefore largely relies on natural gas, making the sector's decarbonization particularly challenging [54].

Holbæk municipality has presented, as part of its medium-term heating plans for both individual heating and DH, a list of potential heating technologies for decarbonizing the heating sector [55]. One of the proposed options is to utilize industrial EH from a neighboring municipality, Kalundborg Industrial Symbiosis (KIS), in the DH network. KIS is an industrial partnership network of 16 public and private companies located approximately 35 km from the border of the Holbæk municipality (see Fig. 1). There is an ongoing project that aims to utilize the EH from KIS in Greater Copenhagen's DH system [55]. Biogas injection into the existing gas grid is also discussed as a way to continue using the already-installed infrastructure while replacing the fuel used.

2.2. Spatial analysis for the heat areas

The BBR database includes spatial coordinates, from which it is possible to divide the Danish regions into municipalities, and further subdivide according to sub-municipalities and building information, including location, building type, year of construction, technical conditions, and heating installation. The database also includes the annual heat demand (MWh/year). When the BBR database is imported into the GIS software, the spatial distribution of the heat demand and its density can be visualized. The spatially visualized data are then grouped into 11 districts based on the following criteria: current heating technology and the density and proximity to the current DH network, and thereafter used as input to the model formulation in TIMES. Fig. 2 shows the heat demand densities in the Holbæk municipality. After iterative discussions with the municipal energy planner, the smallest villages showing the lowest heat demand densities (<6000 MWh/km^2) (gray-colored areas in Fig. 2), were excluded from the analysis.

Fig. 3 shows the resulting categories used as input to the TIMES

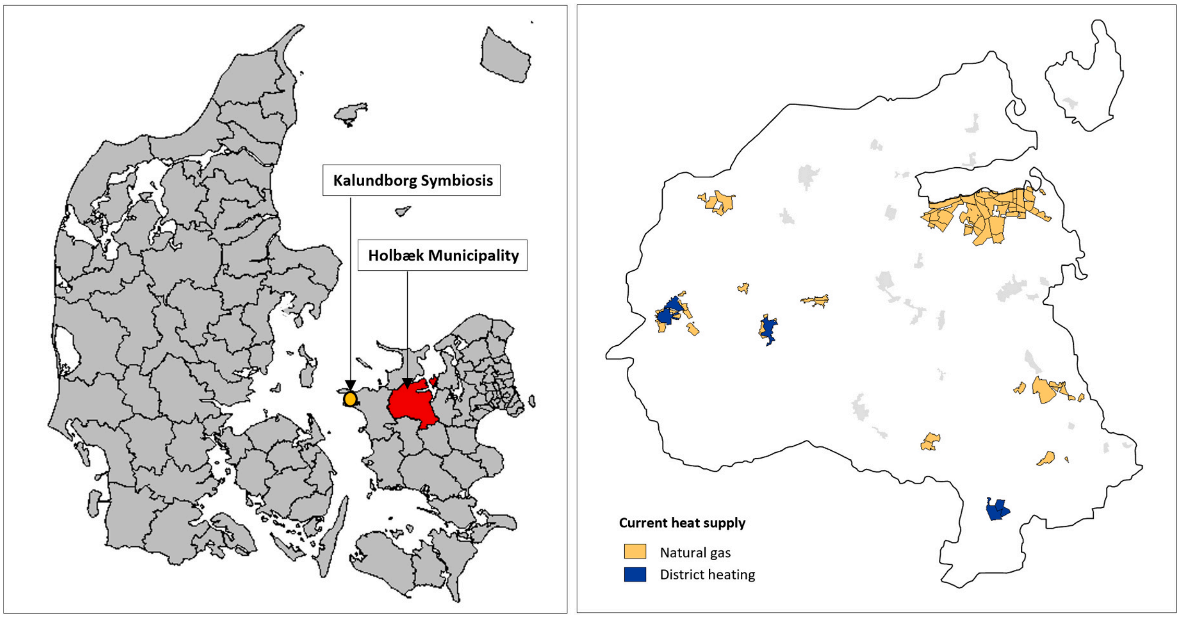


Fig. 1. Distributions of the predominant types of heat supply currently used in the Holbæk municipality (right panel). The left panel shows the locations of the Holbæk municipality and the Kalundborg Industrial Symbiosis.

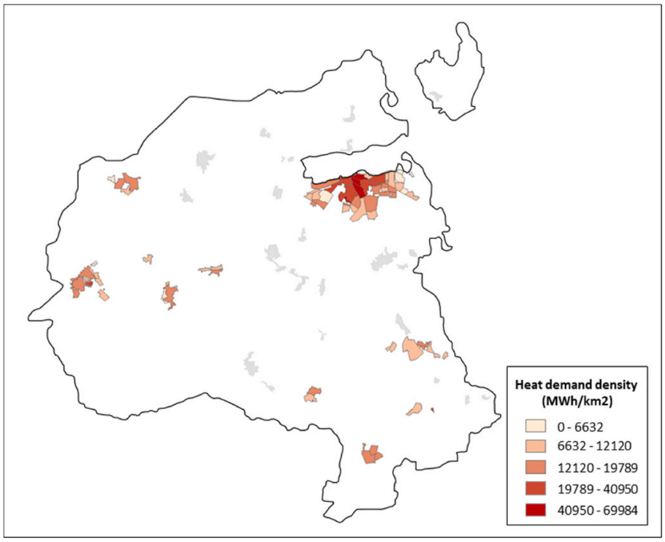


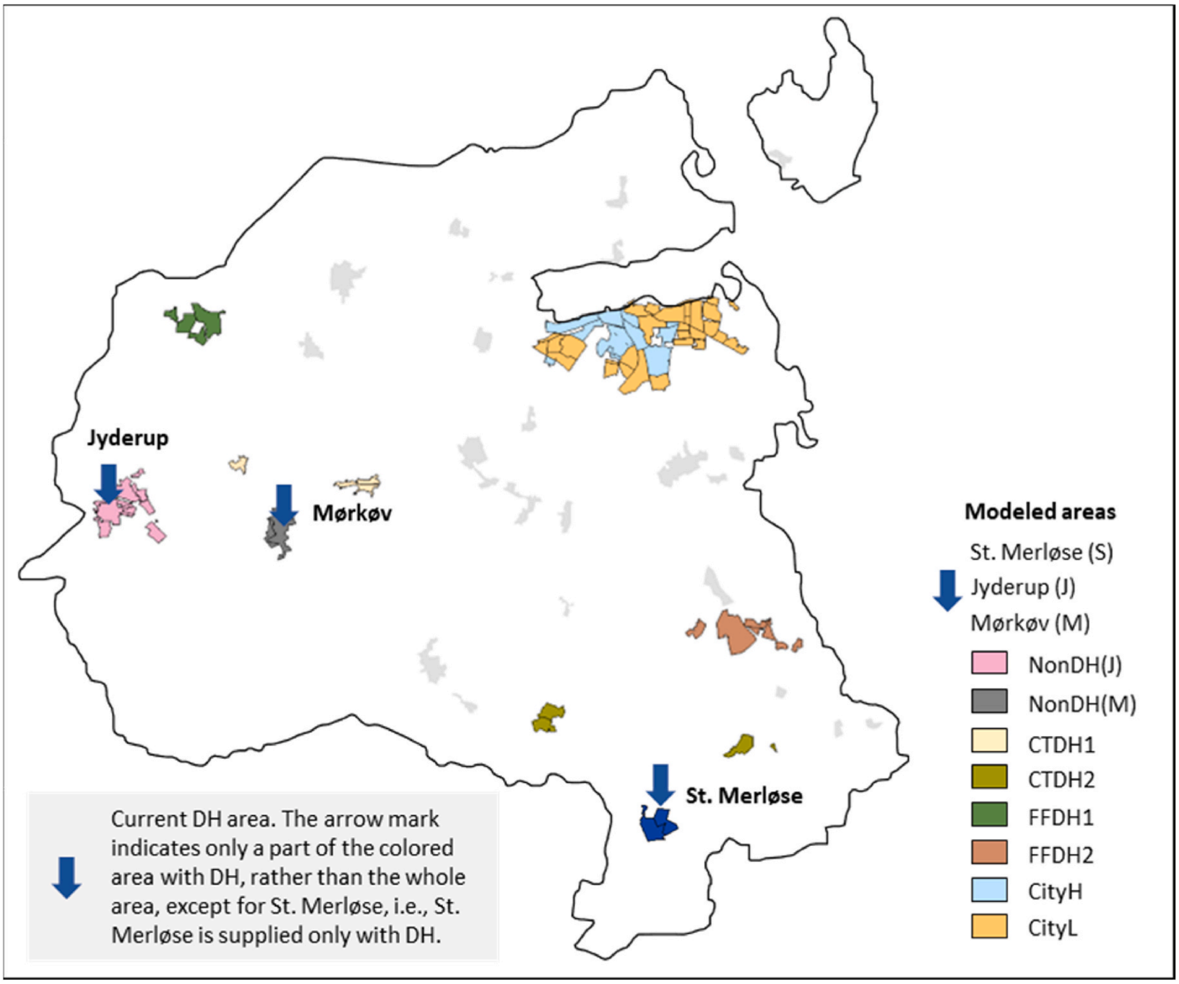
Fig. 2. Heat demand densities in the Holbæk municipality.

modeling with the 11 areas. First, there are three villages that are currently supplied by DH (blue arrows in Fig. 3). These DH systems are supplied by natural gas- and straw-based heating plants. The remaining eight areas, including Holbæk city center, are currently not connected to the DH network. The city center is divided into two areas: a central part with high demand density (CityH); and the remaining part with a lower demand density (CityL). The areas denoted NonDH(J) and NonDH(M) in Fig. 3 contain a sub-region with DH, although most parts of these areas do not have a DH connection and only the marked parts have DH (note that in Fig. 3, the current DH areas marked with blue arrows and the NonDH(J) and NonDH(M) areas are not distinguished by different colors; st.Merløse (S) is fully connected to DH). Two areas are located close to the existing DH network, at a distance of 2.5 – 6.5 km, and are defined as CTDH1 and CTDH2 (as in 'Close to existing DH network'). The last two areas are not located as close to DH as the CTDH, being at a distance of >7.5 km, and they are defined as FFDH1 and FFDH2 (as in 'Far from existing DH network'). The above-mentioned spatial assessment of each area, i.e., heat demand density and distance to existing DH network, is then integrated into the model by the investment cost for connecting DH.

2.3. Modeling with TIMES

The modeling aim in this study calls for long-term optimization modeling that can investigate the decarbonization pathways at local level. The TIMES model has previously been applied to local energy systems in scenarios analysis: to a municipality in central Italy [56]; a city in Sweden [57]; and to a city in Norway [58], confirming the adequacy of the TIMES model as a robust tool to analyse the dynamics of a municipal scale energy system.

TIMES is a linear programming model and its objective function minimizes the total system cost within a specific timeframe [59]. The



Current DH area. The arrow mark indicates only a part of the colored area with DH, rather than the whole area, except for St. Merløse, i.e., St. Merløse is supplied only with DH.

Fig. 3. The 11 areas used as input to the TIMES modeling.

total system cost encompasses investments, operational, maintenance, and activity costs, as well as end-of-life related costs. In addition to the objective function, particular constraints, such as zero CO_2 emissions and associated target years, are imposed which differ from scenario to scenario. The total system cost is minimized in all scenarios over the entire time horizon, reaching zero-CO_2 emissions by Year 2050. In Eq. (1), the discount rate $d_{(r,y)}$ is applied to region r for year y, relative to the base year $REFY$. The term $ANNCOST(r,y)$ denotes the total annual cost in a given region (r) during a specific year (y), encompassing capital costs (investment and dismantling), fixed and variable annual operation and maintenance (O&M) costs, costs incurred for imports and for domestic resource extraction and production, revenues from export, and taxes and subsidies [60]. Techno-economic data are exogenously given to the model.

$$\mathrm{OBJ}(\mathrm{t}) = \sum_{r=0}^{R} \sum\nolimits_{y} \left(1 + d_{r,y}\right)^{REFY-y} * ANNCOST(r,y) \tag{1}$$

The geographic scope of the model is the cadastral boundary of the municipality. This means that any import of energy or fuel from outside the municipality's boundary comes at a certain cost in the model. While the electricity is supplied from the national grid with certain import costs taken from Ref. [61], the costs associated with decentralized balancing, grid fees, and national energy taxes are not included. Fig. 4 shows a schematic representation of the system boundary of the municipal heating system model, along with its main components and inputs. As shown in Fig. 4, the resources inside the dashed line, biogas, solar energy (solar PV and solar heat), biomass, and EH from the existing municipal wastewater treatment plant (WWTP) (EH1), and the industrial EH (EH2) from the neighboring municipality are all considered to be locally available resources. On the other hand, natural gas, heating oil, and electricity are imported from the national electricity and gas grid, respectively. The modeling is a so-called *brownfield investment optimization*, which means that existing electricity and heat generation plants, their remaining lifetimes, and their capacities are taken into consideration.

For a case in which there is already a DH network in place, it is assumed that this will be used throughout the modeled period and that the associated buildings will continue to use DH with options to invest in new DH generation technologies. These assumptions reflect the regulation of the DH sector in Denmark, where municipalities have the authority to mandate that buildings that are already connected to DH maintain their connection, "obligation to remain connected" [62]. For all areas without existing DH, the model optimizes investments not only in individual heating technologies, but also in different DH production plants. Thus, the results from the modeling provide a breakdown of the existing and newly invested technologies for each time-slice, the optimal investment in new production capacity, and the total system cost and levels of carbon emissions for the chosen time horizon.

2.4. Input data and assumptions

The annual heat demand in each area in the base year used in this study is obtained from the BBR database (see Supplementary Material Table A1). The total heat demand is assumed to remain at the same level as in the first modeled year (2020). This assumption is based on combining an expected 1% annual growth in the building stock and a demolition rate of 0.3% [63,64] together with expected continuous increases in the energy efficiencies of new buildings (the newly built buildings have an approximately three-fold lower heat demand per m^2 compared to the current average). In the model, each year is divided into five time-slices: Spring (March–May); Summer (June–August); Autumn (September–November); Winter (January–February); and Peak demand (December), to represent the seasonally variable heat demand. Since the heat demand profile data of Holbæk municipality was not readily available, the data are obtained from Siddique et al. [65]. These authors used Danish heat demand estimate, based on the type and the year of construction of Danish buildings, as a baseline to estimate heat demand profile in a Danish city. The data are considered relevant to use also in the current study since national heat demand statistics should be generally applicable to any city (e.g. small difference in climate across Denmark).

The modeled heating technologies, both the existing technologies and the new investment options, are listed in Supplementary Table B1 with the investment costs. Other techno-economic data, such as O&M cost and efficiencies, are given in Supplementary Table C1 and D1.

For a biogas fuel to be injected into the gas grid, the fuel needs to undergo an upgrading process to remove or separate the CO_2 and other impurities, so as to reach methane content of 95%, thereby securing the natural gas level of heating potential [66]. The fuel cost for biogas, including the cost of the upgrading process, is assumed to be 73 €/MWh in the model [67]. The biogas in the model is produced from the WWTP in the municipality and its availability is assumed to be constant at 100 GWh throughout the year based on the discussion with the municipality [68]. The biogas fuel is assumed to be in the form of biomethane obtained from the upgrading of raw biogas to a quality that can be injected into the natural gas grid. Thus, the upgraded biogas (fuel) is assumed to be distributed through the existing gas grid and used in the existing natural gas boiler (fuel replacement). DH in the model can be invested in either with or without seasonal pit thermal energy storage (PTES); there is an additional cost for such storage [69]. This enables the storage of solar thermal energy, collected during the summertime, and the release of this stored energy to meet the demand for space heating during the winter season [70]. In the model, it is assumed that the efficiency of the solar thermal collector is 40% during the summer season, which is the 1st of June to 31st August [71], and 10% during the remaining period of the year. The solar heating technology included in this study is assumed to be solar thermal collectors mounted on the roof, and the cost includes the pipes, pumps, and hot tap-water tank [71]. The costs for the EH from the municipal WWTP and KIS, at 1 €/MWh and 10 €/MWh, respectively, are assumed to be lower than the lowest fuel cost in the model. Based on an estimation from the municipality, the EH from the municipal WWTP and KIS is assumed to be constant at 97 GWh and 350 GWh respectively throughout the year [68]. In terms of biomass, the model does not limit its availability, but three different levels of availability are applied in the sensitivity analysis (see Supplementary Material F). With the exception of electricity, it is assumed that there are no seasonal variations in the prices of the fuels, i.e., EH, biogas, biomass, in the model (for fuel price, see Supplementary Table E1 and E2). The electricity generated from the existing natural gas-fired CHP is assumed to be sold to the national grid and is represented as an economic benefit in the model. In addition, electricity is an imported commodity and considered carbon-neutral in the model. This should be a fair assumption since the Nordic electricity system is on its way to carbon neutrality with a high and increasing share of renewable electricity.

Fig. 5 presents the cost components of the investment cost calculation for DH pipes. It is evident that the investment cost for DH network expansion reflects the heat demand density and the proximity to the existing DH network of each area. The investment costs for the DH pipes will also depend on the type of pipe used (polymer piping is assumed in this work), as well as the nominal diameter, insulation class, and the pipe-laying costs [72]. The investment cost for distribution network is expressed as the sum of 1) the investment cost of the distribution network *within* districts connecting the buildings and; 2) the investment cost for the network *between* the districts. The investment costs associated with the distribution network within districts rely heavily on the building to area ratio and heat demands [73]. This investment cost for the distribution network per building is calculated based on the ratio between the total area of a district and the total heated floor area within the district. A substation is assumed to be installed in each building and together with the data on the number of buildings, the investment cost for the distribution network within districts can be calculated. The

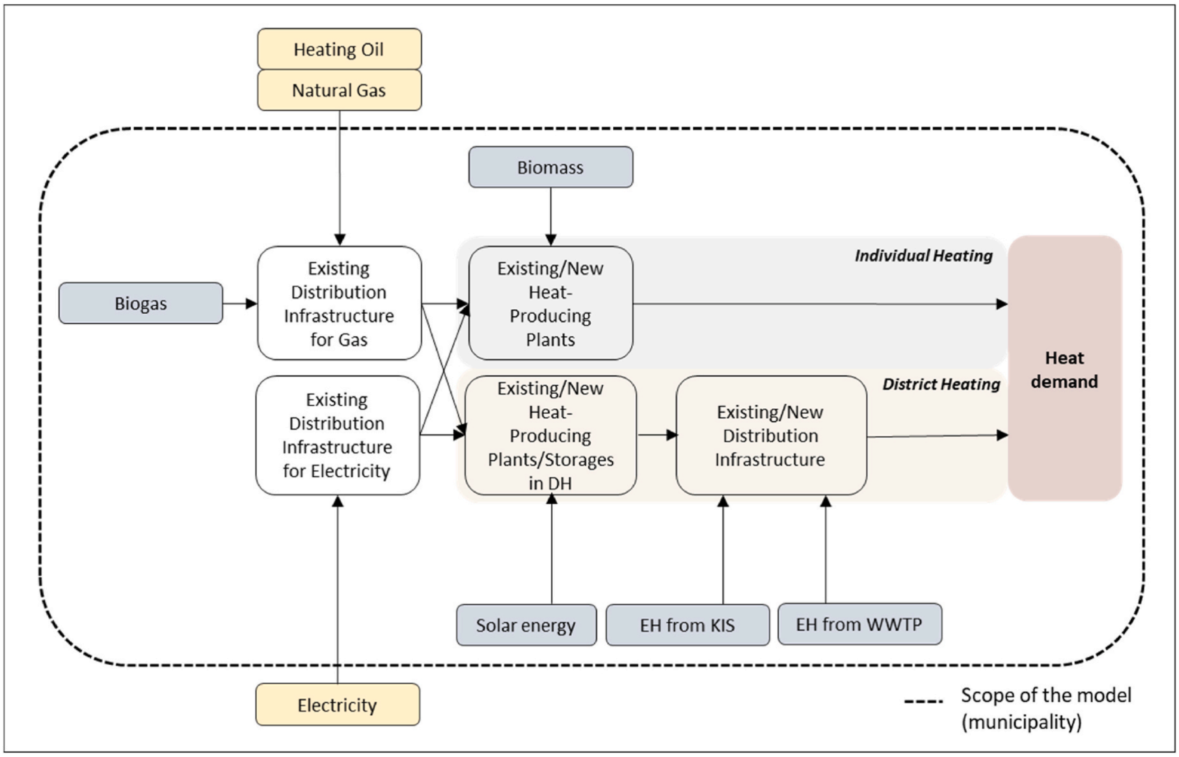


Fig. 4. Representation of the system boundary of the municipal heating system model.

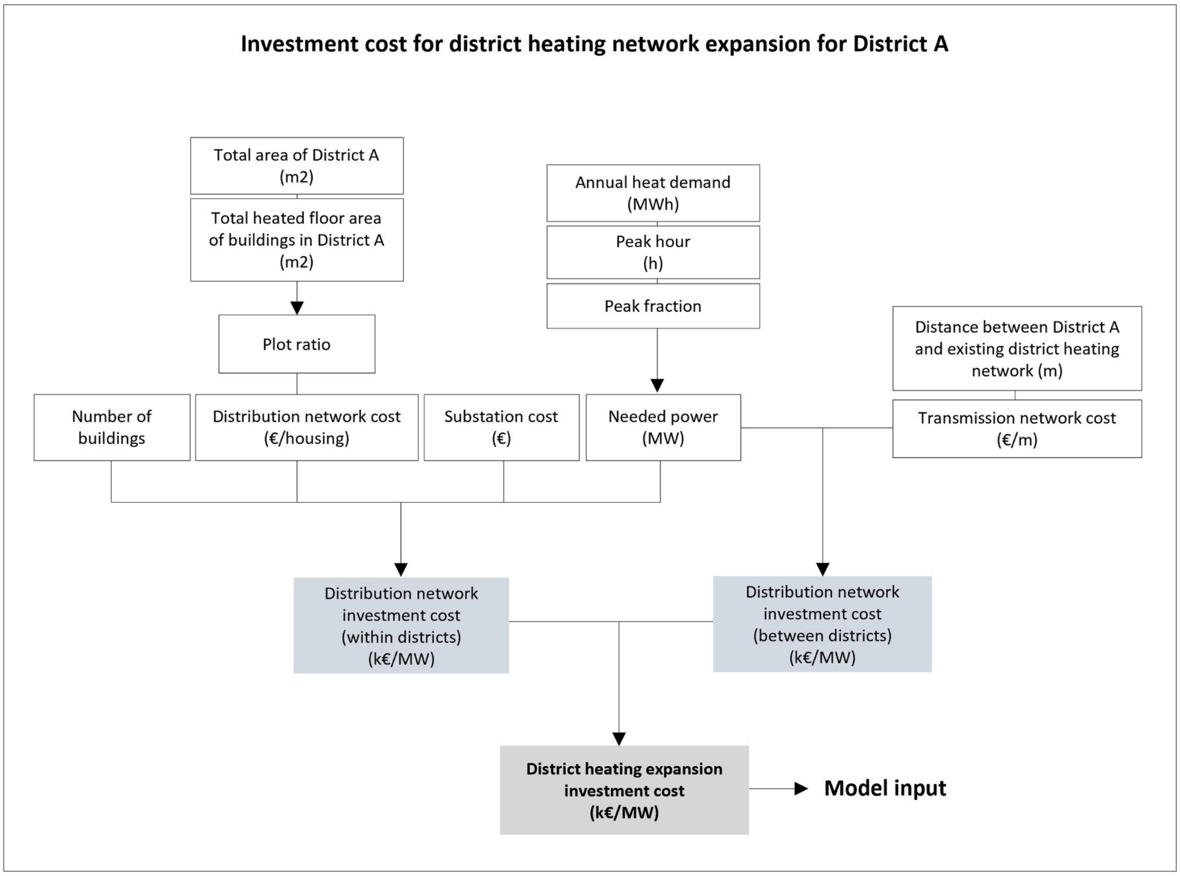


Fig. 5. Cost components of the investment cost for district heating network expansion in District A. The unit for the investment cost of the distribution network is k€/MW in order to reflect the cost per pipe capacity being built.

investment cost for the network between districts is calculated based on the actual distances between the districts. For a detailed calculation of the cost of each component, see Supplementary Table D2.

2.5. Scenarios

In this study, we apply four scenarios (Table 1). The scenario formulations are partly based on previous research on rural heat decarbonization in the six European countries [51,74] and, more importantly and uniquely for the present work, from iterative discussions with the energy planners in Holbæk. The scenario discussions included technology preferences, energy policies, investment plans, and limitations/availability of local resources and infrastructures. Thus, the close involvement of local planners in the scenario work greatly improved the representation of the local context and created a focus on the issues relevant to the stakeholders, while maintaining a broad scenario scope. The four scenarios are divided into two categories, with one focusing on utilizing local resources and one investigating a mix of local resources and electrified heating (see Table 1).

In the *Centralized_Local scenario*, the DH system has the possibility to use two sources of excess heat (municipal WWTP and KIS), together with possible network expansion. Each excess heat source provides heat year-round and, thus, the annual availability in the model is defined by the existing capacity. The excess heat from the municipal WWTP requires an HP to increase the temperature of the wastewater. The excess heat from KIS can be directly fed into the current DH system. The model can choose investment in individual heating solutions if this is more cost-efficient than using DH.

The *Decentralized_Local scenario* investigates how much of the current natural gas could be replaced with biogas. The biogas price is adopted from Ref. [67] and availability is constant at 100 GWh within a year. Due to the large volume of natural gas used throughout the municipality, this scenario would make the most use of the existing infrastructures, i.e., continued use of the natural gas grid and the associated boilers but using biogas.

The *Electrification scenario* assumes that the DH supply is dominated by solar heating and large HPs, coupled with seasonal thermal storage. This is based on a scenario for European heat decarbonization presented by the European Commission [75]; thus, this scenario reflects the EU-level strategy, while the Centralized_Local and Decentralized_Local scenarios reflect local strategies, i.e., the options discussed in the municipality as heating solutions.

Finally, the *Mixed_Integrated scenario* includes all the technologies available to the model, including biomass CHP and heat-only boilers (HOB). Thus, for this scenario, the model can invest in any heating technology.

3. Results

First, the results obtained from the TIMES modeling tool are reported in terms of the heat supply by source, DH supply (district heat), and the costs for investment, fuel, and operation and maintenance for each scenario and for each 10-year interval. The results of the sensitivity analysis (SA) are presented in Supplementary Material F.

3.1. Heating system transition in the Holbæk municipality

Fig. 6 shows the heat supply by technology for the four scenarios. The starting Year 2020 corresponds to the observed data. Heat generation from DH is aggregated in Fig. 6, and the DH technologies are detailed in Fig. 7. This means that with the exception of DH, the technologies in Fig. 6 are all individual heating technologies (indicated as "Indiv." In Fig. 6).

The *Centralized_Local* scenario shows a two-step transition of the current natural gas-dominated heat supply. As the first step, heat generation from individual biomass boilers increases significantly until the EH sources of the municipal WWTP and KIS become available for DH in Year 2027 and Year 2030. When DH that utilizes both of these EH sources expands dramatically, starting from Year 2030, the individual biomass boilers start operating at only 40% of their full-load hours until they reach their end of lifetime in Year 2044, and the remainder of the heat demand is supplied through DH. It may not be economically viable for the system to invest in individual biomass boilers that already after a few years will have to operate in part load. Yet, it should be mentioned that such part-load operation in the result could mean either a number of boilers operating low full-load hours, or fewer boilers operating at their full-load hours during a small number of hours. However, the type of cost optimization model used in this work, which adopts an aggregated representation of the heat demand and supply, obviously does not say anything on how individual boilers are opeating. In Year 2050, the share of individual biomass boiler supply differs in each district, ranging from 4% to 59%. The large span is due to large differences in district properties, e.g., heat demand density and distance to an existing DH network, influence the cost competitiveness of individual biomass boilers. Fig. 7

Table 1

Heating technology options included in the scenarios applied in the modeling. All the scenarios optimize the total system cost. Note that technology options in the *Centralized_Local*, *Decentralized_Local*, and *Electrification* scenarios are based on the stakeholders' inputs, and that the *Mixed_Integrated* scenario includes other possible alternatives, such as bio-based heating technologies. Biomass, biogas, and electricity are considered to be carbon-neutral in the model.

Category	Scenario	Included technology and fuel investment options			
		Individual heating Technology	Individual heating Fuel	DH Technology	DH Fuel
Local resources	Centralized_Local	Biomass boilers Electric boiler Heat pump Solar heating		DH network	EH from WWTP EH from Kalundborg
	Decentralized_Local	Biomass boilers Electric boiler Heat pump Solar heating	Biogas	Heat pump Electric boiler Solar DH with TES	
Mix of local resources and electrification in heating	Electrification	Electric boiler Heat pump		Heat pump Electric boiler Solar DH with TES DH network	
	Mixed_Integrated	Biomass boilers Electric boiler Heat pump Solar heating	Biogas	Heat pump Electric boiler Solar DH with TES Biomass CHP Biomass HOB DH network	EH from WWTP EH from Kalundborg

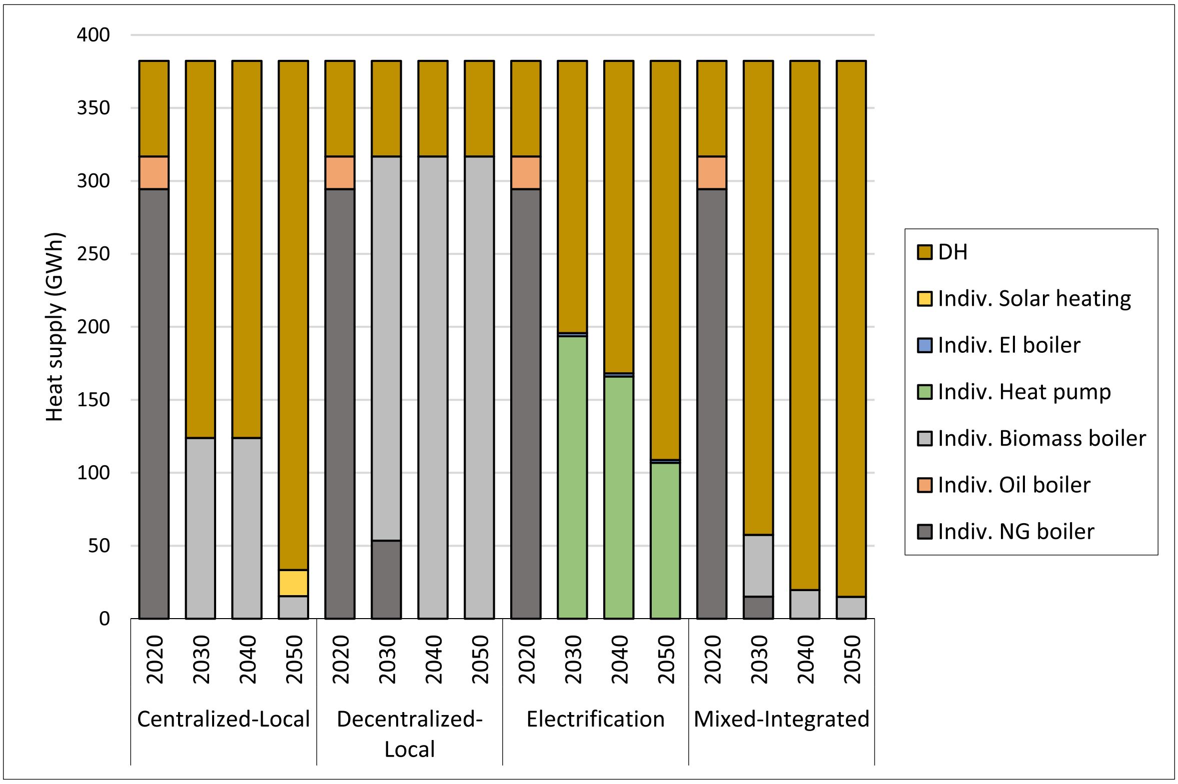


Fig. 6. Heat supply by technology in each scenario at the indicated 10-year intervals.

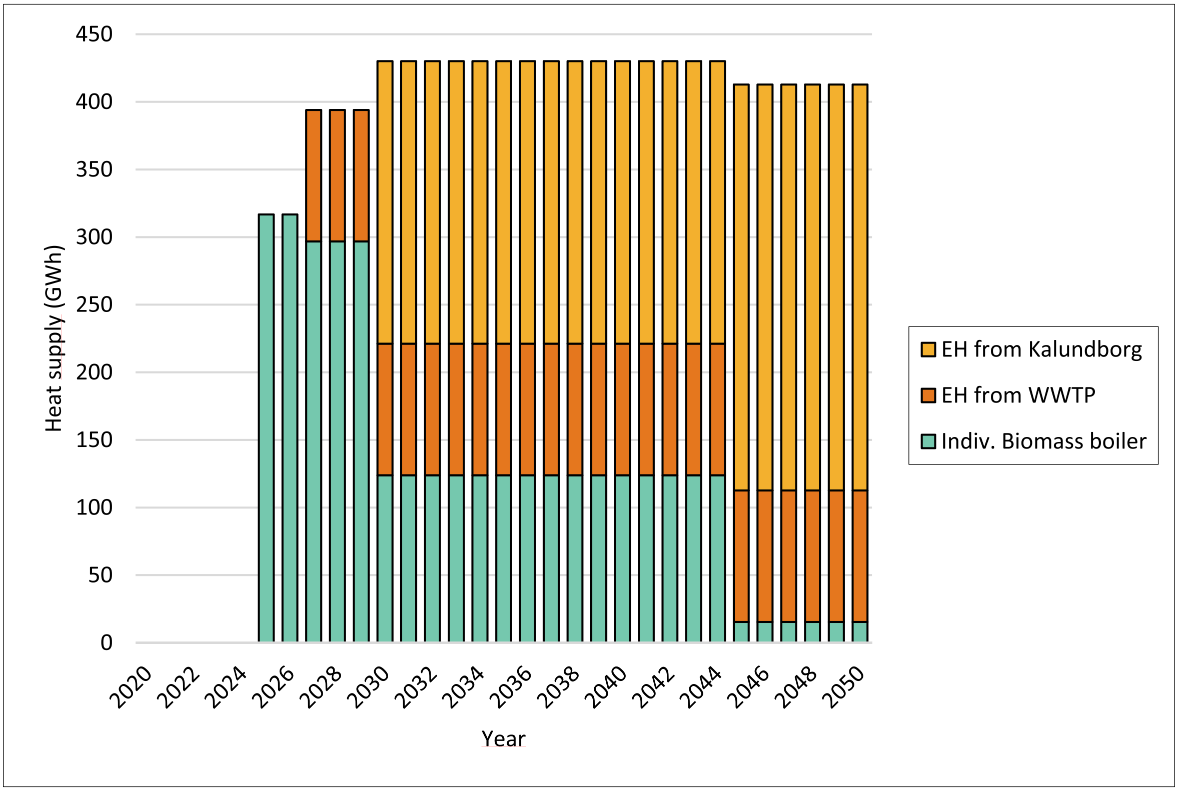


Fig. 7. Interactions between individual biomass boilers and DH derived from the two excess heat sources regarding the supply of heat over time in the *Centralized_Local* scenario.

shows how the heat supply from the individual biomass boilers are replaced by DH over time.

The use of individual biomass boilers increases in response to the declining use of individual natural gas boilers due to the natural gas ban policy[3] and covers on average 80% of the total heat demand until Year 2029, and subsequently declines (see Fig. 7). As shown in Fig. 7, the expanded DH that uses EH from the municipal WWTP and KIS partly replaces the individual biomass boilers, resulting in a decrease in the use of individual biomass boilers in Year 2028. The decreased usage of individual biomass boilers is a result of the progressive market entry of excess heat from WWTP from Year 2027 onwards, and from KIS from Year 2030, along with the extension of the existing DH network to additional users. This indicates that it is advantageous to expand the DH network to further utilize low cost excess heat (the excess heat cost is assumed to be lower than the lowest fuel cost in the model, which is the cost of biomass). This DH expansion marks the second step of the transition in this scenario. The newly built DH network supplied by the two EH sources substitutes 173 GWh yearly, thereby outcompeting the individual biomass boilers until they reach their 20-year technical lifetime in Year 2044. During that period of time, individual biomass boilers are mainly used to cover the high-demand seasons (not shown but observed in the modeling results). From Year 2045, EH-based DH represents more than 90% of the heat generation, with the remaining heat being supplied by individual solar heating (15 GWh) and biomass boilers (18 GWh).

Fig. 8 shows the development trajectories of the DH supply in the four scenarios. It can be seen in Fig. 8 that the heat supply from the DH system increases five-fold when utilizing both of the industrial EH sources to their full potential in the *Centralized_Local* scenario. In Year 2050, DH supplies up to 91% of the total heat demand, and the remaining demand is for buildings that are too-isolated and have too-low heat demand density to be connected to the DH network. Section *3.2. Spatial distribution of DH* addresses the area-specific spatial analysis in detail.

Fig. 9 presents the modeled annual usage levels of natural gas and biogas in the *Decentralized_Local* scenario. The results show that the natural gas used in the existing individual natural gas boilers starts to be substituted by biogas in Year 2023, since biogas production that includes the required upgrade process is assumed available from Year 2023 (sourced from the existing municipal wastewater treatment plant). It is assumed that this will not require any additional investment in the wastewater plant since this plant already produces biogas in the process of anaerobic digestion of waste. As mentioned in the *Methodology* section, the upgraded biogas (biomethane) can be readily employed in the current gas grid. Thus, the model designates Year 2023 as a feasible year for biogas adoption, contingent on the presence of a WWTP that enables biogas recovery in the municipality. Fig. 9 shows that biogas continues to produce heat until Year 2040, when gas boilers are phased out. Afterwards, biomass boilers covers the demand that cannot be met by biogas. Biogas is mainly utilized for seasonal peak heating when the heat demand is highest (not shown in the figures but observed in the modeling results). Here, the biogas not used for heating purposes is assumed to be used in other sectors, which is outside the scope of the study. However, since biomass is a limited resource, it will be allocated to the sectors with a highest willingness to pay for biomass and, thus, the increased competition over biomass is likely to increase the biomass price. This is not reflected in the present study, which assume a biomass fuel price of 21.6 €/MWh similar to the present biomass price [76].

Neither DH expansion nor EH recovery is an investment option in the *Decentralized_Local* scenario. Thus, DH production remains at 65 GWh (same as the base-year level) throughout the period, and only the DH heating mix evolves (Fig. 8). In this scenario, natural gas is rapidly replaced by solar DH, such that by Year 2050, it accounts for up to 83% of the total DH production. After the existing HPs reach their technical lifetimes, there are investments in new HPs in Year 2040 and they supplement the dominant solar DH (Fig. 6).

In the *Electrification* scenario, fossil energy sources are extensively replaced by individual HPs and partially by electric boilers, as can be seen in Fig. 6. Together, the electric boilers and HPs supply 51% of the total heat demand by Year 2030, with the remainder being covered by DH. The gradual expansion of DH replaces individual HPs and accounts for up to 71% of the total heat demand in Year 2050. The heat production from the individual electric boilers decreases as cost-efficient and low-carbon DH that is based on EH takes over towards the end of the analyzed period. DH production in the *Electrification* scenario grows more than four-fold by Year 2050, driven by investments in solar DH supplemented with seasonal thermal storage (Fig. 8). The storage capacity gradually increases throughout the modeled period, and the heat discharged from the storage covers around 20% of the DH demand in Year 2050. As a way to replace the natural gas while covering the increased DH demand, large investments in new HPs are made. The new HPs supply 43% of the total DH production in Year 2030, and this gradually decreases to 11%, as shown in Fig. 8.

In the *Mixed_Integrated* scenario, DH expands the most and becomes the dominant heat supply technology from Year 2028, as shown in Fig. 10. Before this massive expansion of DH, the individual heating supplying the heat demand constitutes individual biomass boilers and individual natural gas boilers through the combustion of biogas. After Year 2030, as shown in Fig. 6, the cheapest heat supply option is DH using the EH from the municipal WWTP, which is utilized at its maximum annual availability every year. Individual biomass boilers supply those areas where the heat demand density is low and DH expansion is unfeasible (Fig. 11). DH increases the most to cover 97% of the municipal heating demand in 2050 in the *Mixed_Integrated* scenario, as shown in Fig. 8. A significant part of the generated heat comes from EH, although in contrast to the *Centralized_Local* scenario, only the EH from the WWTP in Holbæk is fully utilized. The EH from KIS is used at 73% of its potential, and 25% of the DH production comes from solar DH. The reason for this preference is the availability of solar DH investments starting in Year 2025, while EH from KIS is not accessible until Year 2030. As a result, the model prioritizes utilizing the available options initially, maximizing their usage until they can be complemented with the subsequent, more-cost-efficient option.

3.2. Spatial distribution of DH

Fig. 11 gives an overview of the share of the DH supply in the total heat supply (DH share) in the final year of 2050 for each area included in the modeling of the Holbæk municipality for the four scenarios. Table 2 presents the DH share (%) depending on the properties of each district, i.e., the heat demand density and proximity to the existing DH network, as well as the availability of EH. The results indicate that the heat demand density is one of the main drivers for connection to the DH network. It also shows that EH recovery may be a key factor in increasing the economic feasibility of DH expansion and in connecting the areas with lower heat demand densities. This is illustrated by the differences in DH between the *Centralized_Local*, *Mixed_Integrated* and *Electrification* scenarios.

In the *Centralized_Local* scenario, DH provides 88% – 95% of the heat supply in the areas with high demand density (CityH and CityL), while in the area with the lowest heat demand density, the DH share is 40% (CTDH2), as shown in Fig. 10. It can also be seen that in the *Electrification* scenario, the DH share in the high demand density areas (CityH and CityL) reaches 76%, which is lower than in the other scenarios. In the areas with a lower heat demand density, the DH share ranges from 1% to 50%. It shows that the DH shares in the *Mixed_Integrated* scenario are the highest in all the areas. Five areas achieve 100% DH supply in Year 2050, and the remaining areas, even with lower heat demand densities, still have relatively high shares (62% – 83%) of the DH supply.

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[3] In 2013, Denmark announced gas boiler installation bans for new buildings and the elimination of natural gas use by Year 2035 [82].

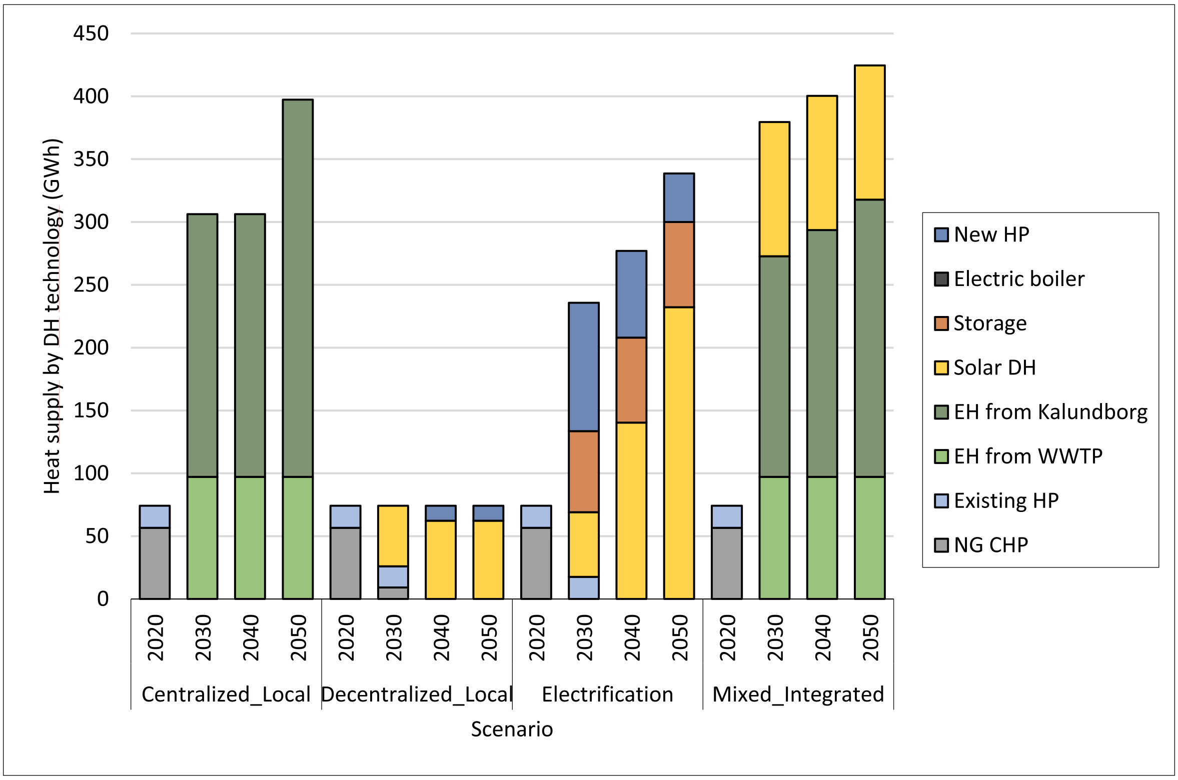

Fig. 8. Heat supply from DH by district heat-producing technology/source for the different scenarios over the modeled decades. It should be noted that in the *Decentralized_Local* scenario, expansion of DH production is not possible due to the unavailability of DH network expansion as an investment option. Production from storage refers to heat recovered from pit thermal energy storage (PTES), coupled with solar heating systems.

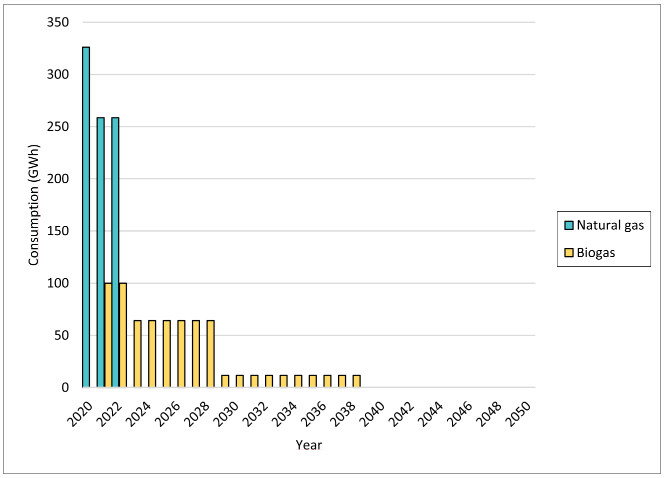

Fig. 9. Annual consumption levels of natural gas and biogas in the *Decentralized_Local* scenario. Note that the same infrastructures are used (grid and individual boiler) for biogas use to substitute natural gas. Thus, it is assumed that there is no investment cost for the fuel substitution from natural gas to biogas, and Biogas indicates upgraded biogas (biomethane).

3.3. Costs – variable/fixed O&M, fuel, and investment costs

Fig. 12 shows the total system cost including the investment cost, fuel cost, and variable cost, over the analyzed period relative to the *Mixed_Integrated* scenario, which gives the lowest total system cost.

The *Electrification* scenario shows the highest total cost, which is mainly attributed to the higher investment cost driven by the need for individual HPs and thermal energy storages, besides DH network expansion. In contrast, the *Decentralized_Local* scenario shows the lowest investment costs, as it continues to utilize the existing natural gas network infrastructure along with the local biomass resource and does not expand the DH system, which requires costly piping construction. However, this lower investment cost comes at the expense of relatively higher fuel costs, as this scenario does not benefit from low-cost EH, and the utilization of biogas is reflected in the high fuel price that includes a substantial upgrading cost, i.e., the upgrading process makes up about 70% of the recovered biogas price [77]. Finally, the *Centralized_Local* scenario gives the second-lowest cost after the *Mixed_Integrated* scenario. The *Centralized_Local* scenario shows a cost structure that is similar to that of the *Mixed_Integrated* scenario, except for the O&M costs, which are the second-highest of the four scenarios. In the *Centralized_Local* scenario, O&M costs are driven by the individual biomass boilers. The results for the *Centralized_Local* and *Mixed_Integrated* scenarios indicate that while the extensive use of industrial EH can be costly due to the need for DH expansion over longer distances, combining industrial EH with investments in renewable heat resources can lower the costs for the heating systems.

4. Discussion

We show that EH recovery can play a critical role in accelerating local DH network expansion, since assuming a low cost for EH will enhance the economic competitiveness of DH. As a result, the modeling shows that when EH is available, the share of the DH supply compared to individual heating in each district is higher, within the range of 63% 100%, and 15% – 84% otherwise. This is particularly relevant in the case of rural areas, where industrial waste heat is generally the most-concentrated. This result is in line with the conclusions drawn in Ref. [46]. It is important to note that the EH from the KIS is not carbon-neutral. Although the partner companies of the KIS include fossil fuel-driven industries, achieving carbon neutrality within the next decades is one of their strategies [78]. In the two tested scenarios allowing

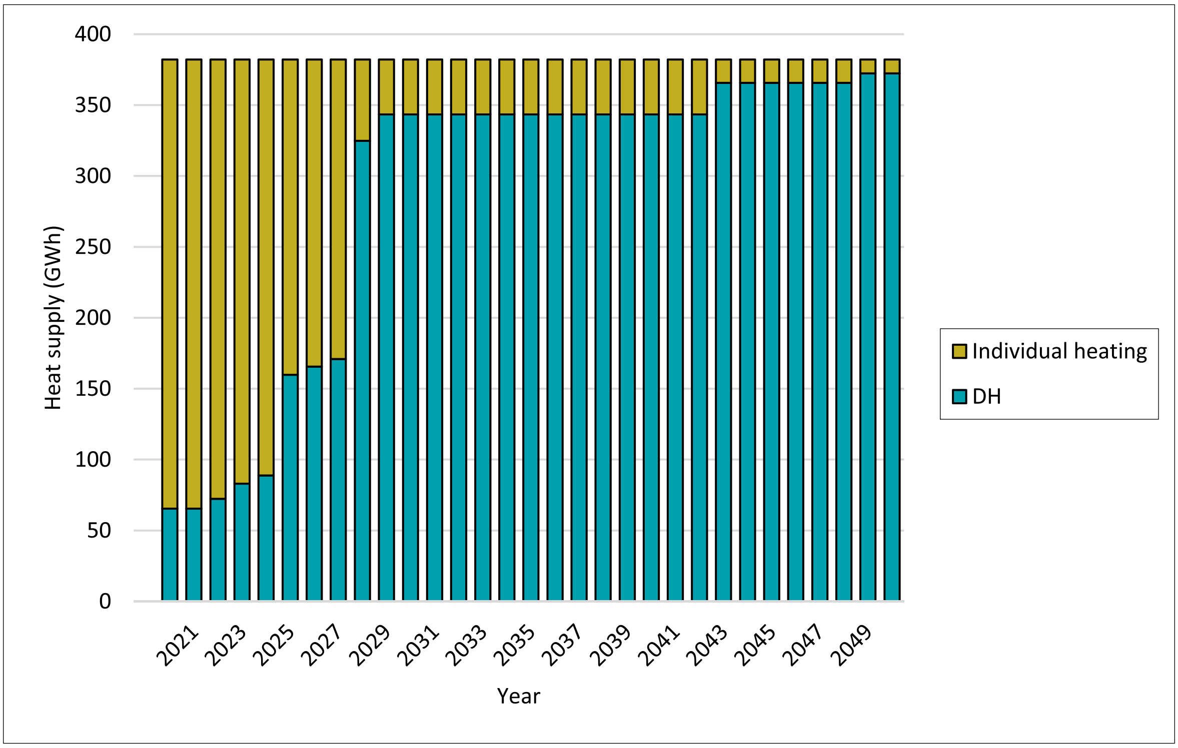

Fig. 10. Heat supply from DH and individual heating over the entire time horizon in the *Mixed_Integrated* scenario.

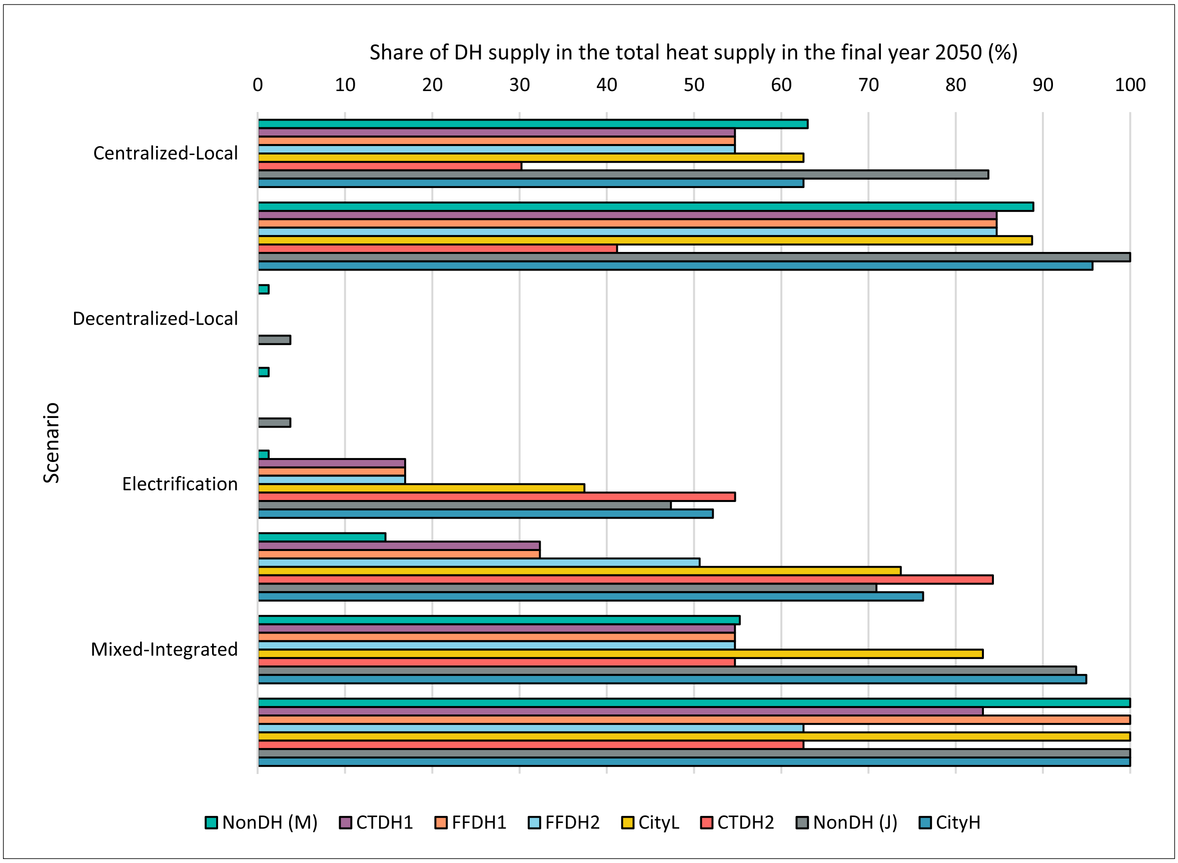

Fig. 11. DH production share in Year 2050 in the different districts modeled and the different scenarios investigated.

Table 2

Maximum DH shares in the final year, as obtained from the modeling, together with the heat demand densities for the districts in the Holbæk municipality.

District	Heat demand density (MWh/km^2)	Proximity to existing DH network (m)	Maximum DH share in Year 2050 (%)	
			EH available	EH not available
NonDH (M)	8000	0	100	14.6
CTDH1	10,800	2713	84.7	32.3
FFDH1	11,000	6737	100	32.3
FFDH2	11,200	7805	84.7	50.7
CityL	13,100	14,293	100	73.7
CTDH2	14,500	7334	62.6	84.3
NonDH (J)	18,600	0	100	70.9
CityH	32,200	14,293	100	76.3

EH, the DH supply grew significantly from 17% of the total heat supply to 91% and 97%, respectively, in Year 2050, with individual biomass boilers covering the remaining heat demand. This result indicates that some of the buildings have two heating systems, i.e., DH and an individual biomass boiler, and that they operate the biomass boiler during certain seasons, e.g., peak month, wintertime. This result may not be viable in reality, since it would be costly for the individual consumers to have such a dual system and the installation of a boiler represents a substantial task that is not a simple addition to the already-connected DH. The reason for acquiring the results for such dual systems is because in the model, the buildings within a district are only represented on an aggregated level and have access to all of the investment options. This is an obvious drawback of this type of model implementation.

In the case of a dual system, combining biomass boilers and solar heating is often employed, with the solar heating producing hot tap-water during the summer [71]. In addition, a dual system of DH integrated with individual electric boilers, which can be seen from the model results for the *Electrification* scenario, should be a realistic solution that could contribute to flexible electricity consumption by offering the possibility to shift HP load with time (say up to 12 h).

Finally, it can be concluded that using EH in DH is not without risks. If the DH operator relies solely on an industrial waste heat supplier, the DH system will be negatively affected by market uncertainties, e.g., industry cessation or recession. Furthermore, as mentioned above, if the EH comes from fossil-fueled processes it may not be the most-favorable choice, and customers may be reluctant to purchase such EH.

When it comes to the electrification of heat, it may not be cost-competitive in rural settings because there are other available local solutions, as investigated in this study. The electrification of heat is interconnected with the decarbonization of other sectors, such as power and industry. Therefore, the success of a heating decarbonization strategy partially depends on the progress made in decarbonizing these sectors. In this regard, solar DH can help mitigate to a certain extent the dependence on other sectors by providing a renewable heat source. The relevance of rural areas to solar energy as a significant energy source stems from the distinctive features of rural landscapes with ample open land, which can be utilized for the installation of solar thermal collectors or panels. This makes solar energy an attractive option for decarbonizing rural heating and electricity systems, contributing to their energy needs, and reducing their reliance on fossil fuel-based energy systems. It is important to note that achieving a high solar fraction in solar DH systems is only possible through the implementation of a substantial seasonal storage component [79].

The last key result of this study is that biogas injection into the existing gas grid may not be a suitable fuel substitution option to replace natural gas. This is due to the current high price of biogas, at 55 – 100 €/MWh [80], which includes the required upgrading cost. The modeling conducted in this work shows that the biogas share of heating provision gradually declines to 10% in Year 2040 and is eventually phased out from Year 2041. The successful utilization of locally available biogas will be dependent upon various factors, such as the presence of a well-established gas grid, sufficient local supply, and optimal proximity of producers, which are conditions that many rural areas in Denmark and other countries, such as The Netherlands, may fulfill. The results of the cost analysis show that the *Centralized_Local* and *Decentralized_Local*

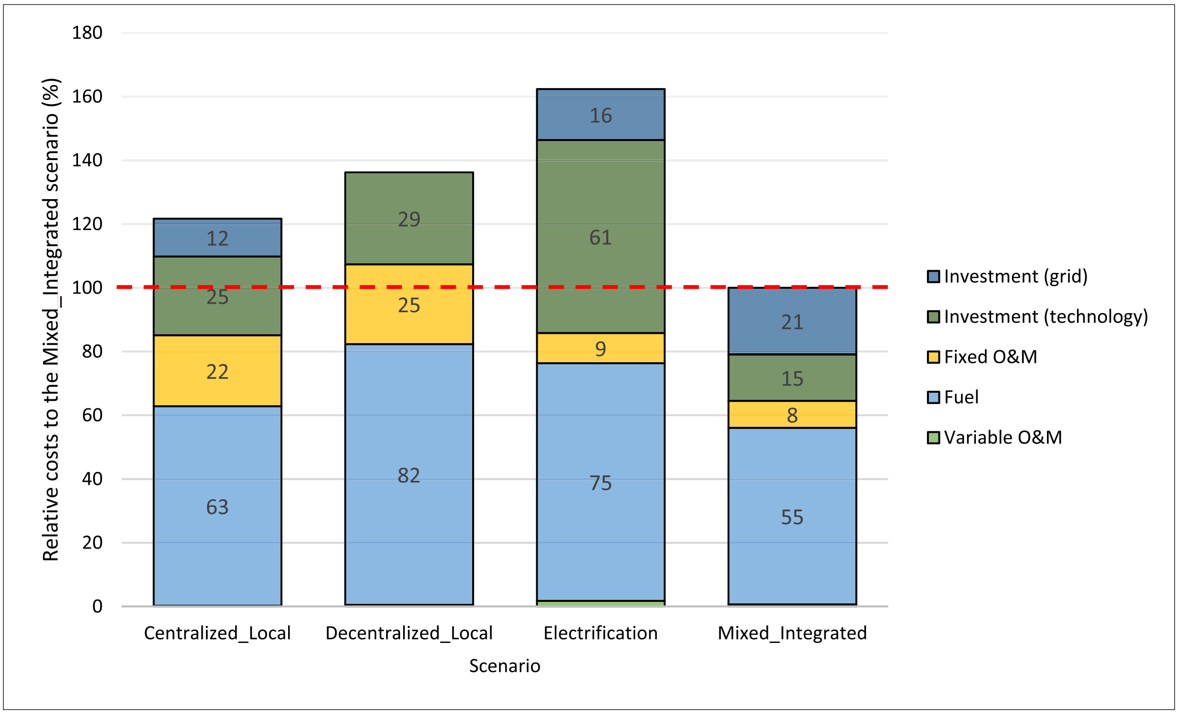

Fig. 12. Overview of the cost elements in each scenario, as obtained from the modeling. The costs shown are relative to the cost of the *Mixed_Integrated* scenario (red dashed line).

scenarios, which are in the 'Local resources' category focusing on utilizing local resources, result in the lowest investment costs. However, in reality, resources are finite, and it is therefore essential to complement these with additional investments in alternative technologies such as solar DH and thermal storage systems, and HPs.

5. Conclusions

This study explores various strategies for transitioning heating systems in semi-rural regions using optimization modeling, under the assumption that local targets related to reducing carbon emissions are reached and considering local resource availability, heat demand, and heat density. The modeling methodology enables "area-specific" analysis that takes into account the specific heat demand density and proximity to the existing DH network, and it includes heating options that use the local fuel resources and infrastructure.

The modeling results show that utilizing EH from the municipal WWTP and neighboring industrial site in DH systems is the most economically viable heating choice that also drives further expansion of the current DH network. In addition, biomass plays an important role as a necessary piece, fulfilling the heating demand that cannot be met by DH alone. However, it is important to consider the risk of being dependent on industrial EH, in that industry cessation or recession will negatively impact the DH system. In the case of biogas, the outcomes of the model and the sensitivity analysis indicate that it is not a suitable fuel option for replacing natural gas. Making maximal use of local resources benefits municipalities in terms of self-sufficiency and lower energy imports, with potentially positive knock-on effects on the local economies. We also conclude that the geographic characteristics of rural areas, such as their remote location, sparse heat demand density, ample availability of open land, and prevalence of agriculture, all attribute to heat decarbonization strategies that use local resources such as biogas from agriculture. These characteristics create favorable conditions for establishing local heating systems that make the most of the available local resources. However, it is essential to consider the risks associated with relying solely on one or a limited number of local heat sources.

In summary, heat decarbonization in rural areas can benefit from the use of resources and infrastructures that are readily available within and in proximity to the local municipality. Yet, the results indicate that there are several possibilities for the transition of the heating sector, depending on the conditions for the available technologies and systems. Thus, it can be assumed that a successful transition will require a policy that aligns with long term planning for the heating sector to ensure the optimal utilization of technologies and avoid the need for continuous investment in new technologies. In addition, a clear decarbonization strategy for industries that can provide EH for DH is required. In the absence of a clear policy, there is a risk that investment decisions will vary over time and between districts in a contradictory way, making the transition less cost-efficient.

Future research should investigate additional technological options and resources for heat decarbonization in rural areas. Furthermore, increasing the temporal resolution of the modeling would enable a more-detailed analysis of the results, including possibilities to allow flexibility in electricity use, so as to ensure efficient integration of wind and solar photovoltaics (PV).

CRediT authorship contribution statement

Hyunkyo Yu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Claire Bergaentzlé:** Writing – review & editing, Resources, Project administration, Conceptualization. **Stefan Petrović:** Writing – review & editing, Validation, Formal analysis. **Erik O. Ahlgren:** Methodology, Funding acquisition, Conceptualization. **Filip Johnsson:** Validation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Erik O. Ahlgren reports financial support was provided by ERA-NET Smart Energy Systems. If there are other authors, they 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

I have shared data used in this research in Supplementary Materials.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2024.100144.

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