THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Heat decarbonization in municipalities

- Accounting for the local spatial context in techno-economic modeling

Hyunkyo Yu

Department of Space, Earth and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

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HYUNKYO YU

Department of Space, Earth and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46(0)31-772 1000

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HYUNKYO YU
Division of Energy Technology
Department of Space, Earth and Environment
Chalmers University of Technology

Abstract

In Europe, 57% of the energy used for space and water heating is derived from the combustion of fossil fuels, whereas only 24% comes from renewables. Compared to the wide-reaching transmission of electricity between countries, the supply of heat predominantly occurs at the local or individual level. Additionally, the local spatial dimension which influences the supply and consumption of heat implies that the choice of heating solutions is heavily dependent upon the local context. At the same time, it has been pointed out that the local spatial dimension does not receive adequate attention when formulating strategies for the energy systems transition. By addressing heat planning at the local level, it becomes possible to tailor solutions that take the unique local spatial conditions into account. The impacts of the local spatial dimension on heating solutions underscore the important roles played by local authorities, which have comprehensive knowledge of the local context, in research on heat decarbonization. This thesis presents a participatory modeling methodology for investigating local heating system transitions, combining techno-economic modeling and spatial analysis. The developed methodology is divided into five steps: Step 1 – Reviewing the planning processes; Step 2 – Inclusion of spatial features; Step 3 – Scenario formulation; Step 4 – Energy systems modeling; and Step 5 – Evaluation of modeling outcome.

The methodology has been tested in both urban and semi-rural case studies, described in the three appended papers. Stakeholder interactions were found to be critical in Step 2 (Inclusion of spatial features) in providing preferences for dividing municipalities into districts to be modeled, and in Step 3 (Scenario formulation) for delimiting the scope of technology options. For example, in the urban case study, the input from municipal planners included their preferences in regard to the number of districts and the criteria to subdivide the municipality to be modeled. Local preferences played a significant role in Step 3, with biomass being excluded as an option due to concerns about local air pollution. In the semi-rural case study, stakeholder interactions were highlighted, particularly on the selection of technology options in the model. As a result, the scenarios took into account the preferences of local energy planners regarding technologies such as biogas injected into the natural gas grid and utilizing excess heat from the municipal wastewater treatment plant and neighboring industries in district heating system. This is particularly significant, as these steps are closely linked to the modeling outcomes, ensuring their relevance for the specific municipality and its unique conditions. The impact of the high spatial resolution is highlighted, with the modeling results showing different heating technology preferences depending on the differences in district properties. This indicates that the model results reflect the local spatial context and thus, can suggest district-specific strategies for the municipality planners.

This thesis concludes that establishing a robust and long-term strategy early in the planning process is crucial, particularly from the standpoint of municipal planning. Furthermore, this thesis shows that the strategies employed for heat decarbonization will differ between urban and semi-rural areas, as well as between districts within these areas due to the large variety of spatial conditions pertaining to heat supply, distribution and consumption. Consequently, it emphasizes the importance of the participatory approach in order to understand the diverse local spatial contexts.

Keywords: Participatory modeling, optimization, local heat decarbonization, energy transition, spatial analysis

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. Yu, H., Selvakkumaran, S., Ahlgren, E. (2021) Integrating the urban planning process into energy systems models for future urban heating system planning: A participatory approach. *Energy Reports*, 7: 158-166. http://dx.doi.org/10.1016/j.egyr.2021.08.160

II. Yu, H., Ahlgren, E. (2023) Enhancing Urban Heating Systems Planning through Spatially Explicit Participatory Modeling. *Energies*, 16, no. 11: 4264. https://doi.org/10.3390/en16114264

III. Yu, H., Bergaentzlé, C., Petrović, S., Ahlgren, E., Johnsson, F. (2024) Combining techno-economic modeling and spatial analysis for heat planning in rural regions: A case study of the Holbæk municipality in Denmark. (*Under Review*)

Hyunkyo Yu is the principal author of **Papers I–III** and performed the modeling and analysis for all three papers. Erik Ahlgren contributed with method development and reviewing of **Papers I** and **II** and the conceptualization of **Paper III.** Sujeetha Selvakkumaran contributed with method development and reviewing of **Paper I.** Professor Filip Johnsson contributed with discussions and editing of **Paper III.** Claire Bergaentzlé contributed with conceptualization and reviewing of **Paper III**, and Stefan Petrović contributed with modeling and discussion of **Paper III.**

Other research and publications by the author, not included in the thesis:

A. Yu, H., Selvakkumaran, S., Ahlgren, E. "Municipal Heating System Modeling towards Urban Energy Transition: Integration of Spatial Dimension based on a Participatory Approach," presented at the *40th International Energy Workshop – IEA*, Freiburg, Germany, May 25-27, **2022**.

B. Yu, H., "Exploring Local Heating System Transition Dynamics," presented at the *2022 International System Dynamics Conference (ISDC)*, Frankfurt, Germany, July 18-22, **2022**.

C. Hwang, J. and Yu, H., "Environmental Cooperation as a Driver of 'Low Politics' in the Baltic Sea: An Actor-Based Analysis," *Korean Journal of European Integration*, vol. 13, no. 3: 332-356. **2022**. https://doi.org/10.32625/kjei.2022.28.331

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Hyunkyo Yu,
Göteborg, January 2024

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1. Introduction

After 2 years of extraordinary patterns of energy use and emissions due to the pandemic, there was a 0.9% increase in global direct and indirect[1] CO_2 emissions in Year 2022, representing a record high level. One-fifth of this increase in emissions was linked to the increased space and water heating and cooling demands of buildings under extreme weather conditions [1]. The provision of warmth in residences during the winter months and the supply of hot water for hygiene necessities are fundamental energy demands. Worldwide, around 40% of households need to heat their living spaces during a certain period each year, and this heating constitutes a substantial proportion of home energy costs, particularly in colder climatic regions [2]. In Europe, a significant portion, 57%, of the energy used for space and water heating comes from the combustion of fossil fuels, which include natural gas, oil, and coal, whereas renewables constitute only 24% of the total [3]. Thus, to align with the European Union (EU) objective of achieving carbon neutrality in Year 2050, the heating and cooling of buildings must transition towards expanded use of zero-carbon energy sources and must implement energy efficiency measures. This shift is essential, as outlined in the 2030 Climate Target Plan (CTP), to decarbonize effectively and to meet the set environmental ambitions. The CTP for the building sector includes doubling or tripling of the renovated areas compared to Year 2020, as well as fuel switching facilitated by the deployment of renewables and low-carbon gases [4]. As part of the EU *Fit for 55* climate package, a new separate emissions trading system (often referred to as Emissions Trading System 2 or ETS 2) will be introduced in Year 2027 and will include fuel combustion in buildings (and road transport). Thus, an increased incentive for decarbonizing the heating of buildings can be expected.

Compared to the wide-reaching transmission of electricity between countries, the supply of heat predominantly occurs at the local or individual level where the consumption points are located. In addition, the different local spatial conditions that influence the supply and consumption of heat, such as access to district heat supply technologies and fuel availability, make heating a local issue. Therefore, heating system solutions are, even more so than electricity systems, spatially diverse and context-dependent [5], with high distribution costs (district heating networks). By addressing heat planning at the local level, it becomes possible to tailor solutions that are better suited to the unique requirements and spatial conditions of each local area.

Emphasizing local heat planning allows cities to produce and distribute heat efficiently, to utilize local fuel and waste resources, and to reduce dependence on national energy grids and fossil fuels. As such, the unique local spatial characteristics of heat underline the importance of local authorities, which have valuable knowledge of the local context, in research on heat decarbonization [6]. This is because the local authorities and municipal planners are directly or indirectly involved in municipal energy planning, e.g., through environmental permitting and

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[1] Direct emissions assign emissions to the sector in which they arise. Indirect emissions refer to the reallocation of emissions from electricity and heat to the sector of final use.

city planning. The framework of the municipal planners varies between countries and regions, and typically involves several actors (e.g., municipal employees, municipally owned district heating companies, environmental permitting authorities, overall city and district planning bodies). Involving municipal planners in research on decarbonizing the heating system of municipalities can assist the planners in making informed decisions. This implies that suggestions made by such research will be aligned with the preferences by the stakeholders' preferences while showing a wide spectrum of possible development of the heating system. This may result in an energy planning process that is more credible and easier to put into action than one not involving the stakeholders in research [7].

This thesis presents a methodology for investigating local heating system transitions. It combines a participatory scenario development, which involves key stakeholders in a municipal setting and energy systems modeling, with high geospatial resolution. The developed methodology has been tested in both urban and semi-rural settings in the three appended papers. The methodology is novel in that it considers the spatial dimension of the heating system transition to resolve the local characteristics of heating systems and it includes a stakeholder participatory approach.

1.1 AIMS AND SCOPE

The overarching goal of this thesis is to provide a methodology for assessing how heat decarbonization can be achieved cost-efficiently while accounting for the local spatial dimension by applying a high spatial resolution and inviting stakeholders to share their knowledge of local conditions. In addition, this thesis focuses on applying the methodology to modeling studies in two different geographic contexts and to investigating both the applicability of the methodology and the results obtained through using the method. The specific aims of this thesis are to:

i. Develop a modeling methodology that can be used to investigate how the transition of local heating systems from fossil fuels to low-carbon options can be achieved cost-efficiently, while taking the local spatial dimension into account. The techno-economic modeling includes the spatial dimensions of the heating systems and the participation of stakeholders towards identifying future scenarios.
ii. Apply the methodology to both urban and semi-rural settings, to define the cost-efficient, long-term local heat decarbonization pathways (Year 2050) in terms of technology and fuel choices.
iii. Discuss how the inclusion of the local spatial dimensions and the participatory approach impact the modeling process and results.

The thesis comprises an introductory essay followed by three appended papers. The geographic scope of the modeling studies is at the municipality level. **Paper I** proposes a methodology to investigate the future development of municipal heating systems, which includes five steps and applies the first two steps to an urban municipality in Denmark. The full methodology is then further applied in **Papers II** and **III**. An urban municipality in Denmark is used as a study case in **Papers I** and **II**, whereas **Paper III** focuses on a semi-rural municipality.

1.2 CONTRIBUTION OF THE THESIS

Paper I develops and presents the modeling methodology, which serves as the basis for **Papers II** and **III**. **Paper I** establishes the need of an integrated approach by discussing the local spatial dimension and the participation of municipal planners, to investigate the long-term heat decarbonization strategies at the local level. In particular, this paper highlights the spatial plans of the municipality and building data in combination with the specific local knowledge provided by the stakeholders involved in the planning of the municipal heating system.

Paper II further develops and applies the modeling methodology from **Paper I** to an urban municipality in Denmark, and discusses how the methodology has the potential to benefit the municipal heat planning process. Key individuals, such as urban and heat planners, are involved throughout the modeling process. In this study, the representation of the local spatial dimension provides a detailed understanding of the heat demand and supply at the district and building levels, allowing for identification of the most cost-effective solutions. It is shown that the methodology strengthens the legitimacy and transparency of the decision-making process.

Paper III investigates local heat decarbonization strategies by applying a techno-economic model to a semi-rural municipality. This study focuses on the distinct spatial characteristics and opportunities and challenges in terms of energy sources within the municipality. A spatial analysis provides district-specific results, whereby the selection of the heat supply relies on both the heat demand density of the investigated districts within the municipality and their proximity to the existing district heating network. This paper contributes to understanding the challenges and opportunities pertinent to heat decarbonization in semi-rural municipalities.

2. Background and related research

The heating and cooling sector is responsible for around half of the final energy consumption in the EU, making the sector's decarbonisation crucial for a carbon-neutral energy system by 2050. More than 60% of the energy demand in this sector is attributed to space and water heating for buildings, including housing units and public and commercial buildings, with the remaining energy demands being for industrial process (32%) and cooling in agriculture, buildings, and industry [8]. In the EU, 57% of the heat supply for buildings comes from the combustion of fossil fuels, highlighting the need for heat decarbonization in the EU. Figure 1 presents an overview of space and water heating in the EU, broken down into sectors, end-uses, technologies, and final energy carriers [9].

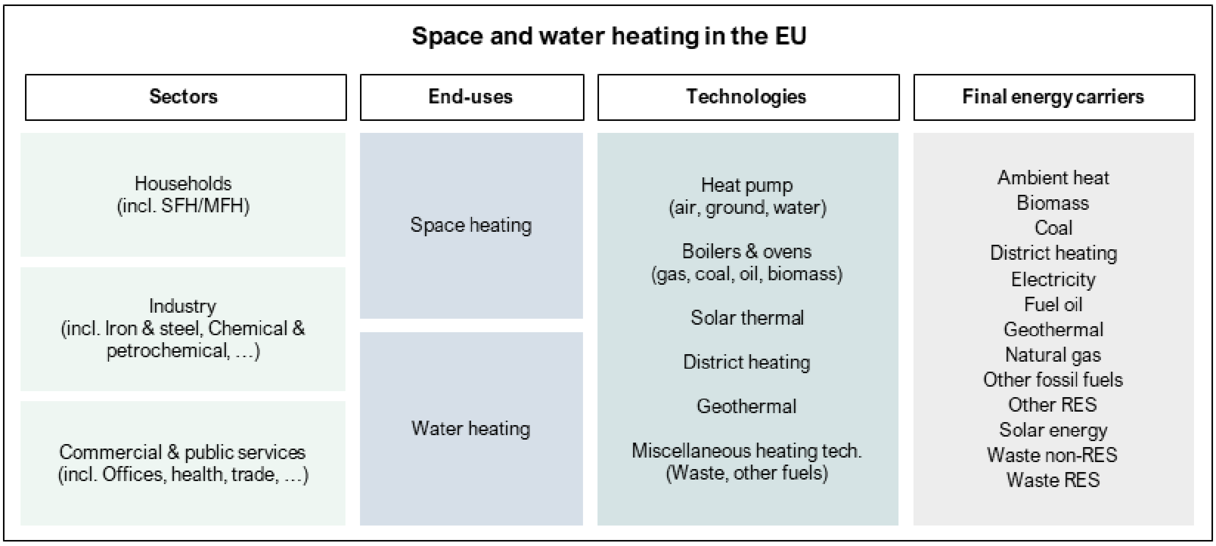


Figure 1. Overview of space and water heating in the EU according to sectors, end-uses, technologies, and final energy carriers. SFH: Single-family housing; MFH: multi-family housing; RES: renewable energy sources. Source: [9].

To achieve the objective of complete decarbonization of the heating system in the long term, heat planning needs to align itself with the national overarching targets and visions, while also taking specific local factors into account. Given the local nature of the heat demand and supply, local authorities, such as municipalities and cities, play a significant role in the transition of the heating system, especially in situations where the heat utilities are operated/owned by the municipality.

Heat planning takes into account a diverse array of factors, including the potentials for various technologies to generate low-carbon heat from renewable sources and the potential to decrease demand through energy efficiency measures. The heating systems investigated in this thesis are separated into two groups: individual heating systems, and district heating systems. Individual heating systems, also referred to as decentralized systems in this thesis, use small-scale boilers, heat pumps, furnaces or heaters for each housing unit and heat homes independently. Individual heating technologies are in some cases more costly, e.g., have higher initial investments, than centralized technologies [10], [11], since such systems do not profit from economy of scale [12]. However, individual heating may provide greater control in terms of ownership, while consumers may need to wait for district heating to become an option, since its availability depends on the municipal planning process. On the other hand, district heating is a collective system whereby heat is delivered centrally to the end users through either hot water or steam across a network of insulated pipes. The heat losses along the pipelines, which depend on the design and heat demand density, represent one of the shortcomings of district heating systems [13]–[15]. Nonetheless, as the heat source for district heating can be any process that generates heat, including low-grade heat, such systems offer the possibility to optimize costs depending on the prices of the energy sources used [16]. This may include recovering various waste fuels in large, centralized heat-generating plants, which can be equipped with advanced fuel handling and gas cleaning systems.

2.1 SPATIAL DIMENSION OF HEAT PLANNING

Within the field of spatial planning, the energy transition is recognized as being fundamentally tied to space [5]. Since the spatial characteristics of a city, region or country have substantial impacts on various aspects of energy systems, e.g., the availability of energy resources, the design and deployment of energy infrastructure, consumption patterns, and the potentials for saving energy and increasing the supply of renewable energy, these aspects must be carefully considered when planning the energy transition [17], [18]. Previous studies have recognized the interrelations between spatial dimensions and the possibilities to shape the energy transition. Madlener and Sunak [19] have emphasized the integration of energy planning into urban structures planning, pointing out that the current design (e.g., building stock) of cities is responsible for high levels of energy consumption in urban areas. In this context, Zanon and Verones [20] have argued that there should be strong coordination between urban spatial planning and energy planning, given the profound interconnections between urban plans and energy usage. The integration of urban and energy planning constitutes a continuously evolving realm of research, with multiple authors contributing with diverse approaches and critical evaluations of the subject, including the systematic reviews of integrated spatial and energy planning conducted in [21] and [22]. Fichera et al. [23] have developed an approach that integrates the spatial and energy considerations within an energy exchange optimization framework, with a neighborhood scale and the results have been represented visually in GIS maps. Collaço et al. [24] have also developed a novel method to integrate energy and urban planning using the urban energy simulation model LEAP. They have compared the results of energy savings and greenhouse gas (GHG) reductions when either only energy (2% energy savings and 18% GHG reduction) or urban planning (10% and 8%) policies are implemented, respectively, and when both policies are integrated (12% and 30%).

In particular, heat planning requires a spatial approach. The availability of heat sources in cities, the spatial density of the heat demand, and the pattern of urban development all influence the potential strategies for providing heat to buildings. Since the costs associated with the heat network infrastructure are significantly influenced by spatial factors, such as the linear heat density, proximity to heat generators, and the length of pipelines [25]–[28], understanding the spatial patterns of heat demand is important when designing communal heat supply systems. It goes without saying that the spatial arrangement is also critical for the installation of individual heating technologies. This is because, from the local energy planner's perspective, both individual and communal heating systems must interact to achieve the optimal economic and environmental outcomes, while effectively meeting the heat requirements.

As discussed above, the cost-efficient design of energy systems is heavily influenced by the spatial dimensions. Yet, it has been pointed out that this aspect does not receive adequate attention during the formulation of strategies for transitioning the energy system [17]. This is in line with the findings of Nadin et al. [29], who conclude that in the EU, the potential for integrated place-based approaches is not generally well-addressed in sectors such as energy and waste. By considering spatial arrangements and the development of space, the quality of planning can be greatly enhanced.

2.2 SPATIAL DIMENSION IN ENERGY SYSTEMS MODELING

The spatial resolution in energy systems modeling is often related to the political or administrative subdivision boundaries that divide the spatial scope, since energy policies are usually designed and rolled out at this level [30]. In this thesis, the spatial dimension considers the spatial variations, i.e., physical entities such as building types/density, and resources and existing energy infrastructures, with higher resolution than that defined by administrative boundaries. Table 1 presents the previous energy systems modeling studies that have investigated how differences in spatial properties between different geographic areas within the model scope can impact the results of energy systems modeling.

Table 1. Selected previous energy systems modeling studies that included the spatial dimensions of the heating system in the optimization modeling [with the exceptions of [31] and [32], where the focus is on electrification of the electricity system]. These studies have analyzed the spatial aspects of energy systems, addressing factors such as technology choices, renewable resource availability, demand, and emissions, with outputs that include optimal system configurations, expansion potential, and spatial representations of various parameters.

Source	System boundary	Model	Considered spatial dimension	Output related to spatial analysis
[31], [32]	National electricity supply system	Open-source cost-optimization (OSeMOSYS) and geospatial electrification planning tool (OnSSET)	• Accounts for geospatial drivers of technology choices • Location-specific discounted costs, electricity demand, technologies, grid specifics • Spatially explicit parameters: population density, distribution and proximity to the transmission network, distance to road, night light	• The population connected per technology option • Visualization of the most cost-effective electrification option

[33]	National energy system	Application of MGA (Modeling to Generate Alternatives) to a cost-optimization model (Calliope)	• Account for different renewable source availability profiles at each location. • Spatial variation of demand, resource availability, weather patterns, legislative power, local RES regulation.	• Near-optimal solutions depending on the spatial configuration of technology deployment. • Spatial representation of the power sector at the bidding zone/administrative level.
[34]	City DH system	Data from Eurostat and QGIS, Google Earth Pro	• Spatial quantification of DHW demand and total aggregated space heating and DHW demand . • Net/heated area of buildings connected to DH and the space heating demand of these buildings. • Number of people in a cell used to estimate hot water demand.	• Spatial representation of space heating and hot water demand, expansion potential of DH in a grid.
[35]	An industrial park	Mixed integer linear optimization model minimizing the length of the grid and an Open-source cost-optimization (OSeMOSYS)	• Accounts for pipe routing, thermal loss, and network cost calculation.	• The least-distance grid network solution, including the lengths and capacities of each pipe. • The network solution is determined using a road network graph retrieved from Open Street Maps (OSM).
[36]	City residential heating system	Mixed integer programming with GIS-based tool using geo-referenced dataset for buildings	• The geo-refe brenced datasets that include buildings' boundaries, types, location, number of floors, heating technologies. • Spatially determined constraints.	• Spatial distribution of emissions.

DH: District heating; DHW, domestic hot water; RES: renewable energy sources.

2.3 PARTICIPATORY APPROACH IN ENERGY SYSTEMS MODELING

Local authorities exert authority over a range of aspects concerning the energy sector, including diverse local and municipal infrastructures, the provision of financial and technical resources, urban planning, authorization processes, incentives to reduce energy demands, and facilitation of coordination among various participants from both the supply and demand sectors [8]. There is a growing body of the literature that applies a participatory approach to energy systems research [37]–[40], including works that discuss the advantages of such an approach [41], [42]. Stalpers et al. [37] have employed Integrated Assessment Models (IAMs), which are co-created by modelers and participants to increase the relevance and credibility of the modeling results. Bertsch and Fichtner [38] have considered multiple targets and preferences of different stakeholders in the energy sector by applying Multi-Criteria Decision Analysis (MCDA), while Hewitt et al. [39] have used a land-use model accompanied with participatory scenario planning. None of these studies has specifically used energy systems modeling. The research in [41] and [42] did not include the stakeholders in the modeling process itself but rather discussed different participatory approaches and their benefits. As indicated previously, a participatory approach in research provides the opportunity to integrate the inputs of the participants, such as municipal planners in the present work, exploiting their preferences and local knowledge to support their decision-making processes. Furthermore, involving stakeholders with diverse backgrounds in an energy system modeling process offers advantages and enhances opportunities for sharing knowledge, which has been highlighted as a crucial element for an efficient energy transition [39], [43], [44]. Another benefit of the participatory approach lies in enhancing the credibility of decisions, meaning that decisions that reflect stakeholders' needs and preferences may be regarded as more legitimate and easier to implement than decisions that are made unilaterally or without meaningful stakeholder input [45]. By engaging external stakeholders in the modeling procedure, the collaboration between researchers and those responsible for making decisions can be enhanced [46]. McGookin et al. [47] have emphasized that this approach, which is based on including a thorough understanding of the local context, aims to support energy planning stakeholders in their decision-making. This is done by incorporating the feedback from stakeholders and thereafter adjusting the energy system model according to this feedback while maintaining an open mind as to the different possibilities obtained from the energy systems modeling. Given the significant influences that stakeholders can exert on energy planning, their involvement in areas of energy systems research, such as energy systems modeling, has the potential to improve the usefulness and credibility of the results, thereby maximizing their capacities to advance energy system transitions.

2.4 HEAT PLANNING IN DENMARK AS CASE STUDY

Given that the participation of municipal planners in energy systems research, with a focus on heat planning, is one of the central elements of the present work, it is relevant to select cases in which municipalities have adopted a relatively active role when it comes to energy planning. Municipalities in Denmark are encouraged to develop voluntarily municipal strategic energy plans These plans serve as frameworks for transitioning towards climate-neutral energy systems. and for aligning with national goals related to eliminating fossil fuels and establishing tailored climate and energy objectives [48]. Accordingly, as is the case for heat planning, Danish municipalities have a high degree of autonomy in relation to the development of their district heating systems. The degree of autonomy granted to Danish municipalities with respect to local heat planning is the reason that the present work takes Danish municipality cases as relevant cases for investigation and their municipal planners as pertinent stakeholders. In addition to the municipal strategic energy plans, municipalities in Denmark must develop municipal plans, which represent the framework for the detailed local plans (urban plans), and these urban plans must comply with the strategic plans prepared at the regional and national levels. Urban plans delineate how each district can be developed and how the land will be used.

Within these plans, various elements are subject to regulations that encompass property size and boundaries, transportation infrastructure, pipelines, transmission lines, building placement and dimensions, the esthetics of buildings and other infrastructure, as well as building density. Furthermore, these plans mandate that any new construction must adhere to low-energy building standards [49].

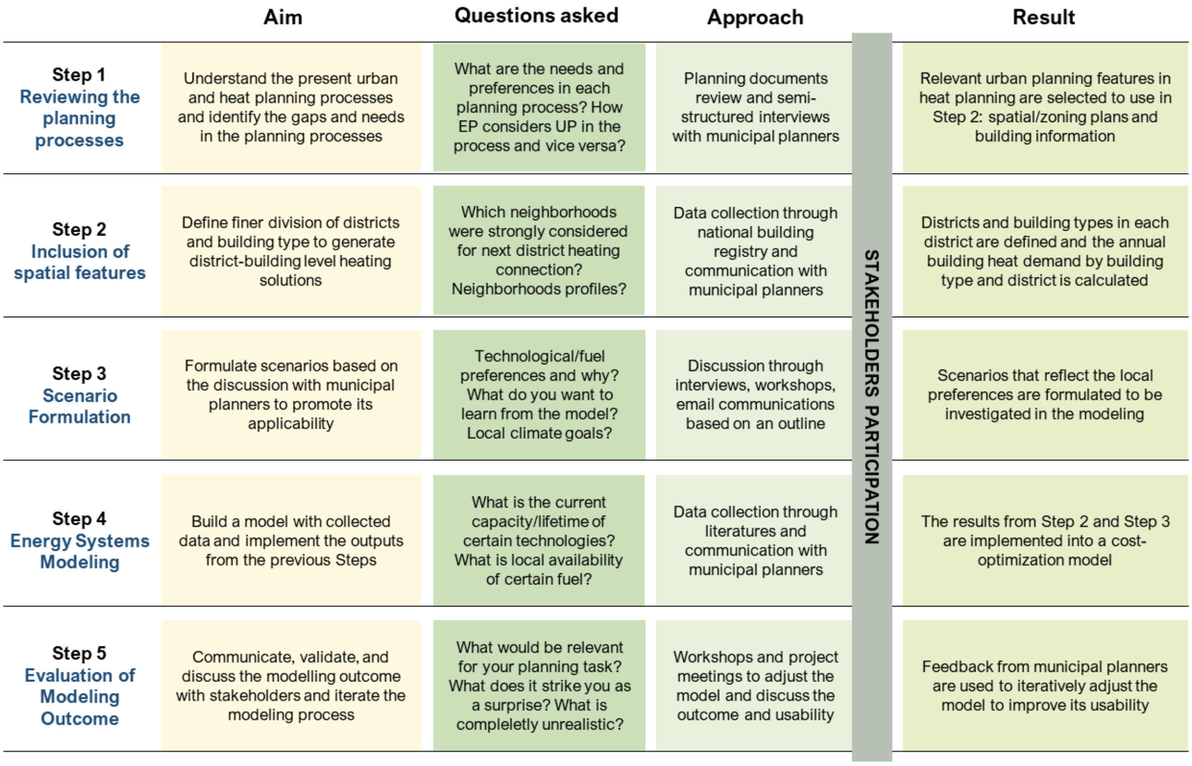
The heat planning process involves several steps. Initially, heat suppliers submit project proposals to the municipality, in which they list their suggestions and estimations and outline the socio-economically optimal heating options. These proposals are reviewed by the municipality in accordance with the national law. Approval by politicians is necessary to proceed to the next stage, which is a public hearing. During this phase, the municipality presents the proposal to the general public, allowing a 4-week feedback period. Ultimately, the politicians grant approval for the proposal after considering the public feedback. This process typically takes 5–6 months, allowing thorough examination by all stakeholders. Heating companies, e.g., district heating utilities, in Denmark are controlled and regulated by municipalities, which are empowered at the local level to approve and implement the local heating strategies and energy projects [50]. In situations where the heating companies operate under consumer ownership and control, municipalities still retain representation on their governing boards, and local city councils have the authority to approve or decline projects. Furthermore, they can mandate that heating companies present heating solutions for new development initiatives [51]. Additionally, it is within the municipality’s sphere of authority that heat planning is incorporated into other local plans, including the land use plan. Given that the national land use planning regulations also mandate municipalities to take into account extensive interconnected systems, such as transportation and buildings, local assets and needs must be comprehensively considered by municipalities when establishing their local land use plans.

3. Method

This section provides a summary of the developed methodology. Each step of the methodology is explained, followed by a detailed description of the modeling procedure.

3.1 SPATIALLY EXPLICIT PARTICIPATORY METHODOLOGY

Figure 2 presents the aim, approach, and output of each step in the methodology. The municipal stakeholders, i.e., energy planners and urban planners, provide input, feedback, and knowledge regarding the local context throughout the modeling process. As can be seen in Figure 2, the modeling is carried out in a five-step process that includes a dialogue with the stakeholders during all the steps. Thus, the application of the participatory approach requires an interest and active participation from the relevant stakeholders.



	Aim	Questions asked	Approach		Result
Step 1 **Reviewing the planning processes**	Understand the present urban and heat planning processes and identify the gaps and needs in the planning processes	What are the needs and preferences in each planning process? How EP considers UP in the process and vice versa?	Planning documents review and semi-structured interviews with municipal planners	STAKEHOLDERS PARTICIPATION	Relevant urban planning features in heat planning are selected to use in Step 2: spatial/zoning plans and building information
Step 2 **Inclusion of spatial features**	Define finer division of districts and building type to generate district-building level heating solutions	Which neighborhoods were strongly considered for next district heating connection? Neighborhoods profiles?	Data collection through national building registry and communication with municipal planners		Districts and building types in each district are defined and the annual building heat demand by building type and district is calculated
Step 3 **Scenario Formulation**	Formulate scenarios based on the discussion with municipal planners to promote its applicability	Technological/fuel preferences and why? What do you want to learn from the model? Local climate goals?	Discussion through interviews, workshops, email communications based on an outline		Scenarios that reflect the local preferences are formulated to be investigated in the modeling
Step 4 **Energy Systems Modeling**	Build a model with collected data and implement the outputs from the previous Steps	What is the current capacity/lifetime of certain technologies? What is local availability of certain fuel?	Data collection through literatures and communication with municipal planners		The results from Step 2 and Step 3 are implemented into a cost-optimization model
Step 5 **Evaluation of Modeling Outcome**	Communicate, validate, and discuss the modelling outcome with stakeholders and iterate the modeling process	What would be relevant for your planning task? What does it strike you as a surprise? What is compleletly unrealistic?	Workshops and project meetings to adjust the model and discuss the outcome and usability		Feedback from municipal planners are used to iteratively adjust the model to improve its usability

Figure 2. Steps used in the methodology.[2] EP, Energy planning; UP, Urban planning.

Step 1 – Reviewing the planning processes. This is a pre-process step to understand and identify the connections between urban planning and heat planning in the context of a municipal planning department. In order to understand how both urban spatial planning and heat planning are carried out at the municipality level, and the extents to which they integrate with each other, planning process-related questions were posed to the municipal planners (for

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[2] The names of Steps 1 and 2 have changed in this thesis to convey more clearly what each step entails. In the appended papers, the names used were: Step 1 – Planning process review; Step 2 – Features of urban planning. The context and contents are the same.

the questionnaires used in the interviews, see Appendix A). The interviewees in this study were municipality employees who are involved in energy/heat planning and urban planning. The features of the urban planning process that are commonly discussed in energy systems planning studies include: spatial/zoning plans [20], [22], [23], [26], [52], [53]; building density [20]; land use [20], [54]; urban morphology [20], [24], [55]; and building information [20], [23], [53], [54], [56].

Step 2 – Inclusion of spatial features. This step divides the municipality into more-refined geographic areas to be evaluated using energy systems modeling. These areas are called 'districts'[3] in this thesis. The division is based on the data sources for heat demand density, building information, and urban spatial plans, as well as on the municipal planners' preferences. The heat demand densities and building parameters, e.g., type, size, and age, determine the energy performances of the buildings and district heating grids. Thus, it is important to consider these characteristics when planning the adoption of heating technologies [57]. Urban spatial plans that contain information such as large construction plans with maps of their geographic distribution, heat plans, and national/local statistics on heating technologies are used as inputs in Step 2. Stakeholders have opportunities to express what they needed to investigate and what types of modeling outcomes could support their decision making.

Step 3 – Scenario formulation. Scenario formulation is a key element of this work, since it defines the context in the modeling scope. Multiple heating system transition scenarios were developed, so that they could be aligned with municipal plans and include all the options in the modeling. A scenario structure that included model parameters that served as the basis for selection and combination of the different parameters was constructed and provided for discussions with the municipal planners (see Appendix C and E). The following points were discussed with the municipality stakeholders: locally set climate goals; technology preferences; national energy policies; upcoming investment plans; expected structural changes; and geographic/environmental limitations. Specifically, the municipal CO_2 reduction targets, technology options, and phasing out of fossil fuel use were established as a result of these discussions. The discussions with the municipal planners were conducted through semi-structured interviews, workshops, and e-mail exchanges. Thereafter, the discussions were translated into data that could be reflected in the model, i.e., in the form of constraints that should be binding in the model, different settings of the model parameters values, and the option to select and combine different elements in order to formulate scenarios.

Step 4 – Energy systems modeling. The methodology of this thesis requires a model that can provide a comprehensive view of the long-term development of the energy system and that aligns with the emissions reduction objectives of the municipality. This step discussed the necessary input data and assumptions for the modeling with the energy and urban planning stakeholders and, as a result, updates were implemented. The goal here was to increase the

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[3] In this thesis, the term 'districts' is used interchangeably with the 'new districts' and 'newly established districts' and 'divided areas' terms in the appended papers, to convey more clearly the intended meaning. All these terms refer to the same concept within the context of our work.

transparency, legitimacy, and relevance of the modeling results, so as to facilitate the actual use of spatially explicit results in the municipal planning work.

Step 5 – Evaluation of modeling outcome. In Step 5, the modeling outcomes are disclosed to the involved municipal planners, so as to receive constructive feedback that will be used to fine-tune the model in accordance with their specific needs and preferences. The presentation encompasses an analysis of the results for the generation mix and technology capacity mix in each of the investigated scenarios. There is iterative development of the model between Steps 3 and 5.

3.2 COST-OPTIMIZATION MODELING AND THE SPATIAL DIMENSION

Energy systems optimization modeling can provide insights pertinent to the transformation of energy systems to meet different targets under various assumptions, and can thereby serve as an important tool for analyzing the dynamics of the energy system transition [58]. In energy systems optimization models, the decision variables may represent electricity and heat generation capacities, the dispatch of different technologies, electricity and heat demand or other relevant quantities, while the constraints may represent physical and technical limitations, environmental targets, economic considerations, and policy goals. The energy systems modeling can generate optimal solutions for the development of the energy system under the conditions and criteria specified, and may provide valuable insights into the potential impacts of different policies and strategies on the performance of the system.

This thesis employs the TIMES (Integrated MARKAL-EFOM Systems) model, which is a linear programming model for minimizing the overall system cost over a specified time span [59], under different assumptions and constraints. In addition to the objective function, the scenarios define specific constraints, such as emissions reduction targets (e.g., target of net-zero CO_2 emissions by a particular year). The time intervals within this timeframe, as well as the division of each year into various time segments (e.g., seasonal or diurnal), can be tailored to align with the specific objectives of the study. The TIMES model operates based on perfect foresight, meaning that the model knows the exact heat demand and costs for all technologies over the entire modeling period. It is a demand-driven model, which means that the model should meet the exogenously given electricity and heat demands in any time-slice. The model outcomes show the dispatch of modeling energy technologies in any time-slice, while also highlighting the most cost-effective investments for expanding generation capacity. In addition, the output provides the overall system cost for the chosen time horizon and the associated carbon emissions. While both electricity and heating systems can be represented in the TIMES modeling, the TIMES model setup in this thesis represents only heating systems, i.e., heat demands and heating technologies, and electricity is considered to be a commodity that is imported to the modeled system (the electricity generated by combined heat and power plants is assumed to be sold to the national grid and is represented as an economic benefit in the model). Thus, the specific way in which the electricity is generated is outside the scope of this work. Figure 3 shows a conceptual diagram of the heating system with the main model parameters used in this study. Individual heating directly supplies heat to buildings, while district heating systems require insulated pipeline systems to distribute heat using water as the medium.

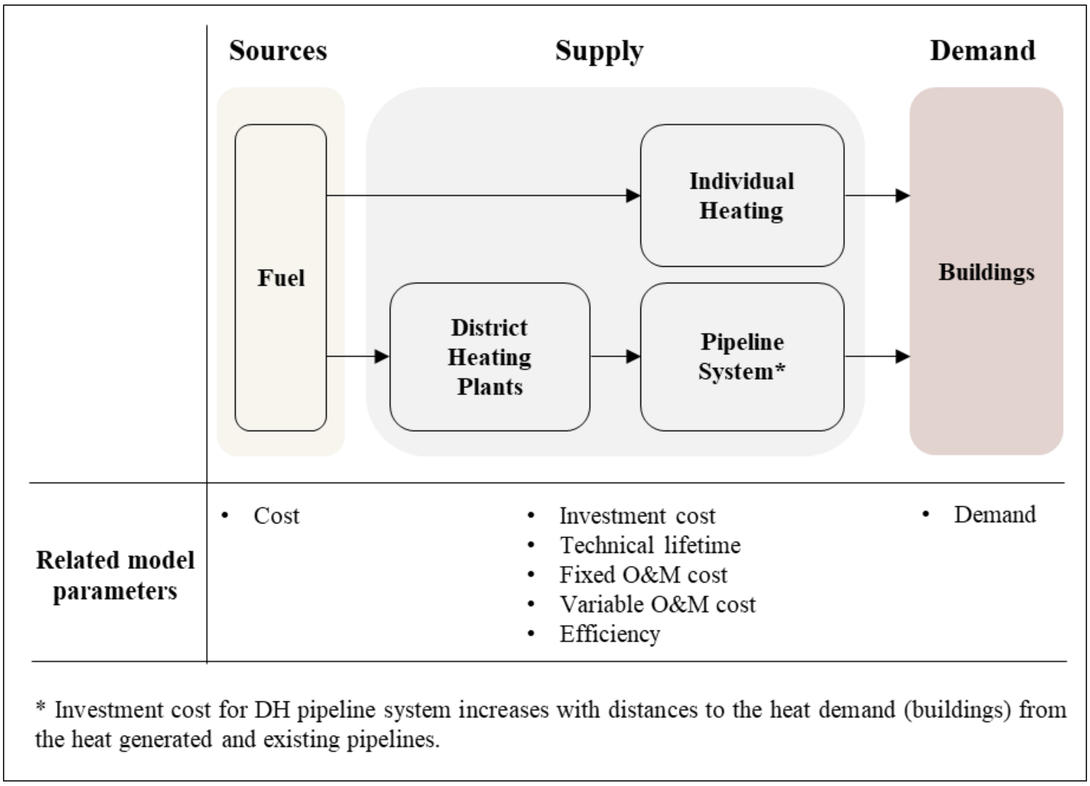

Figure 3. Schematic of a heating system and related model parameters in this study. DH, District heating; O&M, operation and maintanence.

In order to incorporate spatial considerations into the model, the model implements the different investment costs of pipelines representing the distances to each demand point, i.e., districts, from the existing district heating network. This is done by applying the districts and their heat demands defined in Step 2, i.e., the municipality is divided into more-refined geographic areas in this step, to create model regions (referred to as 'r'). Thus, the term ‘region’ in the objective function can be substituted with ‘districts’, to allow representation of the spatially different (small) systems in each district. The set of input data to the model includes techno-economic data regarding the technologies, commodities, resources, and heat demands. Incorporating multiple districts into the model necessitates the inclusion of multiple input datasets, with each set representing the heat supply system for a specific district. The input data provided to the model, which include the heat demands per time interval, heat supply technologies, and associated techno-economic data, are distinct for each district. As a result, the objective function [Eq. (1)], which aims to minimize the total system cost over the chosen time horizon, becomes the sum of the total system costs for all the districts.

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

The term $d_{r,y}$is the discount rate by region r, year y, and the base year $REFY$. $ANNCOST(r,y)$ indicates the annual costs over region r in year y. Each year, the total system cost includes the following elements: the capital cost for investment and the fixed operation and maintenance costs per unit of capacity; the variable operation and maintenance costs for heat generation; fuel costs; taxes and subsidies; and revenues from export. The decision variables include the capacity addition, i.e., the investment for technology p in period v, and region r ($C_{p,v,r}$), and the generation for process p in region r and period t ($G_{r,t,p,}$). In addition to the main types of constraints, [Eqs. (2) and (3)], there are constraints in the modeling reflecting emissions targets, a ban on natural gas, an imposed CO_2 tax, and a heat pump subsidy[4].

$$\sum_p G_{r,t,p} \geq D_{t,r} \tag{2}$$

where Dt is the heat demand in time t in region r.

$$G_{r,t,p} \leq C_{p,v,r} \tag{3}$$

Other important aspects of incorporating the spatial dimension into the model are the distance to the existing district heating network and the linear heat density. The linear heat density concept expresses the annual heat demand per meter of grid length. According to [60], the linear heat density is formulated by connecting other demographic quantities such as population density and specific building space; their work motivated the methodology for using the so-called *plot ratio*[5] in the district heating expansion investment cost calculation in this study. The plot ratio, proximity to existing infrastructure, and linear heat demand density are represented in the model as distinct investment costs for the piping construction, depending on the distance and the linear heat density of each area. Figure 4 shows a schematic representation of this approach.

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[4] There is a central government subsidy scheme for heat pumps (HPs) in Denmark that is administered by the Danish Energy Agency. Currently, the subsidy covers 15% (up to a maximum of 20%) of the market price of the HPs [69].

[5] Plot ratio is a planning and zoning term used in urban development and land-use regulations. It is a numerical value that defines the relationship between the total floor area of a building or buildings on a particular piece of land, as well as the size of that land.

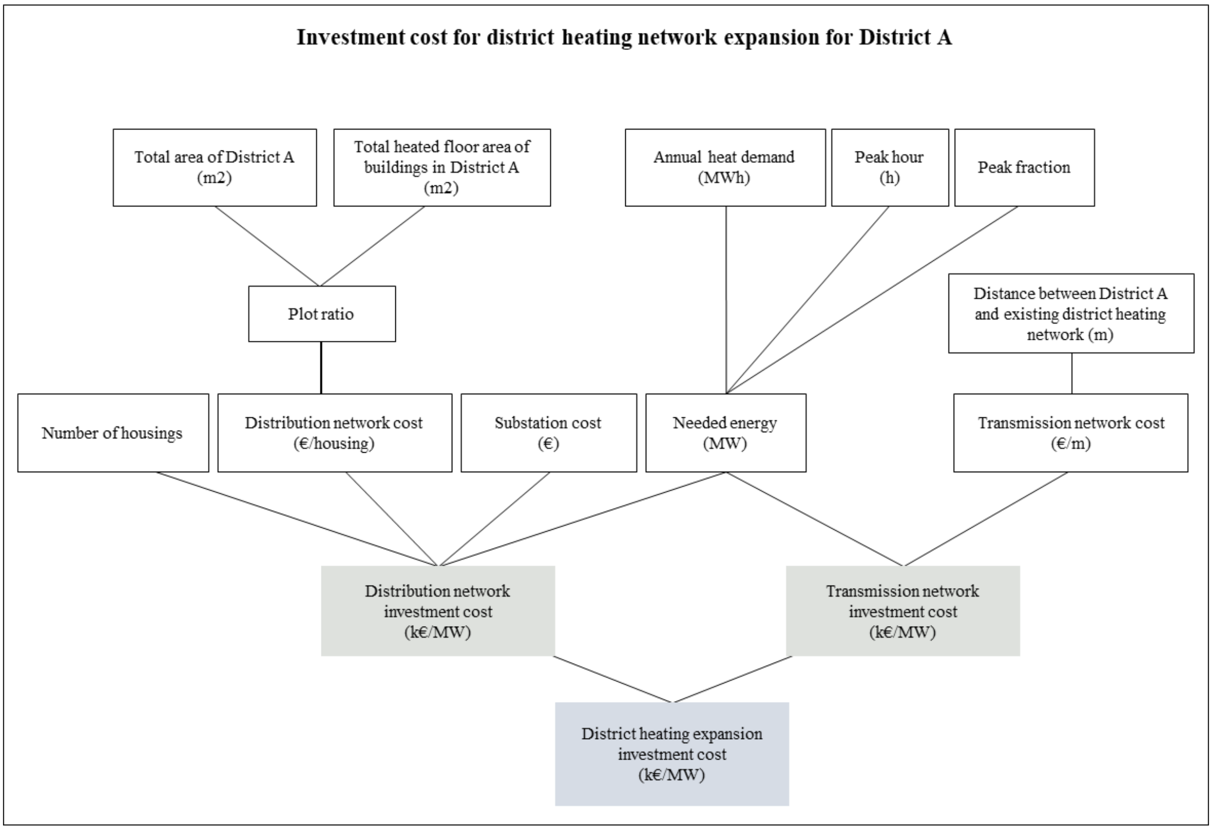

Figure 4. The cost components used to calculate the investment cost for location-specific district heating expansion.

3.3 THE URBAN AND SEMI-RURAL CASES

The spatially explicit participatory modeling methodology developed in this work is applied to two contextually different municipalities in Denmark. Table 2 gives a brief summary of the two Danish case municipalities in terms of their demographics, current heating supplies, and local climate goals.

Table 2. Overview of the cases in this thesis: Lyngby-Taarbæk and Holbæk Municipalities.

Lyngby-Taarbæk Municipality (Urban case)
Lyngby-Taarbæk Municipality, which is situated in the northern suburbs of Copenhagen, Denmark, has a population of 57,826 (in 2022) within a 39 km^2 area, giving an approximate population density of 1,500 individuals per km^2. In LTK, approximately 60% of the municipality's buildings rely on natural gas for heating. The recently approved heat plan for the area, established in early 2022, emphasizes expansion of the district heating (DH) system in the municipality, in areas with a high level of heat consumption and relatively dense building structures. This strategic effort aims to reduce the municipality's reliance on fossil fuels for heating, aligning with its goal of achieving net-zero emissions by Year 2050.
Holbæk Municipality (Semi-rural case)

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. The heat supply in Holbæk Municipality, which encompasses major urban areas such as Holbæk city, relies heavily on natural gas, accounting for 77% of the heat demand through individual gas boilers. District heating covers approximately 20% of the heat demand, with a significant portion of the heat being generated by natural gas-fired combined heat and power (CHP) systems. Like many other municipalities in Denmark, Holbæk is committed to reducing significantly its greenhouse gas (GHG) emissions, so as to align with both national and local climate objectives. Their goal is to achieve a 70% reduction in CO_2 emissions by Year 2030 compared to the Year 1990 levels. This target roughly translates to cutting the current emissions by 50% across the various sectors, including heating, electricity, transport, and industry [61].

The methodology, which includes five steps, is developed in **Paper I** and the first two steps are applied to an urban municipality (this does not include the modeling work). **Papers II** further applies the methodology to the same urban municipality, and **Paper III** addresses a semi-rural municipality. Although the two papers apply the same methodology developed in **Paper I**, several adjustments are made to the methodology as a result of the experiences gained during the work presented in **Papers II** and **III**. Table 3 shows an overview of the settings and assumptions used in the model for the two municipal cases. It is important to note that the technology options in the models are obtained through the participatory approach, i.e., the selection is based on stakeholder preferences and the availability of local infrastructure/resources.

Table 3 summarizes the model settings, i.e., the assumptions, constraints, and included technologies, for the two cases. It is clear that there are differences between the urban and semi-rural cases. This is especially evident in the case of the semi-rural case, where the application of district-level spatial resolution is more appropriate than building-type-level spatial resolution for focusing on the distances to existing energy infrastructure and local resources. Furthermore, the discount rate has been set differently for the two cases. For the urban case, the discount rate used by the Danish planning institutions (4 percent) is applied, while for the semi-rural case, the discount rate in the model is set at a lower rate (3.5 percent). This assumption is based on the perspective that a lower social discount rate may reflect a willingness to invest in long-term strategies and projects which are lacking in rural regions as opposed to densely populated areas [62].

Table 3. Summary of the model assumptions for the two cases investigated.

	Urban setting (Paper II)	**Semi-rural setting (Paper III)**
Future demand assumption	Scenario dependent	Constant
Discount rate	0.04	0.035
Time-slices	Five seasons and day/night	Five seasons
Number of districts	15 (10 of which are NG-dominated)	11 (8 of which are NG-dominated)
Spatial resolution	Building-type level	District level
Number of scenarios	6	4
Natural gas ban	Year 2035	Year 2035
Locally set CO_2 goals	Carbon neutrality in Year 2050, Carbon neutrality of DH in Year 2030	Carbon neutrality in Year 2050, 70% CO_2 reduction in Year 2030, compared to Year 1990

Investigated technology (Individual heating)	HP air to water HP ground to water Solar thermal collector	Biomass boilers Electric boiler HP air to water Solar thermal collector Biogas (fuel)
Investigated technology (District heating)	Air source HP Water source HP Electric boiler, small Electric boiler, large MSW incineration	Air source HP Electric boiler Solar DH with TES Biomass CHP Biomass HOB Excess heat (fuel)

CHP, Combined heat and power; DH, district heating; HOB, heat-only boiler; HP, heat pump; MSW, municipal solid waste; NG, natural gas; TES, thermal energy storage.

As mentioned in Section 3.1, the developed methodology emphasizes municipal planners' participation in the modeling process and this is done by semi-structured interviews in addition to the other communication forms such as e-mails, online meetings, and workshops. Table 4 gives an overview of the interviews conducted – anonymized interviewees, representing them as Interviewee A, B, and so forth, and their positions and the interview dates.

Table 4. Interviewee information for the urban and semi-rural case studies.

	Interviewee	Organization	Position	Interview date (dd-mm-yyyy)
Urban case	A	LTK Municipality	Heat planner	05-08-2020
	B	LTK Municipality	Climate coordinator	04-03-2021 16-05-2022
	C	LTK Municipality	Heat planner	04-03-2021 20-05-2021
	D	LTK Municipality	Urban planner	04-03-2021
Semi-rural case	E	Holbæk Municipality	Energy planner	05-08-2020
	F	Holbæk Municipality	Energy planner	07-12-2021 20-10-2022
	G	Holbæk Municipality	Project developer	20-10-2022

4. Selected results and Discussion

This Section describes selected results from **Papers I–III**. The results are divided into sections that represent different steps of the five-step methodology suggested in this work, and its application to the urban and semi-rural cases:

- Reviewing the planning process (Step 1, **Paper I**)
- Urban case study (results from Steps 2–5, **Papers I** and **II**)
- Semi-rural case study (results from Steps 2–5, **Paper III**)
- Reflections on the results and method.

4.1 REVIEWING THE PLANNING PROCESS (STEP 1; PAPER I)

Through the interviews carried out in Step 1 with both urban and heat planners, it was discovered that, in the Danish case municipalities investigated in this thesis, effective means to communicate/integrate information between urban spatial planning and heat planning actors are lacking[6].

Given that district heating systems are a key element in the energy system of Denmark, one interviewee expressed the importance of dividing the municipality into districts with certain criteria as part of heat planning, so as to identify districts that should be prioritized for the expansion of district heating (Interviewee B). Furthermore, the interview with municipal planners reveals that the urban planning department currently lacks the tools that are necessary to incorporate heating-related information into urban planning processes. Such information would obviously be of high value in terms of facilitating communication with building developers. In addressing this concern, both Interviewees B and D agreed that if urban planners are aware of the heating options suitable for specific districts, this would facilitate the dialogue between urban planners and developers, supporting them in making informed decisions. This is particularly relevant since, as of January 1, 2019, the national law no longer empowers the municipality to mandate that new buildings connect to a district heating network (before 2019, it was possible for the municipality to make the installation of district heating compulsory in new buildings). Now, the municipality can only encourage building developers to select their preferred heat supply option with the aid of appropriate and supportive information (Interviewee C). The gap identified in Step 1, i.e., the lack of integration between urban and heat planning, influences the selections of sources that form the divisions of districts in the subsequent steps.

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[6] A decision-support platform (https://api.flexsus.org/) has been developed to assist urban planners and decision-makers in making sustainable and climate-neutral decisions for their urban district heating systems in the FlexSUS project (https://flexsus.org/). The papers appended to this thesis are part of FlexSUS project, although the platform itself is not within the scope of this thesis.

4.2 URBAN CASE STUDY (RESULTS FROM STEPS 2–5 FOR THE URBAN CASE; PAPERS I AND II)

Strong interest was expressed by the municipal planners in the Lyngby-Taarbæk (LTK) municipality in exploring various heating options, and this motivated their participation and communication in this work. This is important because involving stakeholders is a prerequisite for applying the method.

4.2.1. RESULTS FROM STEP 2

Three sources are overlayed to subdivide the LTK municipality into the districts defined in Section 3.1, so that they can be implemented in the model: 1) the existing geographic divisions of the municipality available in the national building and dwelling registry (BBR); 2) the municipality's official urban quarter divisions; and 3) current heating supply technologies (see Appendix B). In addition to these three sources, municipal planners stated their preferences with regards to the number of districts and the criteria for dividing the LTK municipality. Step 2 resulted in that the municipality was divided into 15 districts, as shown in Figure 5.

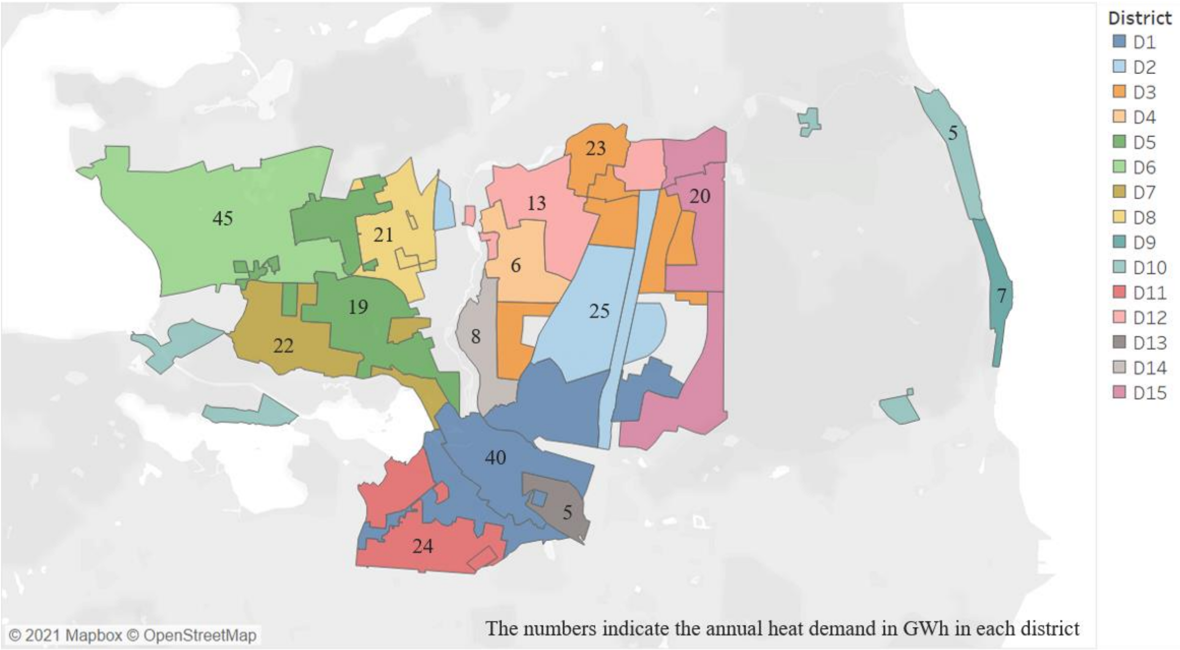

Figure 5. The districts identified through the zoning process in Step 2. The various colors indicate the different districts (D1–D15). The numbers on the map indicate the annual heat demand of buildings in GWh in each district. Districts D1–D5 are connected to DH, and D6–D15 use natural gas for heating.

4.2.2. RESULTS FROM STEP 3

The participatory approach strongly influenced the choice of technologies applied in the scenarios and thus, the modeling work is assumed to reflect the local context. Notably, bio-based technology options are excluded from the model due to the municipality's concerns regarding local air pollution. Table 5 gives an overview of the investment options and parameters that defined the six scenarios investigated. In all six scenarios, the climate goals of a 25% CO_2 reduction (compared to the Year 2018 level) by Year 2025 and net-zero emissions by Year 2050 should be met, and natural gas- and oil-fired heating should be phased out by Year 2035. These are targets defined by the municipality. Towards reaching these goals, the following four deterministic parameters were chosen for the scenarios: *Heat pump subsidy*; *Building renovation rate*; *Electricity price*; and *Individual heating investment*.

The Government of Denmark, through the Danish Energy Agency, offers a subsidy for heat pumps that covers around 15% of the market price. A maximum of 20% of the market price can be covered by the subsidy. The impacts of the subsidy on individual HP investments are investigated in HP expansion Scenarios 1 and 2 by reducing the HP investment cost by 15% and 20% in the model. The building renovation rate parameters examine the impact of renovating existing buildings in the municipality. The parameter *EU average renovation rate* reflects the current European renovation practice, which represents an annual reduction in energy consumption of 1%. The parameter *EU Renovation Wave* reflects the European Commission's strategy introduced in Year 2020, i.e., a deeper renovation rate that makes an 18% reduction in heat consumption by Year 2030, as compared to the Year 2015 level [63]. As for the electricity prices, three different electricity price levels are considered to account for the potential impacts on electricity generation (combined heat and power) and consumption (heat pumps and electric boilers) technologies. Individual heating investment options for LTK are limited outside the DH-planned areas within the next 5 years. This assumption is implemented in the *DH expansion* and the *Combined* scenarios (see Table 5), which investigate the heat supplies in the areas while waiting for the DH connection.

Table 5. Overview of the scenarios that emerge from the participatory process (Step 3) for the urban case (Paper II). The MSW incineration plant is located near Copenhagen and its surrounding municipalities are connected to this DH system. This plant has sufficient capacity to supply the whole LTK (Interviewee C), i.e., there is no investment cost to build this plant in the model.

Scenario	**Parameters/assumptions defining scenarios**	**Investigated technology**	
		Individual heating	**District heating**
DH expansion	• Limiting individual heating investment options in certain areas for the first 5 years • Base electricity price	HP air to water HP ground to water Solar thermal collector	Air source HP Water source HP Electric boiler, small Electric boiler, large MSW incineration
Renovation1	• EU average renovation rate • Base electricity price		
Renovation2	• EU Renovation Wave rate • Base electricity price		
HP expansion1	• HP subsidy covering 15% of investment cost • EU average renovation rate • High electricity price		
HP expansion2	• HP subsidy covering 20% of investment cost • EU average renovation rate • High electricity price		

Combined	• HP subsidy covering 20% of investment cost • EU Renovation Wave rate • Low electricity price • Limiting individual heating investment options in certain areas for the first 5 years		

HP, heat pump; MSW, municipal solid waste.

4.2.3. RESULT FROM STEPS 4 AND 5

Due to the iterative nature of Steps 4 and 5, the results from these two steps are presented together in this section. Overall, the six scenarios formulated in Step 3 differ with respect to which of the parameters explained above are included. The same technology options are included under *Individual heating technology* and *District heating technology*, and the constraints imposed on the emissions and the banning of natural gas and oil heating are binding in all of the scenarios. The scenarios were implemented in a cost-optimization model and the modeling results obtained from Step 4 are presented in Figures 6–8. Figure 6 illustrates the heat generation under the modeled time horizon for four of the scenarios (*DH expansion*, *Renovation2*, *HP expansion1*, *Combined*). The two scenarios of *Renovation1* and *HP expansion2* are excluded from the figures because the results did not show notable differences between the respective coupled scenarios.

In the *DH expansion* scenario, the primary heat supply relies initially on the existing MSW incineration, which provides heat generation at minimal fuel cost. District heating satisfies the majority of the heat demand but gradually diminishes in magnitude starting from Year 2040. The district heating is gradually replaced by individual ground-source heat pumps, and in the district heating system, a large water-source heat pump replaces the existing MSW incineration. Consequently, in the final year, the heat demand is met exclusively by heat pumps, specifically individual heat pumps and a large-scale heat pump in the district heating system, i.e., in the districts where district heating expansion is not cost-competitive there is investment in individual heat pumps. This transition is driven by the need to adhere to CO_2 emission restrictions, i.e., carbon neutrality by the final year. The expansion of the district heating system over time in this scenario is depicted in Figure 7.

In the *Renovation2* scenario, the current natural gas boilers are extensively substituted with individual heat pumps. Comparing this scenario to the *DH expansion* scenario for Year 2030, the modeling results indicate that connecting to a district heating system is not a cost-effective choice when the heat demand is reduced through building renovations. Nevertheless, as the individual heat pumps that received extensive investment reach the end of their technical lifetimes in Year 2035 (not shown in Figure 6), municipal solid waste (MSW) incineration district heating becomes the main source for heating, supplying 85% of the total demand. Approaching Year 2050, MSW incineration is gradually phased out in favor of a large heat pump in the district heating system, due to the model's constraints on CO_2 emissions.

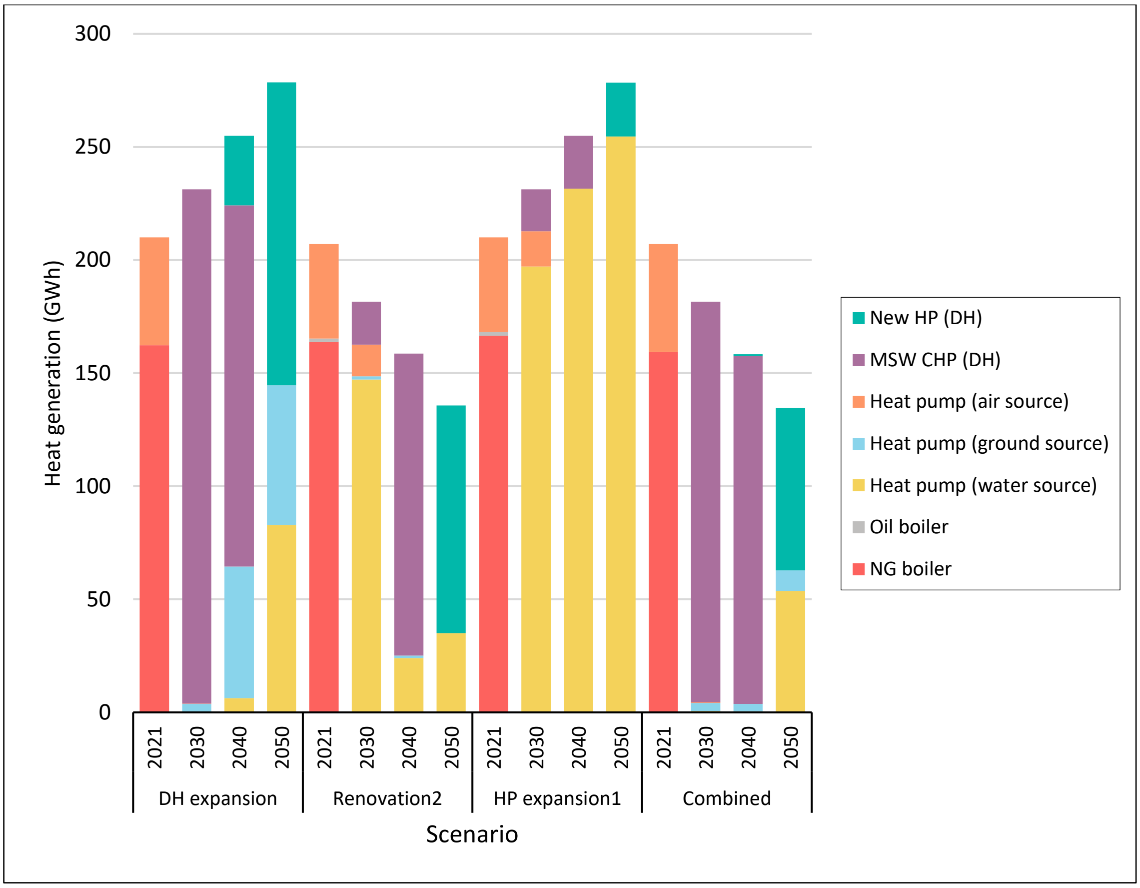

Figure 6. Heat generation level by technology for the selected scenarios at 10-year intervals. HP, Heat pump; DH, district heating; NG, natural gas.

The results from the *HP expansion1* scenario indicate that individual heat pumps outcompete district heating owing to the heat pump subsidy introduced in this specific scenario. While individual air-source heat pumps are invested in extensively, ground-source heat pumps are not a cost-competitive alternative, even in the presence of a 15% subsidy scheme. Although individual heat pumps are the main choice under consideration, district-building-level results indicate (example depicted in Figure 8) that district heating still partially serves multi-family housing in the municipality.

Finally, in the *Combined* scenario, in which extensive building renovation occurs, the reduced heat demand is reflected in decreased investments in a large-scale heat pump for district heating and individual ground-source heat pumps, as compared with the *DH expansion* scenario. Heat pumps (individual HPs and large-scale HP in district heating) eventually fulfill the heating demand in the final years, so as to adhere to the CO_2 emission limit, i.e., carbon neutrality by Year 2050, imposed in the model. This is because MSW contains fossil carbon, causing the model to disfavor MSW CHP towards the end of the modeling period. However, it becomes apparent that the most economically efficient heating technology for the municipality would be district heating based on MSW, if there is no constraint on CO_2 emissions.

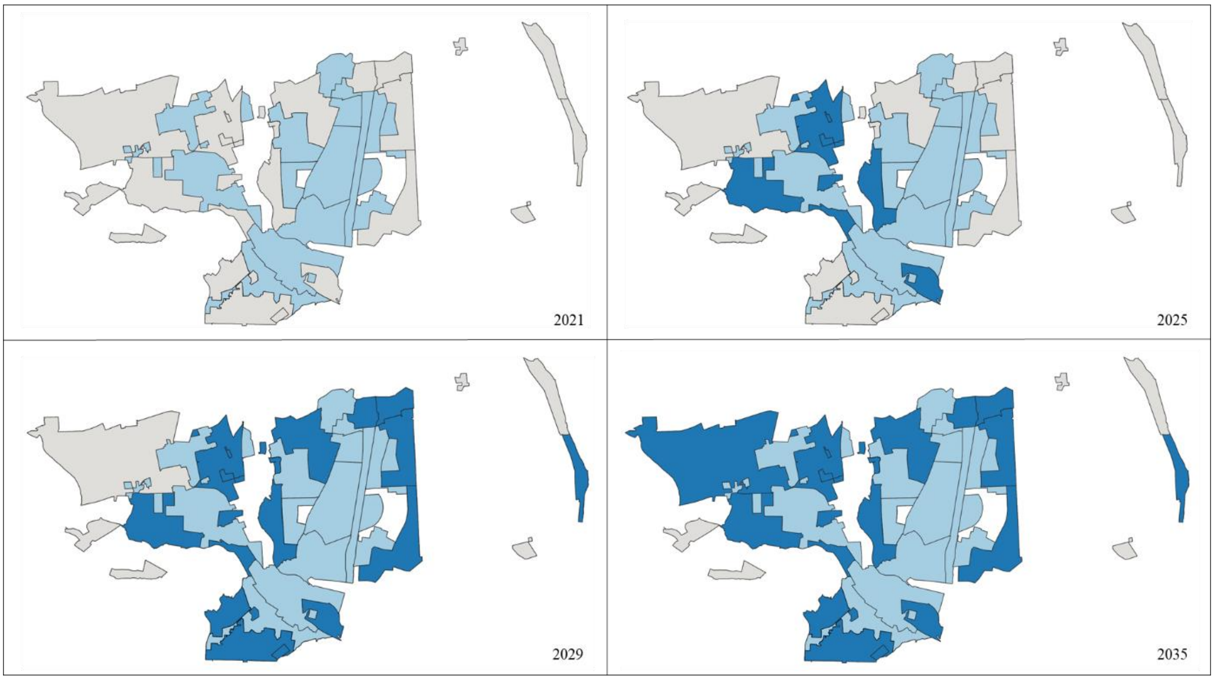

Figure 7. District heating expansion over time in the *DH expansion* scenario. The districts depicted in light-blue represent the current district heating supply area and the areas in dark-blue indicate new connections to the existing district heating network.

In addition to the modeling results at the whole municipality level, as shown in Figure 6, the methodology applied in this study enables further analysis of cost-efficient heating solutions at the district and building levels (all the buildings are categorized into six different building types: Detached houses; Terraced/semi-detached houses; Apartments; Student housing/community residential buildings; Non-residential buildings; and Commercial buildings). Figure 8 illustrates the model results for District 6 and 11, which were specifically chosen to highlight how heat generation differs based on district characteristics, such as the composition of building types, proximity to the existing district heating network, and heat demand density, when identical investment options are available.

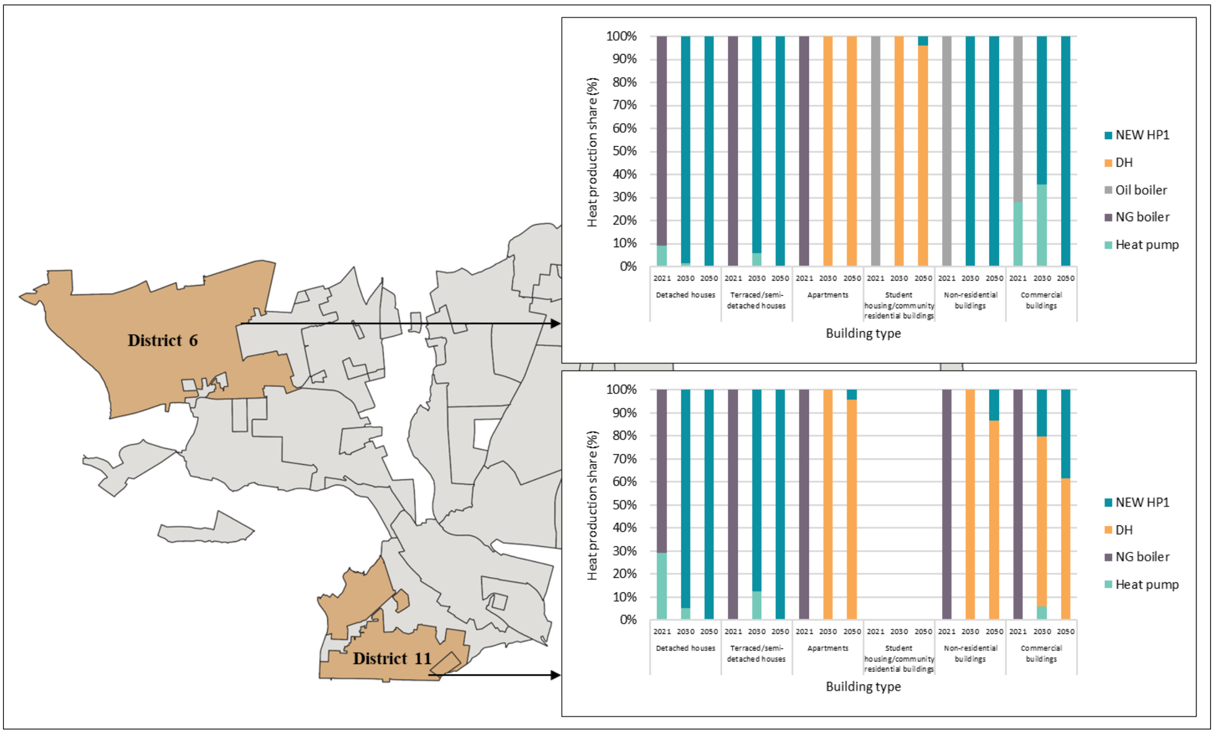

Figure 8. Heating technology shares by building type in Districts 6 and 11 in the *HP expansion2* scenario.

For example, in District 6, both Non-residential buildings and Commercial buildings invest mainly in individual heat pumps, while the same building types in District 11 rely mostly on the district heating system for their heat supply. This is due to the differences in district properties, i.e., each district has a different proximity to the existing district heating network, and a different number of buildings of each type and size. District 11 has a 10% higher heat demand density and a shorter distance to the existing district heating network compared to District 6. Table 6 presents the abovementioned properties in districts where there is no current district heating connection. The reason for having different district heating access years for the different districts (See Table 6) is because of an existing socio-economic evaluation. The municipality has performed its own socio-economic evaluation of prioritized district heating expansion areas and this is reflected in the model, i.e., areas classified as Stage 1 (Districts 7, 8, 13, 14) will receive connections between 2023 and 2027, while Stage 2 areas (Districts 6, 9, 11, 12, 15) will receive access between 2027 and 2030. A techno-economic assessment with a higher spatial resolution is needed to further prioritize districts within the Stage 1 and 2 areas. With the methodology used in this study, we can observe the transitions over time at the district and building levels, i.e., time-based analysis of the breakdown of the Stage 1 and 2 areas, which can add a layer of analysis to the existing evaluation.

Table 6. District properties and district heating share (%) in Year 2050 for each scenario. The remaining share (%) is supplied by individual heating technologies. Note that in the Building type distribution (%) column, building types 1/2/3/4/5/6, respectively, indicate the six building types mentioned above: Detached houses; Terraced/semi-detached houses; Apartments; Student housing/community residential buildings; Non-residential buildings; and Commercial buildings.

	DH access (Year)	Distance to existing DH network (m)	Heat demand density (MWh/km^2)	Building type distribution (%) 1/2/3/4/5/6	DH share (%) in *DH_expansion* scenario	DH share (%) in *Renovation* scenario	DH share (%) in *HP_expansion* scenario	DH share (%) in *Combined* scenario
District 6	2030	687	59,478	82/12/3/1/1/2	33	82	2	39
District 7	2023	659	63,959	42/56/0/0/0/2	100	86	27	100
District 8	2023	1,622	71,199	31/64/2/0/0/3	100	42	7	100
District 9	2027	600	58,717	44/9/38/0/1/8	35	74	26	42
District 10	-	-	-	12/3/14/0/0/71	-	-	-	-
District 11	2027	502	65,511	66/18/12/0/1/4	35	83	8	43
District 12	2027	621	57,966	68/23/4/0/0/5	32	2	1	31
District 13	2023	1,090	65,166	57/13/22/4/0/4	100	7	27	100
District 14	2023	409	60,952	29/6/2/0/1/62	100	76	35	100
District 15	2027	447	54,988	89/6/2/0/1/2	81	82	2	42

In Step 5 of the methodology, the modeling outcomes were disclosed to the municipal planners involved. In particular, the feedback and discussion encompassed the model inputs and usability of the model. In addition, the feedback touched upon the urban planner's perspective, distinguishing between detached housing (subject to national regulations) and semi-detached housing (governed by local regulations), which is important information when it comes to the actual heat planning process in the municipality. The results from the *DH expansion* scenario (Table 6) indicate that for most districts with heat demand density >60,000 MWh/km^2, connecting to a district heating system is a cost-efficient heating solution. The heating plans presented by the Lyngby-Taarbæk Municipality prioritize district heating as a means to achieve carbon neutrality. The modeling in this case study offers insights into the time-based analysis and spatial breakdown of the municipality for district heating expansion, which is crucial for the long-term planning of this municipality.

4.3 Semi-rural case study (results from Steps 2–5 for the semi-rural case; Paper III)

4.3.1. Results from Step 2

The process of dividing the municipality into districts was also carried out for the Holbæk case. The currently used heating technology, proximity to the existing district heating network, and heat demand density data are used as the basis for this process (see Appendix E). The dialogue with the municipal planner revealed their preferences regarding the division of the districts and, as a result, 11 districts are defined for the modeling, as shown in Figure 9.

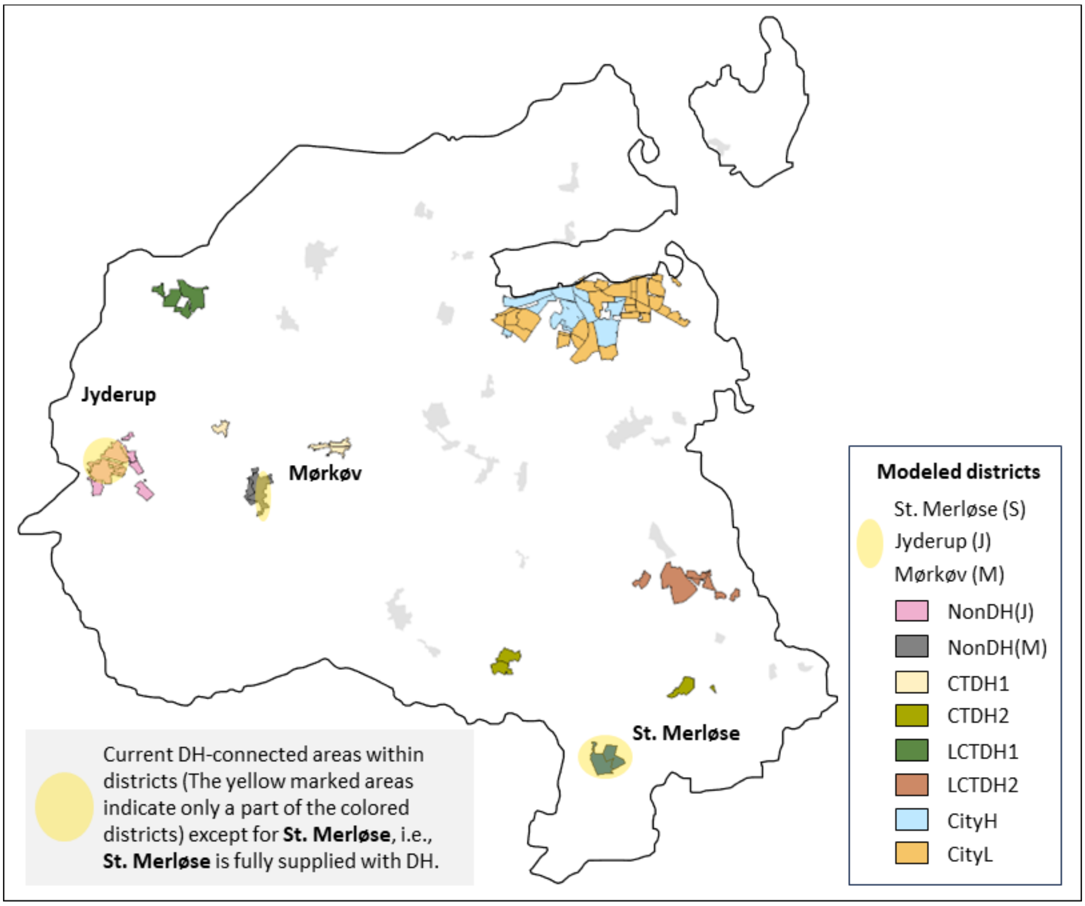

Figure 9. Division of the districts for the modelling. NonDH indicates districts that include the district heating-connected areas but that are not connected to the existing district heating network; CTDH means close to the existing district heating network; LCTDH means less-close to the existing_district heating network; CityH means Holbæk City with high heat demand density; CityL means Holbæk City with low heat demand density.

4.3.2. Results from Step 3

The case study examined four different scenarios for decarbonizing heat in the municipality, as outlined in Table 7. These scenarios were developed partly based on previous research on rural heat decarbonization [64]–[66] and from iterative communication, discussions and validation of the current and prospective heating system with the energy planners in Holbæk. This iterative exchange with the energy planners led to changes to the initial ideas over time and they encompassed various aspects, including local climate objectives, technology preferences, energy policies, investment plans, and resource constraints (for the discussion topics in the semi-rural case study, see Appendix E). For example, the following technology options were added to the scenarios according to their preferences: using biogas in the existing gas grid and using the excess heat from the wastewater treatment plant (WWTP) and neighboring industries; these were added as a result of the discussions with the energy planners. In order to ensure that the model was not limited exclusively to the technologies proposed by municipal planners, the *Mixed-Integrated* scenario encompassed all available options, including technologies that were not initially mentioned during the discussion, such as biomass-based district heating units.

Table 7. Heating technology options included in the model. All scenarios optimize the total system cost.

		Included technology and fuel investment options			
Category	Scenario	Individual heating Technology	Individual heating Fuel	DH Technology	DH Fuel
Local resources	*Centralized-Local*	Biomass boilers Electric boiler Heat pump Solar heating		DH network	EH1 EH2
	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	EH1 EH2

EH1, Excess heat from the municipal wastewater treatment plant; EH2, excess heat from Kalundborg Symbiosis; DH, district heating; TES, thermal energy stoRAGE; HOB, heat only boiler; CHP, combined heat and power.

4.3.3. RESULTS FROM STEPS 4 AND 5

Due to the iterative nature of Steps 4 and 5, the results from these two steps are presented together in this section. Figure 10 shows the heat generation by technology in each scenario with 10-year intervals. In the *Centralized-Local* scenario, there is a two-step shift away from natural gas for heating. Initially, individual biomass boilers supply about 80% of heat demand until Year 2029 (not shown in Figure 10), driven by a natural gas ban by Year 2030, which reduces the use of natural gas boilers. The second phase begins in Year 2027 when excess heat from the municipal WWTP, followed by the excess heat from Kalundborg Symbiosis (in Year 2030) become available for district heating. Thereafter, district heating expansion connects more users and gradually replaces individual biomass boilers. By Year 2044, when individual biomass boilers reach their technical lifetime, these boilers are mostly replaced by the district heating network, providing 173 GWh of heat annually. Starting in Year 2045, over 90% of heat generation in the district heating network comes from excess heat, with the remainder being supplied by individual solar heating units (15 GWh) and biomass boilers (18 GWh).

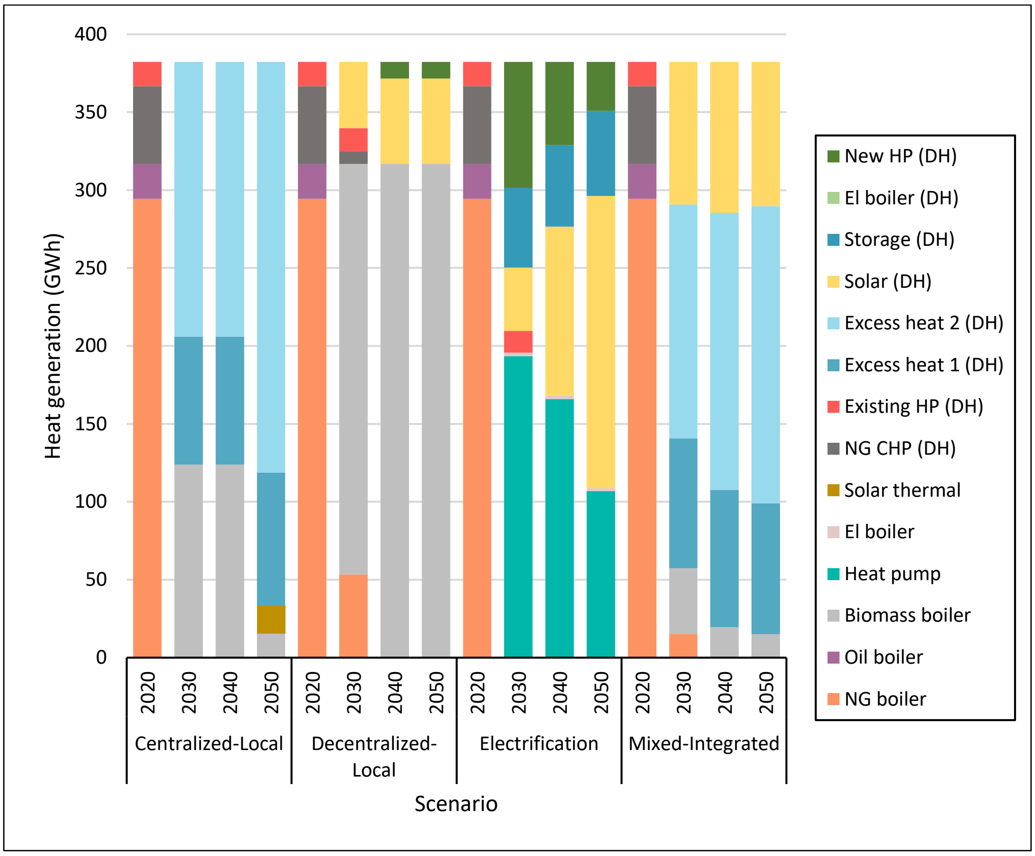

Figure 10. Heat generation by technology in each scenario at 10-year intervals. *Excess heat 1* is from the municipal wastewater treatment plant and *Excess heat 2* is from the Kalundborg industrial site.

In the *Decentralized-Local* scenario, biogas starts to replace natural gas in individual boilers in Year 2023. This switch to biogas is possible with minimal adjustments to existing boilers, making 2023 the feasible year for adoption of the WWTP, enabling biogas recovery within the municipality. Biogas continues to provide heat until Year 2030 due to the natural gas ban and a gradual decrease in the CO_2 emissions cap in the model. Biogas injection into the existing gas grid, despite its current high fuel price, may be a suitable option when there is a supportive financial scheme. This scenario only affects individual heating systems, so district heat supply remains constant at the base year level of 65 GWh. However, district heating sources evolve, with solar-powered district heating gradually replacing natural gas. By Year 2050, solar district heating accounts for up to 83% of the total district heat generation. When existing heat pumps in the district heating system reach the end of their technical lifetime, investment is made in a new HP in Year 2040 to complement the solar district heating.

In the *Electrification* scenario (Figure 10), heat pumps and electric boilers greatly reduce fossil fuel usage, providing 51% of the total heat demand by Year 2030, with district heating covering the remainder. District heating gradually expands and attains a 71% share by Year 2050, while individual electric boiler usage declines as cost-effective district heating from excess heat becomes dominant in later years. Solar district heating investments and seasonal thermal storage contribute to district heat generation increased by a more than four-fold by Year 2050, with the storage meeting about 20% of the district heating demand. To replace natural gas and meet the district heating needs, significant investments are made in large-scale heat pumps, contributing 43% in Year 2030 but gradually decreasing to 11% of the district heating demand. The electrification of heat is interconnected with the decarbonization of other sectors, such as power and industry. Therefore, the success of heating decarbonization depends in part on the progress made towards decarbonizing these sectors.

In the *Mixed-Integrated* scenario, district heating emerges as the primary heat supply technology starting in Year 2028, replacing individual biomass and natural gas boilers. Beyond Year 2030, the most economically viable heat source is district heating that employs excess heat from the municipal WWTP, as depicted in Figure 10. The excess heat from the WWTP is fully utilized, whereas for the excess heat from Kalundborg, 73% of the anuual availability is utilized. It is worth noting that the excess heat from Kalundborg Symbiosis is not entirely carbon-neutral. Furthermore, 25% of the district heat generation relies on solar district heating with the investments commencing in Year 2025, while access to Kalundborg's excess heat will not be feasible until Year 2030.

It is important to note that the modeled scenarios actively reflect the technology options that are preferred by the municipal planners. This means that each scenario can be seen as a 'pathway' to reach the locally set climate goals with certain technologies. As mentioned above, a *Mixed-Integrated* scenario was included that contained all the technology options, to avoid limiting the model solely to the technologies preferred by the municipal planners. This resulted in differences in the technology mix and the development. However, biomass-based district heating units were not chosen.

Figure 11 shows the district heating supply shares in Year 2030 and Year 2050 for each scenario and district. Since each district has different properties, in terms of heat demand density and proximity to an existing district heating network, different district heating supply shares are observed.

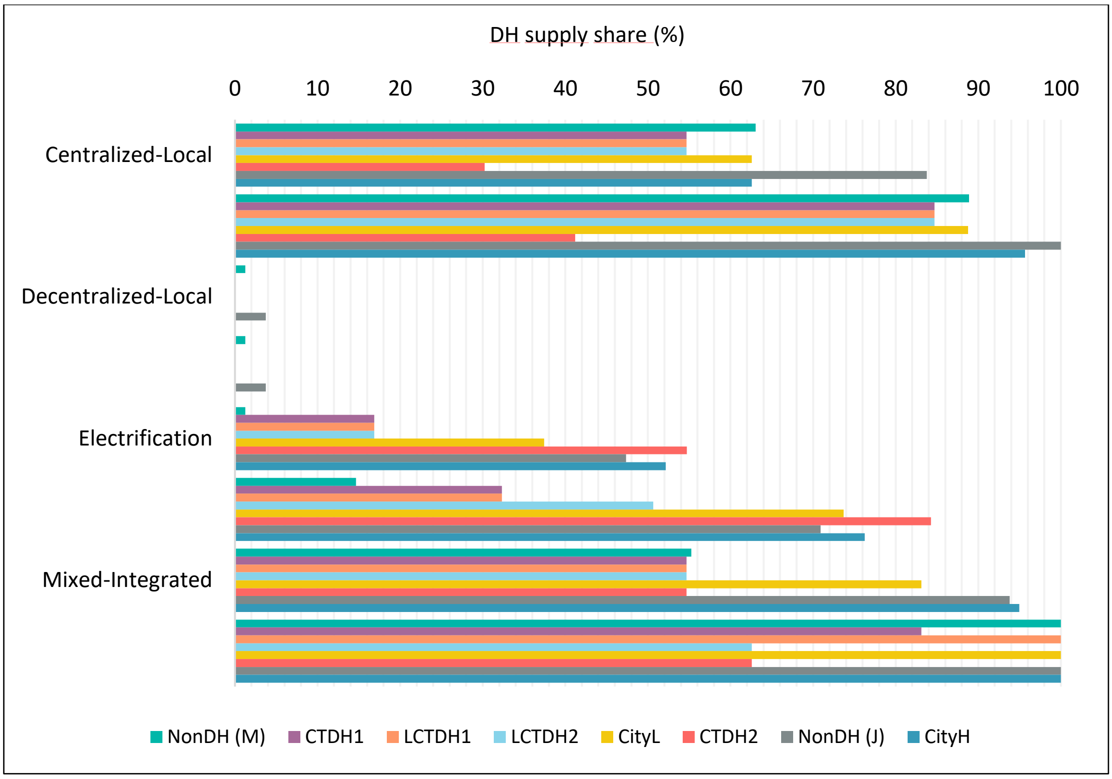

Figure 11. District heating supply share (%) in the different districts in Year 2030 and Year 2050. The districts in the legend are ranked according to heat demand density, i.e., NonDH(M) has the lowest and CityH has the highest heat demand density.

Thus, the share of district heating differs between the *Centralized-Local*, *Mixed-Integrated*, and *Electrification* scenarios. As for the *Electrification* scenario, district heating expansion is not an option and it does not have access to excess heat. Figure 12 presents the results from the CTDH1 and CityH districts. In the *Centralized-Local* scenario, district heating covers 96% of heat supply in CityH in Year 2050, since this is a high heat demand density district, while for CTDH1, a low heat demand density district, the corresponding value is 85%. In the *Electrification* scenario, the district heating share in CityH reaches 76% in Year 2050, while CTDH1 reaches only 32% of district heating share in Year 2050. Figure 11 indicates that district heating shares in the *Mixed-Integrated* scenario are the highest in nearly every district. Five districts in this scenario achieve 100% district heating supply by the final year, and districts with lower heat demand densities still have relatively high district heating shares of 62% and 83%. When almost every district reaches 100% connected to district heating in the *Mixed-Integrated* scenario, the two excess heat sources and solar heating supply heat to the district heating system. In this scenario, the excess heat from Kalundborg was not used as much as in the *Centralized-Local* scenario, and 25% of this heat was replaced by heat from solar district heating. This indicates that including all the options does not necessarily result in different technologies from the other scenarios being chosen, due to the cost-competitiveness of the excess heat.

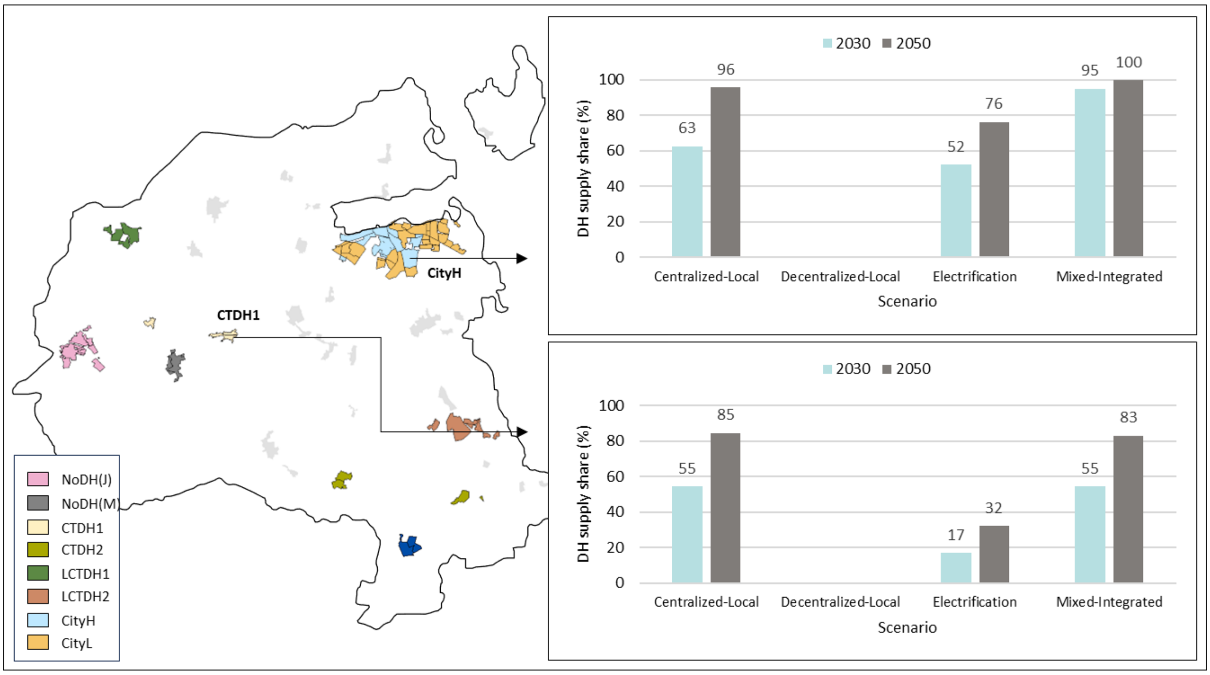

Figure 12. District heating supply shares for the selected districts (CTDH1 and CityH) in Year 2030 and Year 2050.

The district properties data (heat demand density and distance to existing district heating network) and model results (district heating supply share) are outlined in Table 8. The data and the model results indicate, as expected, that heat demand density is the primary driver for district heating expansion. In addition, the availability of excess heat recovery plays a crucial role in enhancing the economic feasibility of district heating, including also connecting areas with lower heat demand densities.

Table 8. District properties.

District	Heat demand density (MWh/km^2)	Distance to existing DH network (m)	Maximum DH share in Year 2050 (%)	
			EH available	EH not available
NonDH(M)	8,016.9	0	100	14.6
CTDH1	10,875.2	2,712.7	84.7	32.3
LCTDH1	11,016.0	6,737.1	100	32.3
LCTDH2	11,205.4	7,805.2	84.7	50.7
CityL	13,135.5	14,293.4	100	73.7
CTDH2	14,495.6	7,334.6	62.6	84.3
NonDH(J)	18,618.4	0	100	70.9
CityH	32,174.5	14,293.4	100	76.3

EH, Excess heat.

Figure 13 shows the sum of the undiscounted annual cost components, including investment cost, fuel cost, and variable cost, over the analyzed period relative to the *Mixed-Integrated* scenario, which is the first-best scenario with the lowest total system cost. In the *Electrification* scenario, costs are notably high due to the need for individual heat pumps alongside the district heating network expansion. In contrast, the *Decentralized-Local* scenario has the lowest investment cost, given that it utilizes the existing natural gas infrastructure and local biomass resources without district heating expansion, although it faces higher fuel costs and substantial expenses related to biogas upgrading. The *Centralized-Local* scenario, which is the second least-costly option after the *Mixed-Integrated* scenario, has a cost structure similar to that of the *Mixed-Integrated* scenario, albeit with higher operation and maintenance costs, driven by the individual biomass boilers. Both the *Centralized-Local* and *Mixed-Integrated* scenarios highlight that extensive use of industrial excess heat can be expensive due to district heating expansion, although combining it with renewable heat investments can create a cost-efficient heating system, while reducing reliance on fossil fuels and potentially saving costs in the long run.

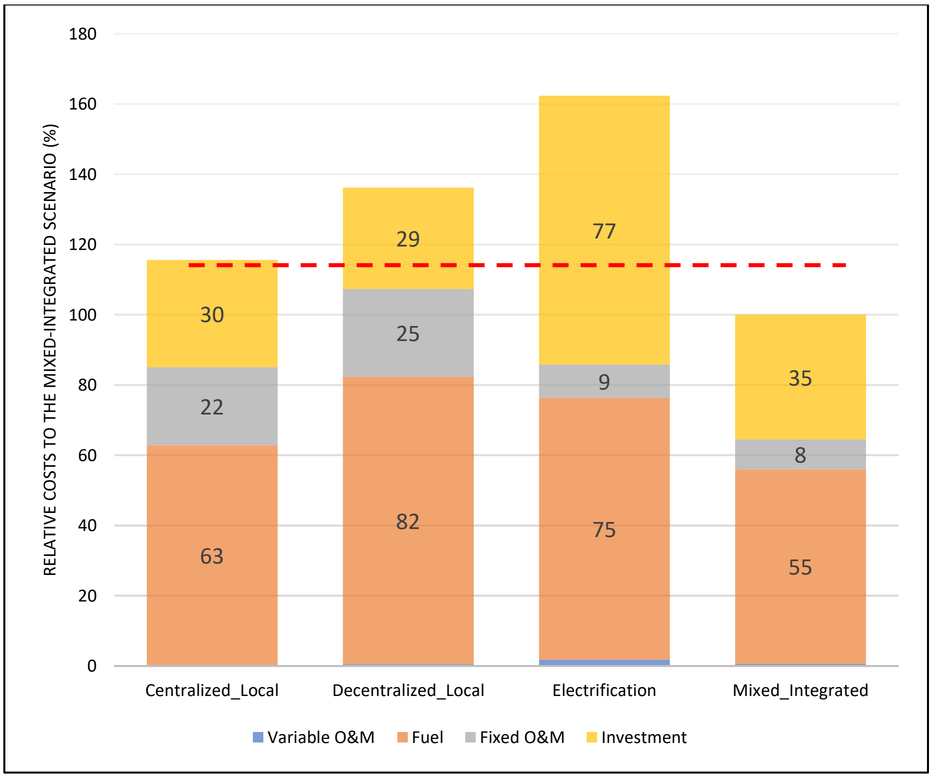

Figure 13. Overview of the cost elements for each scenario. The red dashed line represents the *Mixed-Integrated* scenario, which has the lowest total system cost.

During Step 5 of the methodology, the modeling results were shared with the municipal planners, with the goal of gathering valuable feedback that could be used to alter the model so as to better align with their specific requirements and preferences and to enhance the usability of the model results. This presentation encompasses a detailed analysis of the results on the heat generation mixes and heating technology capacity mixes in the four different scenarios that we have explored.

4.4 REFLECTIONS ON THE RESULTS AND METHOD

This study started out by pointing out that the spatial characteristics, e.g., density, proximity to energy infrastructure and resources, and building types, affect the choices as to the ways in which the heat supply can be decarbonized in the areas in question. Municipalities in urban and rural settings often differ in terms of such spatial characteristics. While the investigated heating technologies and resources are not identical between the two case studies, the comparison of the cases is meaningful. The urban municipality in this study is characterized by a high heat demand density and concentrated heat consumption points, whereas in the semi-rural municipality, heat consumption points are scattered and have a lower heat demand density. Furthermore, different percentages of the buildings are already connected to district heating, i.e., 40% and 20% in the urban and semi-rural municipalities, respectively. In the scenarios in which district heating is expanded to the greatest extent in both cases, as expected, the modeling shows that district heating expansion reaches its maximum level earlier in the urban municipality, i.e., in Year 2035 in the LTK case and in Year 2050 in the HK case. This is due to the degrees of accessibility to heat sources that can be used in the district heating systems. In the urban case, there is already available MSW incineration capacity and district heating systems being prevalent in the nearby municipalities, whereas in the semi-rural case, the excess heat sources are not yet available to be utilized in the district heating system.

When it comes to how much of the heat demand is to be supplied by district heating or individual heating, several decisive factors must be considered. In the urban municipality case, for example, the dominant type of housing and the distance to the existing district heating network seem to play key roles. The decrease in heat demand that results from building renovations may favor individual heating systems over district heating systems, as can be expected. However, from the modeling, the opposite is observed in districts (Districts 6, 9, 11) that have more Detached and Terraced/semi-detached houses, as compared to other types of housing. The reason for this is that these buildings are located close to the existing district heating network (Table 6), which makes district heating a cost-efficient option in these specific districts. These results underline the importance of high spatial resolution for capturing district-specific strategies.

The urban case study demonstrates the relevance of municipal planners' Inputs, such as district-level local knowledge. This includes district heating expansion plans and the assessment by the municipality regarding the prioritization of areas to be connected, as well as local preferences, which notably excluded biomass as an option (CHP/boilers) due to concerns related to local air pollution issues. In the semi-rural case study, the stakeholder interaction also has an impact, especially on the technology options included in the modeling. Thus, the expressed preferences of local energy planners on technologies such as biogas injection into the existing gas grid and the possibility to utilize excess heat from the WWTP and Kalundborg and their annual availability, have been incorporated into the scenarios. Therefore, the participatory approach within the modeling process makes it possible to connect the modeling capabilities with the needs and preferences of the stakeholders by providing the local context and resource availability in both the urban and semi-rural cases.

In discussing the usability of the method used in this thesis, the following aspects are considered: (1) the addition of a new layer of information to those generated in previous energy systems modeling studies; and (2) the provision of what the municipal planners seek to learn from the model. First, it is clear that the modeling results can illustrate how the district heating network expands across different areas during the specified time period. The model results reveal a cost-efficient expansion of district heating on a district-by-district basis as time progresses. In addition, the results show how district heating connections evolve over time, categorized according to building types within each district. This evolution is influenced by the following factors: proximity to the existing district heating network; the density of the heat demand; and the specific building types of the present building stock. All of these factors directly influence the costs associated with the distribution and transmission pipes. Municipal planners could use this information not just for their planning activities, but also to engage in productive discussions with energy utilities operating in their areas. For example, planners could propose various options for prioritizing areas and buildings for district heating connections and other individual heating systems. This can allow for close collaboration with district heating companies, so as to create expansion plans that are economically and environmentally viable. In essence, having access to such data is vital for municipal planners, as it assists them in informed decision-making and the formulation of strategies for district heating network expansion indifferent areas. While the model can suggest what would be economically optimal under different scenarios from the planners' and suppliers' perspectives, it lacks the consumers' perspectives. Therefore, additional analyses are needed to understand the additional elements of heat transition, e.g., the willingness of consumers to pay for different heat supply options.

The methodology of this thesis involves municipal planners in the modeling process, in term of defining the current system's status, providing data, formulating scenarios, articulating needs and preferences, and analyzing the modeling results, thereby integrating their inputs and perspectives into the modeling. This ensures alignment with the local context and needs, fostering collaboration between urban and energy planners and enhancing communication [67], [68]. It also enables the model-based analysis to capture more-diverse perspectives and real-world knowledge, which may not be captured by techno-economic models alone. The municipal planners can provide insights into local conditions, community needs, and practical constraints that can inform model assumptions and parameters, as well as insights into existing policies, regulations, and barriers that may affect the feasibility and implementation of proposed heating system changes. Furthermore, interactions with stakeholders can help to refine the inputs, e.g., infrastructure availability and public preferences, and to validate the models by providing feedback on model results and comparing them to real-world observations. This iterative process can improve the relevance of the modeling results.

However, it is important to note that involving stakeholders in each step is a time-intensive exercise. The potential application of this methodology to other cases hinges on the availability of stakeholders who will engage in the process. In addition, the availability of a comprehensive database, such as a national building registry (BBR in this study), may entail some limitations, as it may not be accessible in all countries. Furthermore, close stakeholder involvement may restrict the scope of the study to needs-driven scenarios, potentially overlooking the broader aspects or alternative viewpoints, necessitating a balance between stakeholders' interests and the researchers' goal of satisfying the interests and needs of Society. When stakeholders are closely involved, they often prioritize their specific needs, concerns, and goals, while researchers are expected to bring all perspectives to the table. Another point that needs to be acknowledged is that this study exclusively involved municipal planners, omitting other stakeholders, such as citizens and actual heat consumers. To address these limitations, future research should focus on developing more-integrated methods of this nature for broader application and, ultimately, to advance integrated energy planning in urban areas.

5. Conclusions

In this thesis, a spatially explicit participatory heating system modeling method was developed and applied to urban and semi-rural municipalities. This method integrates the local context and knowledge of local stakeholders into five modeling stages: Step 1 – Reviewing the planning processes; Step 2 – Inclusion of spatial features; Step 3 – Scenario formulation; Step 4 – Energy systems modeling; and Step 5 – Evaluation of modeling outcome. In particular, the impact of the stakeholder interaction appears to be critical in Step 2 (Inclusion of spatial features) by providing preferences for dividing the municipality into districts to be modeled, and in Step 3 (Scenario formulation) by delimiting the scope of the technology options, since they are closely related to the modeling outcomes to be relevant to a specific municipality and its condition. The impact of high spatial resolution is highlighted, with the model results showing the different heating technology preferences depending on the differences in district properties. As mentioned with the examples of districts applied in Sections 4.2.3 and 4.3.3, it is evident from the modeling that the most cost-efficient heating technologies for a certain building type differ between districts due to differences in district properties. This indicates that the model applied in this work reflects the local context and, thus, can suggest district-specific strategies to the municipality planners.

The approach chosen in this work can address the selection of heating solutions in the different geographic areas within a municipality by analyzing which districts benefit most from specific heating technologies. The analysis can also provide municipalities, heat utilities, and residents with potential cost savings. Furthermore, comparing the modeling results with and without stakeholder participation would be an interesting future work, to gain insights into the impacts of such participation on energy systems modeling practices.

As for the modeling results, the findings from the urban case study suggest that expanding the district heating network and maximizing the use of municipal solid waste incineration heat until the goal of carbon neutrality is achieved is a cost-efficient strategy in the Lyngby-Taarbæk Municipality. It also suggests investing in power-to-heat technologies towards the final year to achieve the carbon-neutrality goal. However, it is important to emphasize that such a shift towards substantial investments in power-to-heat technologies will be contingent upon the availability of carbon-free electricity sources. The results obtained from the semi-rural case show that rural heat decarbonization can benefit from using existing local resources and infrastructure. The best economic choice among the investigated technologies in the modeling in this work is to use excess heat from the municipal wastewater treatment plant and nearby industrial sites in district heating systems, which also encourages expansion of the local district heating network. However, biogas injection into the current gas grid is found not to be cost-competitive for natural gas substitution from the modeling results. This is due to the current high cost of the fuel, and so it would require financial support. Rural areas, which are characterized by remote locations, low heat demand density, open land, and agriculture, offer favorable conditions for utilizing local resources for heat decarbonization. Nevertheless, it is important to emphasize the risks related to excessive reliance on a limited number of local heat sources.

Overall, the heating solutions discussed with the municipal planners in connection with the model results in this thesis require substantial investment in infrastructure. Once the infrastructure has been established, implementing fundamental technological changes after only a few years is challenging and results in sunk costs. Therefore, establishing a robust and long-term strategy early in the development process is crucial, particularly from the standpoint of municipal planning. It is also essential to acknowledge that the strategic approach will differ between urban and rural contexts, due to their inherently distinct dynamics and needs.

6. Future work

The process of decarbonizing heating systems is intricately linked to the progress and developments occurring in other sectors, such as the increasing adoption of renewable energy sources within the electricity grid and advancements in the transportation system. In order to understand thoroughly how these sectors influence one another, it is essential to delve into the intricate details of their interactions. This means that future studies could involve analyses with a higher level of time resolution, as renewable energy generation is not constant but rather intermittent, and it varies not only across different times but also across different, larger geographic locations. By employing more-detailed time-based analyses, we can better comprehend the dynamic relationships between heating systems and other inter-related systems.

While municipal planners play a pivotal role in the planning process for heating systems, it is important to acknowledge that they are not the sole players in this process. To gain a comprehensive understanding and to make well-informed decisions, it is imperative to involve a wider range of stakeholders. This includes citizens and energy utilities, and entails consulting with other relevant actors in the field. However, this inclusive approach must maintain a balance, as the needs and priorities of these stakeholders may sometimes conflict with what is best for meeting societal needs, and it is important to remember which questions one answers when cases and choices are allowed to be influenced by stakeholders. Discussions regarding the model results obtained with the methodology used in this thesis have the potential to facilitate collaboration and compromise among stakeholders, and the participatory approach becomes even more relevant when a wider range of stakeholders is engaged.

To achieve carbon-neutrality by Year 2050, the building sector must transition towards greater use of zero carbon energy sources and must improve its energy efficiency through renovation. This thesis places less emphasis on the energy efficiency measures for buildings. Given that decisions regarding energy efficiency targets are influenced by various barriers and drivers, which range from individuals to organizations, future research on the topic of building energy efficiency could utilize the developed participatory approach, involving a broader range of actors.

Spatial analysis, when combined with studies examining the speed with which energy transitions occur, can provide a richer and more-comprehensive perspective on the transformation of energy systems. This means that future investigations can incorporate spatial considerations into studies of the energy transition rate, to gain insights into not only the pace of change but also the regional and local variations in energy transition dynamics.

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Appendix A. Interview Materials

Information for Potential Participants

Optimization modelling as a decision support tool in municipal energy planning: Heating system in two municipalities in Denmark

What is this research about?

This research aims to investigate a way to more effectively utilize the energy systems modelling process and its results in municipal strategic energy planning in Lyngby-Taarbæk and Holbæk. It is assumed that the energy systems modelling process can be improved in a more useful way for decision making by incorporating knowledge from energy planners who know the local complexities well. In addition, it will be more suitable to utilize the modelling results in decision making since the model contains/address sufficient local knowledge which could result in a more meaningful analysis. This research is a part of the FlexSUS project which supports city planners and decision makers in their cities' sustainable transition towards climate neutrality (https://flexsus.org/) and it will supplement and be supplemented by the FlexSUS project.

What will be asked?

For the purpose of the research some questions will be asked, and topics are suggested as below:

- Municipality's energy plan/goal
- Energy issues each municipality has been addressing and concerning
- Decision making process of municipal energy planning and its pros and cons
- Involved stakeholders, institutions, etc. and their interests/roles/interaction
- Challenges and obstacles in achieving climate targets

What will happen after the research?

It is planned to publish this research in the form of a research paper. The purpose of publication is to share our findings with other people who may face with similar issues. We would like to share with you as well. In this situation where municipality's roles are considered critical to meet climate goals, you as a participant will also gain reflections and ideas in developing better ways to incorporate energy systems modelling into your strategic energy planning.

Will my personal information be protected?

To secure your privacy, you will be asked to choose whether your interview should be kept confidential and you should be anonymous. Please see the possible options in the consent form.

Contact

Hyunkyo Yu, PhD Student
Chalmers University of Technology
Department of Space, Earth and Environment
Division of Energy Technology
Mobile: +46(0) 76 585 50 69
Email: hyunkyo.yu@chalmers.se

Participant Consent Form

The purpose of this statement is to secure your privacy and ensure that your voluntary participation in this research and the agreement on any further use of the information you provide.

Please read the following statements carefully and check the clauses that you agree with.

- ☐ I have been given sufficient information about the purpose and contents of this research project and the opportunity to ask questions and discuss about the research.
- ☐ I understand that I am not obliged to participate in this research project.
- ☐ I agree that the contents of this interview conducted by Hyunkyo Yu contribute to her publication which will be submitted to an academic journal.
- ☐ I agree that if appropriate, Hyunkyo Yu can record this interview, transcribe it and transfer the recording files and transcription onto computer and use the collected data for the purpose of this research. I have been given enough information about the data management procedure. I understand that the electronic files will be deleted by the end of 2021 unless I specify the date.
- ☐ I agree that wherever appropriate, Hyunkyo Yu may share the results of this research and with other participants and interested audiences.

Please read carefully the following statements on publicity and choose your answer.

	Yes	No
Your name		
Your position		
Your opinions		
Your organization’s name		
Your organization’s opinions		
Materials you provided		

Please state any other opinions that Hyunkyo Yu should be aware of, if any.

By signing the agreement, I understand that I can withdraw my permission at any time by contacting Hyunkyo Yu.

Name:

Signature:

Date:

Questionnaire

*Before beginning, please declare that you have fully understood the purpose of this interview and provided your consent.

1. Introduction

- Please tell me your expertise and experience in municipal energy planning in Lyngby Taarbæk and Holbæk Municipalities.
- What are your expectations of this research and what are your objectives?
- Do you know about your municipality's goals regarding energy use and emissions reductions?
    - What is your opinion about these goals in general?
    - How do they impact your energy planning process?
    - How do you envision the future system?

2. Municipality of Lyngby-Taarbæk/Holbæk

- Who and which institutions are involved in the municipality's overall energy/climate policy? (e.g., local authorities, potential investors, local communities, academic institutions, environmental groups, governments, citizens, etc.)
    - Who are directly involved in the actual energy planning process?
    - What is the directly-involved actors' role in the municipality's strategic energy plan?
- What are the major challenges and problems for achieving climate goals? (e.g., increase in electricity demand, the pressure for reduction of greenhouse gas emissions, the cost of conventional fuels, etc.)

3. Energy planning process

- Can you explain the energy planning process?
- Where do energy planners gain data (scientific data, socio-economic data, etc.) for planning? We have gaps in collecting data for modelling such as heat supply demand profile el, gas consumption and there is a way to estimate heat demand of each building based on the BBR data out there, any suggestions or recommendations for data collection?
- What is your opinion on incorporating municipalities in modelling process for better analysis?
- What are your opinions about the current energy planning process in your municipality?
- How does the interaction between energy planners and urban planners look like?
    - For example, when considering energy efficiency measures or connection to district heating network or new building plans, etc. How does the process, communication, and cooperation take place?

4. Current heating system

- Are there any updates in the energy system in your municipality since latest energy plan document?
    - How is the 7% of heat pump operated today?
    - How does the pipelines are connected in the three district heating connected villages? Are there official plans to expand it?
    - Is low temperature district heating being discussed?
    - Is storage in the district heating grid being discussed?
    - What are the new building project plans in the urban planning department?

- Could you specify the option for changing high gas consumers to gas boiler with hybrid gas heat pumps/boilers?
- Are you considering introducing more local energy (surplus heat, geothermal)? How much and where would these be?
- Could you specify the community heating based on heat pump and natural gas for cold days?
- Could you specify how the individual geothermal application works?
- Could you specify the biomathane injection into the natual gas grid?
- Could you specify the small district heating systems in three villages and what are the future plans for them?

*The questionnaire is partly extracted from the original material.

Appendix B. Sources used for the Districts in the Urban Case

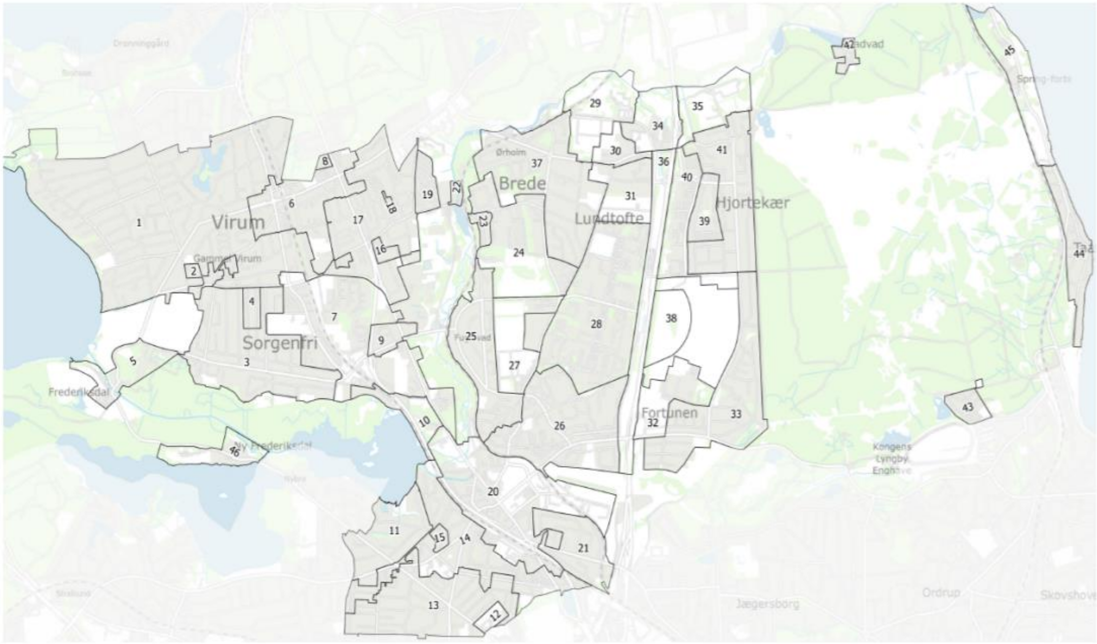

Figure B1. Existing geographic divisions of the municipality available in the national building and dwelling registry (BBR).

Figure B2. Municipality's official urban quarter divisions.

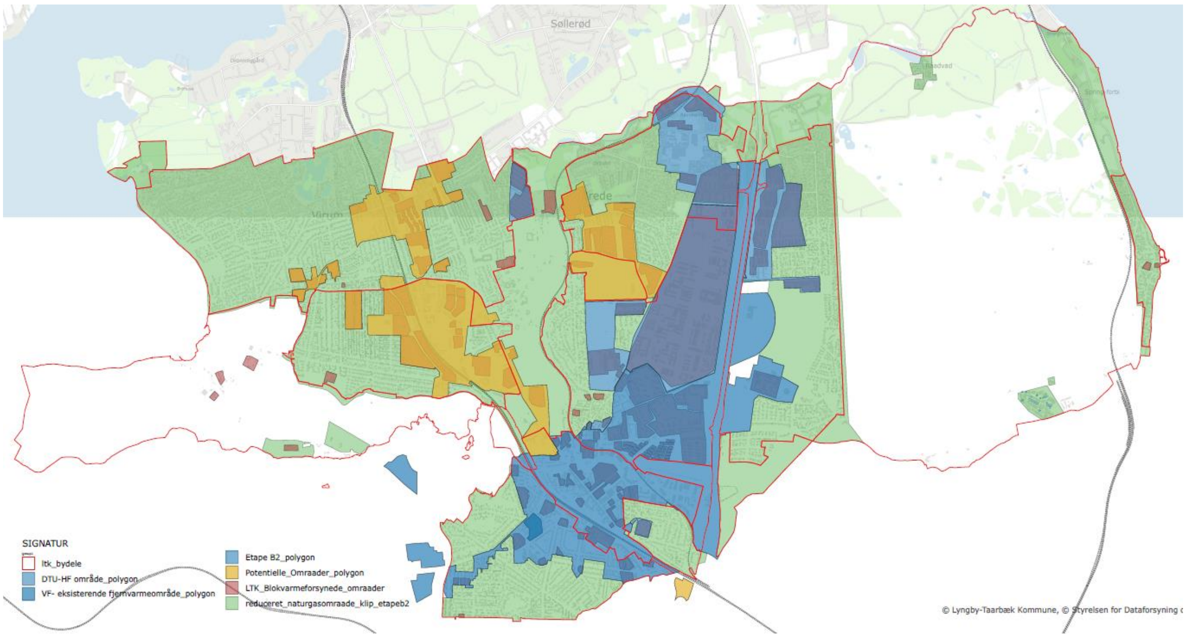

Figure B3. Current heating supply technologies in Lyngby-Taarbaek Municipality.

Appendix C. Material for Scenario Discussion in the Urban Case

Table C1. The initial layout of the scnearios for Lyngby-Taarbaek Municipality. BAU scenario: No policy measures are introduced beyond those that have been decided or already implemented. The reference scenario is the continuation of existing policies on climate change mitigation and existing heat supply technologies. It assumes that only existing policies are in place to mitigate climate change. It only has developing CO2 cap with time; Scen 1: Environmental scenario with building renovation to reduce building heat demand and NG ban; Scen 2: HP expansion and restricting NG scenario; Scen 3: Restricting biomass and NG with reduced demand; Scen 4: All included.

	BAU scenario	**Scen 1**	**Scen 2**	**Scen 3**	**Scen 4**
CO2 cap of 25% reduction by 2025	X	X	X	X	X
CO2 cap of 50% reduction by 2030	X	X	X	X	X
CO2 cap of 100% reduction by 2050	X	X	X	X	X
Biomass tax introduction				X	X
Minimizing biomass use				X	X
HP subsidy			X		X
Electricity grid tariff			X		X
Building renovation		X		X	X
CO2 tax increase		X			X
Ban on NG by 2035		X	X	X	X

Table C2. Material for scenario discussion during the stakeholders workshop. The participants were notified that these scenarios are not fixed ones and that their inputs are needed. This table served as the starting point of the discussion of what kind of scenarios the municipality would like to see in the TIMES model from system point of view. Also, the participants were informed that they can re-combine the existing constraints in the second column (Constraints included in the model run) and create new ones or add new constraints according to their preferences.

<table>
<tr><th>Scenario</th><th>Constraints included in the model run</th><th>Potential slider in the web-based platform</th></tr>
<tr><td rowspan="2">Reference scenario</td><td>No new investment</td><td>-</td></tr>
<tr><td>CO2 cap (Climate goal) 2025, 2030, 2050: 25, 50, 100%</td><td>-</td></tr>
<tr><td colspan="3">No policy measures are introduced beyond those that have been decided or already implemented. The reference scenario is the continuation of existing policies on climate change mitigation and existing heat supply technologies. It assumes that only existing policies are in place to mitigate climate change and the heat demand increase follows the average.</td></tr>
<tr><td rowspan="5">Scen1: Environmental Scenario</td><td>New investment options</td><td>-</td></tr>
<tr><td>Natural gas ban by 2035</td><td>-</td></tr>
<tr><td>Stricter CO2 cap 2025, 2030, 2050: 30, 55, 100%</td><td>-</td></tr>
<tr><td>Biomass tax</td><td>0,24 / 0,12 / 0,48 DKK/kwh</td></tr>
<tr><td>CO2 tax 2021, 2030, 2050 (0,024 / 0,2 / 0,4 DKK/ton CO2)</td><td>-</td></tr>
<tr><td colspan="3">In this scenario, the municipality focuses on minimizing negative environmental impact by implementing different types of environmental policies. Specifically, new investments are allowed and the municipality has to meet a stricter climate goal along with fuel/emission taxations and a ban. Biomass usage is restricted due to the limited availability of the resource and the issue of local air pollution.</td></tr>
<tr><td rowspan="5">Scen2: HP expansion</td><td>New investment options allowed</td><td>-</td></tr>
<tr><td>HP subsidy</td><td>15 / 20 / 25% (of HP investment cost)</td></tr>
<tr><td>Natural gas ban by 2035</td><td>-</td></tr>
<tr><td>Stricter CO2 cap 2025, 2030, 2050: 30, 55, 100%</td><td>-</td></tr>
<tr><td>CO2 tax 2021, 2030, 2050 (0,024 / 0,2 / 0,4 DKK/ton CO2)</td><td>-</td></tr>
</table>

In this scenario, the municipality focuses on expanding HP installation of both individual HPs and also a large-scale HP for connecting to the district heating network. NG will be banned which is expected to play a role in investing more HPs.		
Scen3: Energy efficiency measure	New investment options allowed	-
	HP subsidy	15 / 20 / 25% (of HP investment cost)
	Electricity grid tariff	Current el tax + 5% 10 / 15% increase
	Building renovation – Deep renovation Reference: No more than 15% of demand reduction is achieved in reality.	1.5 / 2 / 3% of building stock: how much heat demand could be reduced by these percentage of renovation? 10%? 15%?
	CO2 cap (Climate goal) 2025, 2030, 2050: 25, 50, 100%	-
	Natural gas ban by 2035	-
	Biomass tax	0,24 / 0,12 / 0,48 DKK/kwh
In this scenario, energy efficiency measures are reflected in the model as a form of reduced heat demand.		
Scen4: All	New investment options	Same as above
	HP subsidy	Same as above
	Electricity grid tariff	Same as above
	Building renovation	Same as above
	Stricter CO2 cap	Same as above
	Natural gas ban by 2035	Same as above
	Biomass tax	Same as above
	CO2 tax	Same as above

Appendix D. Sources used for the Districts in the Semi-rural Case

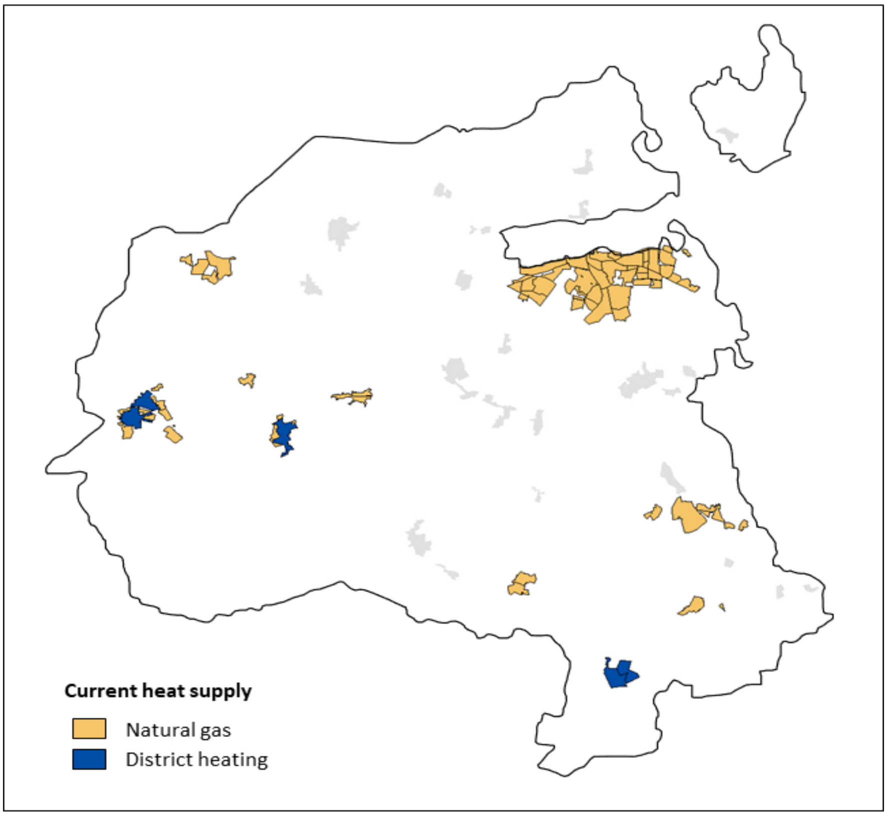

Figure D1. Current heating technology in Holbaek Municipality.

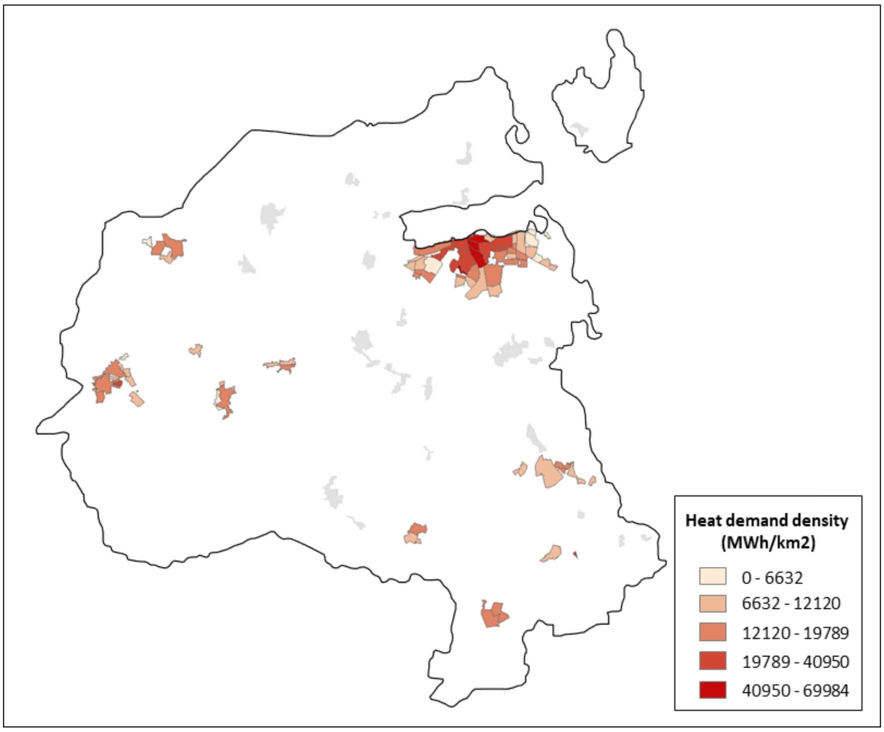

FIGURE D2. **HEAT DEMAND DENSITY IN HOLBAEK MUNICIPALITY.**

Appendix E. Material for Scenario Discussion in the Semi-rural Case

Table E1. Scenario discussions with Holbaek Municipality stakeholders (partly extracted from stakeholder interviews' transcription).

Topics	Initial setup/questions brought to discussions	Discussion with Holbaek municipality	Changes made to the model
Utilization of waste heat in district heating system	Potential use of Kalundborg industrial excess heat and excess heat from two wastewater treatment plant in the Municipality	Kalundborg industrial waste heat is in a very early step of development and it will take many years to use in Holbaek Municipality (not earlier than 2028–2030). On the other hand, excess heat from the wastewater treatment plant in the municipality would be more realistic in the short-term use.	The start years of Kalundborg excess heat and wastewater treatment plant are set 2030 and 2025 respectively.
		The wastewater treatment plant in Gislinge is a bit outside of Holbaek municipality	One wastewater treatment plant is removed as an excess heat source option
Biogas injection technology	Biogas production from the two wastewater treatment plants in the municipality. Questions regarding the lifetime of the gas grid and the potential for biogas production.	There was a political change - some local politicians are fond of gas infrastructure and prefer it instead of district heating but there is national level agreements on not using natural gas and biogas for heating purposes with time constraint.	A scenario where the biogas injection technology is investigated is added (*Decentralized-Local* scenario).
		There is no plan to get rid of the gas grid and this grid usually stays in the ground even when district heating network comes.	The existing gas grid remains throughout the modeled period (2020-2050).
Sector coupling scenario	100% heat pump (HP for DH network and individual) and might consider solar heating.	Thermal storage is very relevant since Holbaek Municipality has the space for renewables and seasonal thermal storages are mostly applied with solar thermal heat generation.	Sector coupling scenario is removed. Instead, a scenario that investigates seasonal storage with solar thermal and electricity-consuming technologies is added (*Electrification* scenario)