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Heating System Transitions in Cities

From Participatory Insights to Network Details in Spatially Resolved Energy Systems Modeling

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Abstract

Decarbonisation of heating in buildings is an important component of the European energy transition. While EU, national and regional policies set overarching targets, the planning and implementation of low-carbon heating solutions takes place largely at the municipal level, where supply and demand are shaped by localised spatial and infrastructural conditions. Yet, most energy system models and transition strategies treat the local spatial dimension only superficially, typically overlooking variations in building density, network coverage, infrastructure age, and proximity to local resources. These variations can decisively influence the cost-effectiveness and feasibility of heating technologies. Addressing heat planning at the municipal level allows for strategies tailored to these local spatial conditions and aligned with the practical realities faced by planners and decision-makers. This thesis develops and applies two methodological approaches for investigating municipal heating system transitions: a spatially explicit participatory modelling framework and a high-resolution techno-economic city energy system optimisation model. Together, these methods enable a multi-layered analysis of how spatial context, infrastructure conditions, and local resource availability shape cost-effective and sustainable heating transitions.

The participatory modelling methodology, tested in urban and semi-rural Danish municipalities, consists of five steps. Step 1 Reviewing planning processes; Step 2 Inclusion of spatial features; Step 3 Scenario formulation; Step 4 Energy systems modelling; and Step 5 Evaluation of modelling outcomes. While stakeholders were engaged throughout the process, their participation was particularly critical in Steps 2 and 3, providing locally grounded definitions of spatial boundaries, technology scope, and planning priorities. This ensured that scenarios were aligned with institutional realities and local acceptability, while still enabling technically rigorous analysis. In the urban case, expanding district heating (DH) and using waste incineration heat until carbon neutrality proved cost-efficient, with late-stage power-to-heat investments dependent on carbon-free electricity. In the semi-rural case, using excess heat from local sources supported cost-effective DH expansion while biogas substitution for natural gas was not competitive.

The city-scale optimisation model, applied to Gothenburg, Sweden, integrates high spatial and temporal resolution, and explicit representation of DH networks and electricity system. It examines how DH network refurbishment strategies and waste heat (WH) availability influence long-term system performance under carbon neutrality constraints. The results show that abundant, low-cost WH can stabilise DH's role in the heating mix, while reduced or spatially concentrated WH availability leads to increased adoption of individual heat pumps. Refurbishment costs are generally a small share of total system costs, but their impact varies substantially across nodes depending on infrastructure age, demand density, and supply source proximity.

Across both methods and case studies, the findings demonstrate that spatial heterogeneity is a determining factor in cost-optimal heating strategies. The integration of stakeholder perspectives ensures that technical results are not only spatially detailed but also institutionally relevant, bridging the gap between techno-economic optimisation and practical municipal planning. This thesis concludes that achieving cost-effective and sustainable heating transitions requires approaches that integrate spatial detail, infrastructure dynamics, and local institutional knowledge. Strategies must be spatially differentiated, resilient to resource uncertainty, and informed by both technical analysis and stakeholder priorities. With the participatory and technically detailed modelling, this work provide a basis for developing framworks for municipalities to design heating transitions that are both technically viable and grounded in the realities of local governance and infrastructure.

Keywords: *Urban heating transitions, District heating, Waste heat, Spatially explicit modeling, Participatory modeling, Heat decarbonization, Optimization, Energy systems modeling*

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. *Smart Energy*, 14, 100144. https://doi.org/10.1016/j.segy.2024.100144

IV. Yu, H., Göransson, L., Johnsson, F. (2025) Modeling of Future District Heating: Waste Heat and Network Refurbishment Dynamics, submitted

Author contributions

Hyunkyo Yu is the principal author of Papers I–IV and performed the modeling and analysis for all four 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 and IV. Claire Bergaentzlé contributed with conceptualization and reviewing of Paper III, and Stefan Petrović contributed with modeling and discussion of Paper III. Lisa Göransson contributed with method development, discussion and reviewing & editing of Paper IV.

Other publications, not included in the thesis:

- 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.

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

- 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

- Yu, H., Göransson, L., Johnsson, F., “The Future of Distriact Heating System in an Interconnected Energy System – Proposal of a Multi-node City Model,” presented at the *37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS),* Rhodes, Greece, 30 June – 4 July, 2024

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Göteborg, 25th Aug, 2025

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1 Introduction

Despite the fact that heating, including space and water heating in buildings, as well as heating in industrial processes, is a large contributor to the global energy demand and CO_2 emissions, climate mitigation efforts have focused primarily on electricity decarbonization and the electrification of the transport sector. However, the energy crisis of Year 2022 brought the heating sector info focus as well [1] The resulting volatility in natural gas markets and increased residential gas prices have highlighted the importance of ensuring a robust, adaptable, and sustainable heat supply throughout Europe. In this context, the European Union's amended Energy Efficiency Directive enforces mandatory heat planning in all cities with a population above 45,000 [2]. In buildings, providing heating and hot water is essential in terms of energy needs, especially for maintaining comfort during colder months and meeting hygiene requirements. Globally, approximately 40% of households require space heating at some point during the year, and this demand accounts for a large share of household energy expenses, particularly in cold climates [3]. In the European context, 57% of the energy consumed for space and water heating is still derived from fossil fuels, such as natural gas, oil, and coal, while renewable sources contribute only 24% [4]. These figures underline the challenge associated with decarbonizing the heating sector.

Achieving decarbonization of the heating sector requires more than changing energy sources. It demands a coordinated transformation of the systems that produce, distribute, and consume heat. This transformation is inherently spatial. Unlike electricity, which can be transmitted over long distances, heating systems operate primarily on the local scale. Heat production and consumption are located in close proximity, and the efficient provision of such heat depends on local conditions, such as heat demand density, building stock characteristics, infrastructure status, fuel accessibility, and opportunities for waste heat (WH) recovery or integration of renewables [5,6]. These spatial dependencies result in highly context-specific heating systems, rendering one-size-fits-all solutions impractical. Therefore, effective heat planning must reflect local variations and must be closely aligned with urban spatial development. Locally based and devised heat planning enables municipalities to tailor solutions to their unique geographic, technical, and institutional contexts, thereby facilitating the use of local resources, enhancing efficiency, and reducing peak loads on national electricity grids [5,7], particularly as heating becomes increasingly electrified through technologies such as heat pumps (HPs).

As municipalities take on increased responsibility for strategic heat planning, driven by the EU's amended Energy Efficiency Directive, which mandates heat planning in all cities with populations over

45,000 [2], the need arises to align these efforts with broader land-use and spatial planning [8]. However, such integration is complex. Municipalities, which are typically responsible for spatial planning, often face limitations regarding technical capacity, data availability, and institutional resources to incorporate the long-term, system-wide implications of energy issues into spatial planning [7,9]. In addition, governance frameworks vary significantly across regions and typically involve multiple actors, including local governments, municipally owned utilities, and permitting authorities. While planners possess critical local knowledge and play key roles in shaping energy-relevant decisions, the complexity of heating transitions demands robust technical analyses. In this context, spatially resolved energy system modeling can provide valuable insights into how heating systems can evolve along different decarbonization pathways.

Despite the growing recognition of the spatial dimensions in heat planning, current tools often fall short with regards to capturing the intra- and inter-city variations. Most energy models apply spatial aggregation to capture an overarching transition of the heating system, but this often obscures important local and network-level dynamics. Urban planning tools, on the other hand, rarely consider the dynamics of energy system transitions or the techno-economic implications of different energy technology choices. This limits the abilities of local governments to identify and evaluate tailored heating strategies that are both spatially grounded and systemically robust. Addressing these gaps calls for integrative approaches that include high-resolution modeling and spatial analysis, together with local stakeholders' perspectives. In addition, participatory modeling, where local stakeholders such as municipal planners, utility providers, and other relevant actors are involved in the modeling process, can help to align technical insights with institutional realities, fostering more-credible and actionable planning processes [10,11]. At the same time, spatially explicit system modeling can enhance understanding of long-term infrastructure needs and allow exploration of the long-term urban heat transition pathways under various system constraints.

This thesis contributes to the field of heating system research by proposing and applying two methodological approaches at the city level. The approaches proposed in this thesis combines two techno-economic models that both incorporate urban spatial characteristics, with one of the models also integrating stakeholder engagement. This thesis underscores the need for a granular understanding of local dynamics and spatial diversity to facilitate municipal heat planning. By highlighting these spatial dependencies, this thesis contributes to ongoing efforts to support municipalities in making informed decisions on the infrastructures for sustainable and resilient urban heating systems.

1.1 Aim and scope

The overarching aim of this thesis is to develop and apply a methodology for assessing cost-efficient urban heat decarbonization strategies, with particular emphasis on accounting for the spatial characteristics in urban energy systems. The thesis addresses the need for long-term planning of heating infrastructures in municipalities by incorporating the spatial characteristics and contextual factors into energy systems optimization models. A key feature of this workis the representation of district heating (DH) systems as geographically distributed networks, enabling detailed spatial assessments of decarbonization pathways. The methodology is applied to a range of contexts and temporal futures, addressing different types of municipalities and planning questions.

The specific research questions addressed in this thesis are:

i. How can a spatially detailed techno-economic optimization methodology be developed and applied to support municipalities in identifying cost-efficient heat decarbonization pathways?

ii. How do local spatial characteristics, stakeholder knowledge, and future uncertainties, such as those related to industrial electrification, increased hydrogen demand, and competition for biomass, influence the planning and transformation of municipal heating systems in urban and semi-rural contexts?
iii. How do pipeline refurbishment strategies for the aging DH infrastructure affect future system development, and what factors shape the suitability of regional heating solutions for urban energy systems?
iv. How might changes in the availability of industrial WH due to evolving industrial processes impact the future development of DH systems?

The thesis comprises this introductory essay and four appended research papers. The first three papers describe the construction and application of a spatially explicit participatory modeling framework in Danish municipalities, while the fourth paper applies an optimization model that incorporates technical details of the DH networks in Gothenburg, Sweden. This fourth paper expands the scope by including long-term DH network refurbishment strategies, thereby linking infrastructure aging with system-level planning.

Figure 1.1 presents the different dimensions of municipal energy system transitions investigated in the four appended papers, spanning diverse case study contexts, energy sectors, modeling approaches, and spatial resolutions.

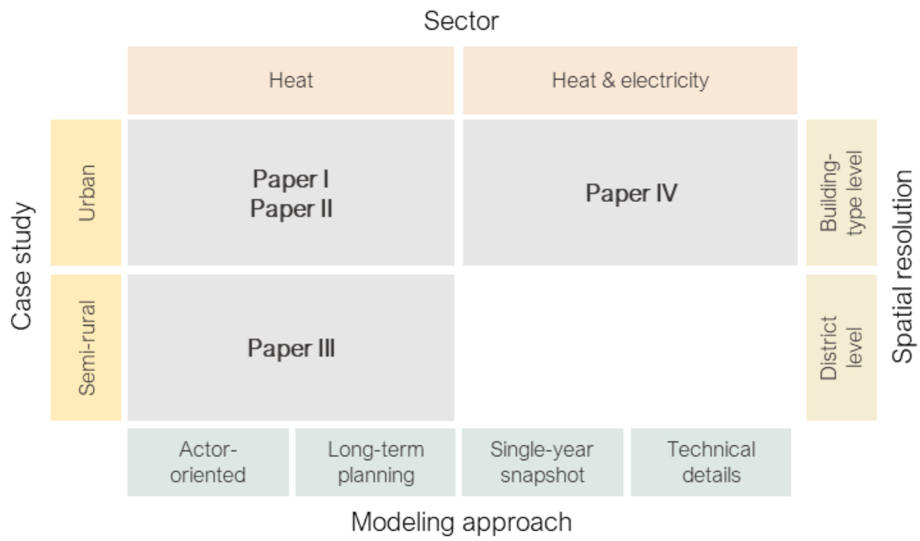

Figure 1.1. Overview of the sectors, case studies, modeling approaches, and spatial resolution considered in the four appended papers.

In terms of energy system sectors, **Papers I–III** focus exclusively on the heating sector, while **Paper IV** integrates the heat and electricity sectors in parallel, reflecting a broader system context. The case studies vary from an urban Danish municipality in **Papers I** and **II**, a semi-rural Danish municipality in **Paper III**, to a large Swedish city in **Paper IV**. Each paper applies and extends the energy system modeling methodology, albeit with different emphases. **Papers I** and **II** develop and implement a long-term planning framework with strong stakeholder orientation and spatial integration at the building-type level. **Paper III** emphasizes the technical feasibility and planning constraints in less-densely populated areas, focusing on spatial factors such as demand density and infrastructure proximity at the district level. **Paper IV** advances the methodology toward a different optimization model, extending the city model developed by Heinisch et al. [12,13], with technical details and hourly resolution, while assessing refurbishment of an aging infrastructure and future system scenarios in a single-year snapshot. The papers collectively move from the conceptual and actor-inclusive planning described in **Papers I–III** to the detailed, technical-oriented modeling in **Paper IV**, with spatial resolution evolving from the aggregated district level to the building-type level depending on the modeling needs and available data.

1.2 Contribution of the thesis

This thesis contributes to methodological improvement by developing a spatially explicit techno-economic modeling framework that integrates local stakeholder knowledge and spatial dimension, so as to support municipal heat decarbonization planning. All four papers apply this framework to different contexts, with three of the papers incorporating local stakeholder knowledge and one focusing on a technically detailed representation of DH pipelines. **Papers I–III** demonstrate how participatory approaches, combined with detailed spatial data, can inform cost-effective, district-level heating strategies in both urban and semi-rural settings. Specifically, 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). **Paper 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 as developed in **Paper I**, several refinements are introduced based on the experiences gained during the works presented in **Papers II** and **III**. **Paper IV** extends the framework by incorporating the long-term infrastructure dynamics, such as DH network aging and refurbishment needs, and explores how varying industrial WH availability, which is linked to broader energy system transitions, affects the competitiveness of DH. Together, the thesis provides a robust and adaptable modeling approach for strategic, spatially grounded municipal heat planning.

Paper I introduces the overall modeling methodology, laying out a structured five-step approach for participatory energy systems modeling. It demonstrates the initial application of the methodology to an urban municipality in Denmark, focusing on integrating spatial plans, building-level data, and stakeholder inputs, in order to generate credible decarbonization scenarios.

Paper II applies the full five-step methodology to the same urban municipality as in **Paper I**. It highlights how the inclusion of local knowledge and spatial detail reinforces decision-making and provides clear guidance on cost-effective, district-specific decarbonization strategies. The study shows that the participatory spatial approach enhances legitimacy, transparency, and implementation relevance.

Paper III expands the methodological application to a semi-rural Danish municipality, offering insights into how spatial characteristics, such as heat demand density and distance to existing infrastructure, affect the feasibility of different heating solutions across districts within the municipality. It highlights the unique challenges and opportunities in less-densely populated areas and illustrates the importance of district-level planning.

Paper IV applies and expands the methodology in a Swedish urban context, focusing on the future DH systems in Gothenburg. This study investigates the yearly refurbishment rate of DH infrastructure and explores which factors shape the suitability of regional heating solutions in urban energy systems. It also integrates varying assumptions about the future availability of industrial WH, which is linked to a broader system transition.

The thesis provide knowledge and insights which can support municipalities and planners in making informed decisions under various uncertainties, offering a methodological bridge between detailed local realities and long-term, system-wide planning for heating transitions.

1.3 Outline of the thesis

This introductory essay outlines the key findings of the four papers within the context of the overall aims of the thesis and is structured as follows. Building on the introduction in Chapter 1, Chapter 2 provides background on DH in urban energy systems, outlining both its strengths and its risks. It further examines the spatial dimensions of heating systems, which serve as a key thematic foundation for the subsequent chapters of the thesis. Chapter 3 describes the modeling frameworks developed and applied in this thesis, including spatially resolved optimization models, scenario design, and data sources. Chapter 4 presents the key findings from the four appended papers, covering spatially explicit participatory modeling studies of Danish municipalities and spatially explicit energy systems modeling of Gothenburg, with respect to future DH systems. Chapter 5 offers a summary of the results and discusses their implications for urban energy planning as well as the methodological contributions, and the limitation of this work. Finally, Chapter 6 presents the conclusions of this thesis and directions for future research.

2 Background

The provision of heat in buildings relies on diverse technologies, which can be broadly categorized into centralized and decentralized systems. Centralized systems primarily include DH system that supply heat to multiple buildings through a network of insulated pipes that carry hot water or steam. DH systems can utilize efficiently diverse heat sources, including WH from industry, power plants or renewable sources, enabling large-scale heat distribution with potentials for high energy efficiency and low CO_2 emissions [14,15].

Decentralized systems, which consist of individual heating units such as HPs, boilers based on biomass, natural gas, oil, and electricity, and direct electric heating, typically serve single buildings or small clusters. Among these, individual HPs are essential for the transition to secure and sustainable heating. Heat pumps are becoming increasingly prominent, as they are highly efficient and can significantly reduce fossil fuel use by using ambient heat from the air, ground, or water, especially when powered by renewable electricity [1]. Their growing importance has been reinforced by recent policy shifts: in response to the 2022 energy crisis, the European Union (EU) introduced the REPowerEU Plan to accelerate the phasing out of fossil gas imports, particularly from Russia, well before Year 2030. Building on the EU Fit for 55 package [16], this plan emphasizes the large-scale replacement of gas boilers with HPs as a key strategy for reducing gas dependency and decarbonizing heating [17].

The uptake of individual HPs has increased in areas where the establishment of DH infrastructure is technically or economically non-viable. In fact, the electrification of heating primarily through individual HPs alongside the expansion of DH has been identified by the European Commission as one of the key strategies for decarbonizing the heating sector [18]. This strategy, involving individual HPs and expansion of DH, reflects the spatial and infrastructural diversity seen across Europe. The deployment and suitability levels of different heating solutions depend on multiple factors, including building density, availability of local energy sources (such as WH or renewable electricity), existing infrastructure, and economic and regulatory conditions. In urban areas, for example, the presence of a concentrated heat demand and potential sources of industrial excess heat or waste incineration may support the development or expansion of DH systems. At the same time, the growing availability and efficiency of HPs, both individual and large-scale, make them a central technology for decarbonizing heating across diverse spatial contexts. Individual HPs are particularly suitable for areas where DH is less feasible due to dispersed demand or lack of infrastructure. Meanwhile, large-scale HPs are also being increasingly integrated within DH systems as part of the evolving generation mix. Often powered by renewable electricity, these centralized HPs can deliver low-carbon heat to DH networks, by upgrading ambient or low-temperature excess heat sources. Rather than being mutually exclusive, these two systems often coexist and evolve in parallel, shaped by local spatial and system-specific considerations. Therefore, understanding the role of DH and individual heatings and how they are planned, developed, and integrated within urban energy systems is an important component of assessing cost-effective and sustainable pathways for heat decarbonization.

The following sub-sections provide an overview of the key themes relevant to the decarbonization of urban heating systems in this thesis. Section 2.1 discusses the characteristics of DH in urban contexts, including the associated economic and technical opportunities and challenges such as technological lock-ins and aging infrastructure. Section 2.2 discusses the spatial dimension in the context of heat planning and energy systems modeling. Section 2.3 reviews the integration of participatory approaches in energy system modeling, with the focus on involving local stakeholders. Finally, Section 2.4 presents the case studies of municipalities in Denmark and Sweden both of which serve as empirical and model-based cases in this thesis.

2.1 District heating in urban energy systems

Urban areas are central to the energy transition not only due to their high population densities and high energy demands, but also because they enable coordinated infrastructure development, integrated energy systems, and efficient use of resources. In the context of heating decarbonization, DH is often cited as a key solution in cities. This is mainly because DH can utilize low-grade residual heat – such as that from industrial processes, wastewater, or power generation [19]. The recent literature has emphasized the importance of DH in smart, low-carbon urban energy systems, stressing its ability to connect multiple energy vectors, such as electricity, heat, and transport, while providing flexibility and lowering emissions [20–22]. As the energy system becomes increasingly reliant on variable renewable electricity sources, DH can play a crucial role in sector coupling, enabling more cost-effective balancing of electricity and heat. Large-scale HPs integrated within DH networks can absorb excess electricity during periods of high renewable generation, converting it to heat that can be stored in short-term or seasonal thermal energy storage units and dispatched when needed [23–25]. This not only enhances energy system efficiency and resilience, but also strengthens the business cases for DH and renewable energy technologies [26,27]. The development paradigm for sustainable thermal energy infrastructure, such as the 4th and 5th-Generation District Heating system, illustrates ongoing efforts to improve DH systems through renewable integration, large-scale thermal storage, and smart control systems that enable flexibility and sector coupling [28–30].

2.1.1 Economy of scale and diversification of heat sources

District heating systems offer the advantage of economies of scale, making them particularly suitable for supplying heat in densely populated urban areas [31]. Unlike individual heating technologies, DH centralizes heat generation and distribution, enabling more-efficient use of fuel and infrastructure per unit of heat delivered. This centralization reduces both the capital and operational costs when serving large and densely populated areas, as the fixed costs of production units and pipelines are spread over a large amount of delivered heat [14,27].

Several factors contribute to this economic advantage. First, DH systems allow for the aggregation and use of low-grade or surplus heat from industries, waste incineration, data centers, and other sources of heat that would otherwise be lost to the environment [32–35]. By connecting multiple buildings and facilities into a single thermal network, DH systems can exploit these local resources in a cost-effective manner: something that would be technologically or economically unfeasible for individual heating units. Second, urban density is a critical enabler of the economic viability of DH. In high-density settings, the concentration of heat demand per unit of pipe length, referred to as the linear heat density, is high, meaning that less infrastructure is required per unit of heat delivered [36,37]. This reduces the installation and maintenance costs of the DH networks and improves the return on investments for both public and private stakeholders. In addition, the spatial proximity of WH sources to end-users in cities facilitates efficient heat recovery with minimal transmission losses [38]. Moreover, DH systems benefit from economies of scale with regards to technological integration and operational flexibility. Large systems can justify investments in advanced technologies, such as combined heat and power (CHP) plants, large-scale HPs, biomass boilers, and solar thermal fields. These technologies are often more efficient and less expensive per unit of output when deployed at scale [39,40].

Another key advantage of DH systems is their ability to incorporate a diverse range of heat sources. Diversification enhances energy security by reducing dependence on any single fuel or technology, while also enabling more-flexible and adaptive responses to changes in fuel prices, policy targets, and technological developments. In the context of heat decarbonization, it allows DH systems to shift gradually towards low-carbon or renewable sources without requiring major changes at the building level, thereby supporting more-resilient and sustainable urban energy system. Despite their systemic benefits, the centralized and large-scale nature of DH systems may introduce operational and strategic risks. High upfront investment costs and the dependence on stable, long-term heat demand can lead to path dependency and reduced flexibility. In rapidly changing policy or market environments, such fixed infrastructure may limit the ability to quickly adapt to new technologies or spatial demand shifts. Moreover, diversification of heat sources, while beneficial, can increase planning complexity and introduce coordination challenges across different energy suppliers and infrastructures.

2.1.2 Waste heat utilization

Waste heat plays a central role in efficient and low-carbon DH systems. In cities located close to industrial facilities, such as oil refineries, manufacturing plants or waste incineration sites, surplus heat from these operations is often integrated into DH networks. This approach improves overall energy efficiency, reduces fossil fuel use for heat generation, and provides a reliable, cost-effective, and environmentally favorable heat supply [41–45]. The stable availability and the temperature levels of industrial WH have made it particularly well-suited for centralized distribution, strengthening the competitiveness of DH in several European countries [46].

However, despite its historical importance, the future availability of industrial WH is increasingly uncertain, due to fundamental transformations in the industrial sector. Developments that include industrial electrification and the expanded hydrogen-based processes are expected to alter significantly both the quantity and quality of available WH [47,48]. Electrified processes, such as electric arc furnaces and high-temperature HPs, typically generate less-utilizable excess heat than fossil fuel-based systems. Likewise, the shift toward green hydrogen production and the redesign of industrial processes to reuse heat internally reduce the levels of thermal waste and may also lead to the spatial relocation of facilities [49,50].

These shifts present new challenges for DH planning. Future WH sources may no longer be located in proximity to urban heat demands or may operate at temperatures that are unsuitable for existing DH networks [51,52]. Moreover, industrial actors themselves are undergoing uncertain transitions, often involving ownership, new technologies, and process changes, making long-term supply contracts and infrastructure investments significantly more risky for municipalities and utilities [53,54]. Given these uncertainties, the continued integration of industrial WH into DH systems will depend on the introduction of more-flexible and adaptive planning approaches. Policy-makers and urban energy planners must anticipate potential reductions and spatial shifts of WH availability and consider diversification of heat sources, to ensure system resilience. This may include the integration of alternative low-carbon resources, such as ambient heat via large-scale HPs, solar thermal energy, geothermal sources, and bioenergy [39,55,56]. Furthermore, investments in thermal energy storage (TES), demand-side management, and smart grid controls can enhance system flexibility and allow DH to accommodate fluctuating and intermittent heat inputs.

Strategic coordination between industry, energy providers, and urban planners will be essential towards aligning future industrial developments with the needs of local DH systems. This includes identifying stable, long-term industrial partners, mapping local heat potential, and designing DH networks that are capable of integrating a wider variety of heat sources. Doing so will ensure that DH continues to play a central role in urban heat decarbonization, even as the landscape of WH availability evolves.

2.1.3 Risk of lock-in to combustion-based technologies

While DH is widely recognized as a key strategy for decarbonizing the urban heat supply, its future development is not without challenges. One of the pressing concerns is the risk of technological lock-in to combustion-based systems, particularly biomass-fired CHP plants and boilers, which currently serve as the primary pathway for reducing greenhouse gas emissions in many DH networks [57]. Lock-in occurs when the existing infrastructure, investments, and institutional frameworks reinforce continued reliance on a particular technology, making it difficult to shift to more-sustainable or flexible alternatives over time [58,59].

The use of forest biomass for energy supply has attracted growing scrutiny in both academic and policy circles owing to its ambiguous climate impacts. While forest biomass is often considered to be carbon-neutral at the point of combustion, the broader carbon balance depends heavily on forest regrowth dynamics, land-use changes, and supply chain emissions [60–62]. As such, the long-term climate benefits of biomass are increasingly contested, particularly in the context of stringent net-zero targets. Moreover, biomass combustion contributes to local air pollution, raising public health and environmental justice concerns, especially in densely populated urban areas [63,64].

An additional challenge relates to the growing competition for sustainable biomass resources. As electrification advances in sectors such as transport and industry, biomass is increasingly reserved for applications where electrification is more challenging, such as heavy industry, aviation, and shipping. This shift is expected to make biomass a scarcer and more expensive commodity [65]. Competing demands for biomass as feedstocks for bio-based materials, biofuels, and high-temperature industrial processes may make its continued use for DH both economically and environmentally questionable. This raises important questions about the prioritization and allocation of limited renewable resources within the energy system. Similarly, reliance on waste incineration through CHP plants, once regarded as a viable method for utilizing municipal waste while generating heat and electricity, is facing growing criticism. These systems reflect a linear approach to resource use, which stands in contrast to emerging models of the circular economy, which prioritize material recovery, recycling, and the development of chemical recycling technologies [66,67]. As policy frameworks evolve to favor material recirculation over incineration, waste-to-energy plants may become increasingly incompatible with sustainability goals.

These developments underscore the risk that DH systems, particularly those reliant on combustion-based technologies, may face structural lock-ins that hinder adaptations to future low-emission and resource-efficient energy systems. Large-scale investments in biomass CHP plants, while contributing to short-term emission reductions, may prove difficult to repurpose or phase out when biomass becomes constrained or politically contested. This underlines the need to design DH systems that can adapt over time, throught reducing reliance on combustion-based technologies and instead supporting more-diverse and flexible system setups. In light of these risks, researchers and planners increasingly advocate for diversification of heat sources and the placing of greater emphasis on non-combustion-based solutions, such as large-scale HPs, solar thermal fields, ambient heat utilization, geothermal energy, and excess heat recovery from industrial or commercial sources [30,44,68].

2.1.4 Aging pipelines

A significant and growing challenge for the future viability of DH systems is their aging pipelines In many European cities, large portions of the DH networks were constructed between the 1960s and 1980s, during a period of rapid expansion of centralized energy infrastructures. These pipelines are now nearing, or have surpassed, their typical technical lifetimes, generally estimated at around 40–50 years [69]. As such, an increasing share of DH networks requires reinvestment, refurbishment, or full replacement to maintain service reliability and efficiency.

The aging DH infrastructure raises several technical and operational concerns. Thermal losses, already inherent to long-distance heat distribution systems, tend to increase as the pipeline insulation materials degrade over time [70]. The deterioration of the pipeline insulation due to moisture infiltration, physical wear, and temperature-induced stress leads to higher energy losses and reduced overall system efficiency. More critically, the risk of leakage increases with age due to corrosion, mechanical damage, or shifting soil conditions, posing threats to both energy security and public safety [71,72]. As DH systems typically rely on centralized production, any failure in the distribution network can disrupt heat supply for thousands of consumers simultaneously, underscoring the need for high system resilience and reliability.

In response to these challenges, long-term asset management and strategic reinvestment planning have become essential for municipalities and utilities operating DH networks. Proactive maintenance and targeted replacement of high-risk segments can help to reduce lifecycle costs, minimize unplanned outages, and extend the economic lifespan of the system. Several studies have investigated innovative pipe refurbishment techniques, including trenchless technologies such as relining or cured-in-place pipe (CIPP) methods. These approaches significantly reduce the need for excavation and can reduce refurbishment costs by up to 70% compared to conventional open-trench replacement [73–76]. In addition to the cost savings, these methods limit social disruption and environmental impacts, which are critical factors in densely populated urban environments.

However, even as new technologies offer cost-effective solutions at the component level, broader system-level uncertainties remain. Decisions regarding DH pipeline reinvestment must be made in the context of future energy system transitions, which could alter the demand for a centralized heat supply and reduce the competitiveness of DH relative to emerging alternatives. As mentioned above, the future availability of low-cost excess heat, a key economic enabler of DH, could diminish due to industrial decarbonization and shifts in waste management practices [47,67]. At the same time, electrified and decentralized heating solutions, such as individual air-to-water or ground-source HPs, continue to improve in terms of both performance and cost-effectiveness, especially in buildings with high energy efficiency standards [55,77,78]. This ongoing technological evolution may influence whether municipalities prioritize extensive DH refurbishment or consider alternative heating pathways that offer greater flexibility and lower capital risk.

These developments highlight the need to regard DH infrastructure renewal not merelyonly as an engineering challenge, but as part of an integrated urban energy planning process. Infrastructure decisions made today will shape the trajectory of city heating systems for decades. Consequently, it is essential to align DH reinvestment strategies with long-term decarbonization goals, spatial development plans, and technological change. Scenario-based planning, multi-criteria decision-support tools, and participatory approaches involving local stakeholders can support more-robust and adaptive choices [79–81]. Figure 2.1 summarizes the strengths and risks that are identified in Section 2.1.

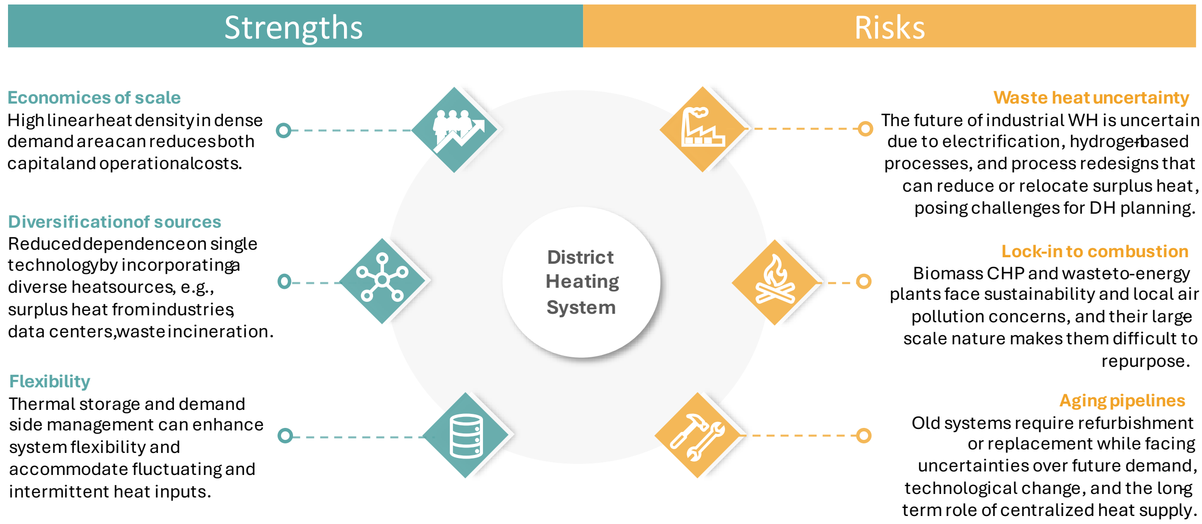

Figure 2.1. Summary of key benefits and risks shaping the future of DH in urban energy systems, based on Section 2.1.

2.2 Spatial dimensions in heating systems

As cities pursue sustainable and efficient energy transitions, heating systems are increasingly recognized as spatially embedded infrastructures that require careful geographic consideration. Unlike electricity, which can be transmitted efficiently over long distances, heating system is inherently local – heat transmission is strongly influenced by spatial parameters such as building density, land use, proximity to heat sources, and infrastructure layout. These factors affect the technical and economic viabilities of different heating solutions, and therefor need to be included in the planning processes and modeling frameworks used to guide the development of heating systems.

This section reviews how spatial aspects are addressed in the context of heating systems, from both the planning and modeling perspectives. Subsection 2.2.1 examines how spatial characteristics influence heat planning and the integration of energy considerations into urban development. Subsection 2.2.2 focuses on how spatial resolution is treated in energy systems modeling, particularly when analyzing heating systems at different geographic scales.

2.2.1 Spatial dimensions in energy planning

Energy transitions are inherently spatial processes, as the availability, distribution, and use of energy are all closely tied to the built environments and territorial characteristics of cities and regions [5,82]. Since the spatial characteristics of a city, region and country, such as the urban morphology, building typology, land use, energy demand density, and infrastructure layout, have substantial impacts on various aspects of the energy demand and the feasibility of different supply options, these aspects must be carefully considered when planning the energy transition [83–85]. Previous studies have emphasized the importance of coordinating energy planning with urban development, highlighting key features of the urban planning process that are commonly discussed in energy systems planning studies, including: spatial/zoning plans [86–91]; building density [86]; land use [86,92]; urban morphology [86,93,94]; and building information [86,88,91,92,95]. Dab'at and Alqadi [96] have showed that urban form decisively influences energy performance. Similarly, Esfandi et al. [86] have called for greater coordination between spatial and energy planning due to their strong interdependencies. Broto et al. [82] have further stressed that spatial scale and local physical contexts play critical roles in shaping urban energy transitions. Overall, the integration of spatial and energy planning remains a growing area of research, as evidenced by the diverse perspectives and analyses presented in systematic reviews, such as [87,97].

A spatial perspective is particularly crucial for heat planning. The costs of the heat network infrastructure are strongly influenced by spatial elements, such as linear heat density, distance to heat sources, and pipeline lengths [89,98–100], making it essential to understand the spatial pattern of heat demand when planning communal heating systems. Spatial arrangement is equally important for the placement of individual heating technologies. From the local planner's perspective, both individual and collective systems must be considered together, to achieve economically and environmentally optimal outcomes while satisfying the heat demand.

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 [83]. This is in line with the findings of Nadin et al. [101], who have 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.

2.2.2 Spatial dimensions 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 [102]. In this thesis, the spatial dimensions are understood as intra-regional variations in the physical, infrastructural, or demographic properties, such as building types and density, technology siting constraints, available resources, or existing energy infrastructure, that affect energy system design and operation than that defined by administrative boundaries. The focus of this thesis is particularly on heating systems, but relevant insights are also drawn from broader electricity or energy system studies where spatial dimensions significantly influence model outcomes. Table 2.1 presents the previous energy systems modeling studies that have investigated how differences in spatial properties between different geographic areas within the model scope impact the results of energy systems modeling. The selected studies in Table 2.1 go beyond administrative disaggregation by considering spatially explicit parameters that influence system configuration and outcomes. While not all studies focus exclusively on heating systems, each includes a spatial component relevant to the energy system being modeled. A review carried out in [103] has further emphasized the importance of incorporating spatial detail into energy system models, identifying various approaches and highlighting their implications for policy-relevant insights.

Table 2.1. Selected previous energy systems modeling studies that included the spatial dimensions of the energy system. These studies have addressed factors such as technology choices, renewable resource availability, demands, and emissions, with outputs that include optimal system configurations, expansion potentials, and spatial representations of various parameters.

Source	**System boundary**	**Model**	**Considered spatial dimension**	**Output related to spatial analysis**
Spirito et al. [104]	National heating system	Oemof open source optimization model	· Spatial distribution of heat demand, sources, and current individual heating technologies	Spatial distribution of DH potential at neighborhood level
Persson et al. [105]	EU DH system	Energy system modelling combined with GIS spatial mapping	· Regional ratio between heat demand and excess heat volumes · Distribution, concentration of heat demand centres, DH systems, and excess heat	Identification of heat synergy regions (Expansion, New development, Refurbishment regions)
Kumar et al. [106]	City DH system	Geospatial and Open-source cost-optimization (OSeMOSYS) model	· Distance between excess heat sources and existing heating grid	Cost-optimal locations for DH extension and urban excess heat sources
Fichera et al. [88]	Urban neighborhood	GIS database combined with a linear programming optimization model	· Mapping and classification of electricity consumption in buildings · Accounting for rooftop orientation, typology, available area for PV · Threshold distance of feasible links to electricity networks	· Optimized configuration of electricity network links · Design of the network of energy exchanges · Identification of hub buildings
Collaco et al. [93]	City energy system	LEAP urban energy simulation model	· Accounting for urban form (population, building density), · Spatial distribution of building and transport infrastructure	· Energy savings and GHG reduction 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%)

Pappis et al. [107] Moksnes et al. [108]	National electricity supply system	OSeMOSYS model and geospatial electrification planning tool (OnSSET)	· Accounting 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 lighting	· The population connected per technology option · Visualization of the most cost-effective electrification option
Lombardi et al. [109]	National energy system	Application of MGA (Modeling to Generate Alternatives) to a cost-optimization model (Calliope)	· Accounting 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
Meha et al. [110]	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
Kumar et al. [111]	An industrial park	Mixed integer linear optimization model that minimizes the length of the grid, and OSeMOSYS model	· Accounting for pipe routing, thermal loss, and network cost calculation	· The least-distance grid network solution, including the length and capacity of each pipe · The network solution is determined using a road network graph retrieved from Open Street Maps (OSM)
Wyrwa [112]	City residential heating system	Mixed integer programming with GIS-based tool using geo-referenced dataset for buildings	· The geo-referenced datasets that include buildings' boundaries, types, location, number of floors, heating technologies	· Spatial distribution of emissions

	· Spatially determined constraints

DH, district heating; DHW, domestic hot water; PV, photovoltaics; RES, renewable energy sources.

As illustrated in 2.1., incorporating spatial dimensions into energy systems modeling enhances the ability to capture local variations in demand, resource availability, and infrastructure characteristics. This added spatial resolution supports more-realistic and policy-relevant insights by allowing the model to reflect geographically specific conditions. It can reveal regional differences in system performance, identify the optimal locations for technologies, and guide targeted investments. As the need for place-based energy strategies grows, especially in the context of urban decarbonization, spatially resolved modeling is becoming an increasingly valuable approach for both research and planning endeavors. However, relatively few studies focus specifically on urban heating systems while simultaneously addressing spatial variations in urban area and existing energy infrastructure. Based on this understanding, this thesis develops a spatially resolved modeling framework tailored to the local heating system context, thereby provides policy-relevant insights for urban decarbonization strategies.

2.3 Participatory approach in energy systems modeling

Local authorities exert authority over many aspects of 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 sides [113]. There is a growing body of the literature that applies a participatory approach to energy systems research [114–117], including works that discuss the advantages of such an approach [118,119].

Wilson et al. [114] and Burg et al. [120] have employed Integrated Assessment Models (IAMs) and Agent-Based Modeling (ABM) approach, which are co-created by modelers and participants to increase the relevance and credibility of the modeling results. Bertsch and Fichtner [115] and Dean [121] have considered multiple targets and preferences of different stakeholders in the energy sector by applying Multi-Criteria Analysis (MCA), while Hewitt et al. [116] have used a land-use model accompanied by participatory scenario planning. Krzywoszynksa et al. [122] have adopted a prototype model that is built from scratch while collaborating with community members, while Simoes et al. [123] have combined quantitative energy systems modeling and MCA based on participatory scenario development. Bernardo & D'Alessandro [124] have used a participatory system mapping approach to generate a causal structure of the studied system, through meetings with local administrators and officials. The outcome is thereafter applied to system dynamics modeling for quantitative analysis. The research studies described in [118,119] did not include stakeholders in the modeling process itself, but instead 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 have been highlighted as crucial for an efficient energy transition [116,125,126]. Another benefit of the participatory approach lies in its ability to enhance 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 [127]. By engaging external stakeholders in the modeling procedure, the collaboration between researchers and those responsible for making decisions can be enhanced [128].

McGookin et al. [129] 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 processes. 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 identified during the energy systems modeling.

However, several studies have also pointed to challenges in effectively integrating stakeholder input. One common issue is that there may be a tendency to limit designing scenarios and model assumptions to conditions perceived as realistic or acceptable under current political or institutional landscape, potentially overlooking more transformative or long-term alternatives [130]. This can reduce the model's ability to challenge prevailing assumptions or explore disruptive transitions. Moreover, participatory modeling also faces challenges in sustaining collaboration across diverse actors. Forming a balanced group with varied expertise and knowledge types is often limited by project constraints and facilitation costs [131,132]. Disciplinary differences and the complexity of the modeling process itself may also act as a barrier to meaningful participation, requiring careful facilitation to avoid passive involvement [133]. Therefore, while participatory modeling holds promise for improving the relevance and uptake of energy system analysis, it also requires critical reflection on who participates, how participation shapes model content, and what is excluded as a result.

Awareness of the importance of involving stakeholders in the modeling process is increasing. However, in practice, stakeholders and the public are often still excluded from the core modeling process, with their involvement typically limited to early-stage inputs or final-stage consultation [134]. Moreover, recent reviews of energy systems modeling have emphasized technical developments while overlooking the importance of stakeholder and public inputs [135]. This misalignment between model development priorities and the needs of end-users, e.g., policymakers, highlights the need for deeper stakeholder engagement, not only in providing input data but also in shaping the research design and modeling goals [119]. 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. Addressing this gap, the thesis adopts a participatory modeling approach that engages stakeholders throughout the modeling process, particularly municipal planners, not only as data providers but also as active contributors to model framing and scenario development. This aims to improve the policy relevance and practical value of the modeling results.

2.4 Overview of studied areas

In the Nordic countries, heating plays a central role in energy planning due to the cold climate, strong municipal involvement, and long-standing DH infrastructure. The Nordic region has historically emphasized energy security, local resource use, and coordinated planning, fostering the early development of DH as a cornerstone of urban heating systems [136,137]. This study applies the proposed methodological approaches, which include spatially resolved energy systems modeling and stakeholder engagement, to three case studies: two Danish municipalities and one Swedish city, with the latter not involving a participatory approach. These Nordic cases are selected not only for their well-established DH systems, but also because the cold climate in the region creates significant and consistent heating demands, making space heating a central component of local energy systems. In both Denmark and Sweden, DH has historically played a key role in urban energy provision, supported by favorable policy frameworks and a high degree of public acceptance. These cases allow for a focused yet comparative exploration of how spatial and strategic factors shape cost-effective and context-specific pathways for heating decarbonization.

Denmark's DH sector has long been recognized as a leader among the global DH community. Early and systematic planning efforts have resulted in an extensive DH network that currently serves around two-thirds of all Danish households, which is one of the highest penetration rates globally [138]. The gas grid in Denmark, linked to supplies from the North Sea and Germany, has enabled the widespread development of gas-fired CHP plants nationwide [15]. The two Danish municipalities chosen are Lyngby-Taarbæk and Holbæk Municipalities. Lyngby-Taarbæk Municipality, located in the northern suburbs of Copenhagen, has a population of 58,713 as of Year 2025 and a population density of around 1,500 people per km². About 60% of buildings currently use individual natural gas boilers for heating. A heat plan approved in early 2022 outlines the expansion of DH in dense, high-demand areas to reduce fossil fuel use and support the municipality's goal of net-zero emissions by Year 2050. Holbæk Municipality, located in eastern Zealand, spans 583 km² with a population of about 74,490 as of Year 2025 and a population density of around 130 people per km². The heat supply relies heavily on individual gas boilers, meeting 77% of the demand, while DH covers around 20%, largely from gas-fired CHP. To align with national and local climate goals, Holbæk aims to reduce CO_2 emissions by 70% by Year 2030 compared to Year 1990, requiring a roughly 50% cut across all sectors, including heating.

Currently, most of the municipalities operate DH systems in Sweden [139]. Sweden's DH sector has developed along a different path than Denmark's, shaped by access to biomass and waste resources, as well as supportive policy measures. Carbon taxes introduced in the 1990s made fossil fuel-based heat generation expensive, while biofuels such as wood waste, biogas, and waste incineration remained exempt [140]. The synergy with Sweden's forest and paper industries, along with the 2000s landfill ban, further accelerated the use of biomass and waste incineration in DH systems [41]. For the Swedish case study, the city of Gothenburg (including the Mölndal municipality) is chosen where 90% of all buildings are connected to a DH system supplied mainly by refinery excess heat and waste incineration. Sweden has a similarly high share of DH to Denmark, especially in urban areas. The total supply share of DH in Sweden is over 50% and 64% in Denmark [141]. Unlike Denmark, the Swedish DH system is more market-based, with varying degrees of municipal and private ownership [139,142]. Swedish DH systems have successfully integrated biofuels, waste incineration, and excess heat from industrial sources [143]. Since fossil fuels account for less than 2% of total heat production in Sweden's DH sector, their contribution to overall greenhouse gas emissions is relatively small. Instead, waste incineration, which is responsible for about one-fifth of the heat supply, accounts for the majority of the carbon emissions. Table 2.2 presents a comparative overview of the three study areas, Lyngby-Taarbæk, Holbæk, and Gothenburg, highlighting the key characteristics relevant to modeling studies. These include population density, current heating system, heating plan, local specificities, and DH ownership.

Table 2.2 Overview of the three case study areas and key characteristics relevant for heating system transitions [144–146].

Country	Denmark		Sweden
Municipality	Lyngby-Taarbaek (LTK)	Holbaek	Gothenburg (including Mölndal)
Classification	Urban	Semi-rural	Urban
Area (km²)	39	583	448
Population density (people/km²)	1500	130	1400
Current heating system	48% DH, 45% natural gas, 3% individual HPs, 2% oil, 2% others	10% DH, 56% natural gas, 7% individual HP, 8% oil, 8% biomass, 11% others	90% DH for larger buildings, and 20% DH for smaller single-family houses. Rest is

			electricity, either directly or with HPs.
Heating plan	· 98% of DH based on industrial WH, wastewater heat, large-scale HPs by 2030, and HPs for the areas without DH connection · CO_2-neutral heat supply by 2035	100% reduction in greenhouse gas emissions from heating by 2030	Fossil-free heating and electricity from 2026.
Local specificities	· Heating is the largest contributor to CO_2 emissions in the LTK (40%). · A number of green DH sources identified that can be utilized with HPs, e.g., wastewater and sludge incineration, groundwater, seawater, industrial WH	· Potential to use excess heat available in Kaludborg Symbiosis ·Dispersed heat demand points ·There are three small DH towns scattered in the HK.	· One of main industrial cities in Sweden · No big expansions planned, as the network already covers most of the city · 75% of district heat supply is waste heat.
DH company ownership	Municipally owned	Two of the three DH towns are municipal supply and one community-owned and operated as a cooperative	Municipally owned

3 Method

This chapter outlines the methodological approach taken to develop integrated, city-level energy system models, with a particular focus on a spatially explicit representation of heating systems. The methodology builds on two complementary modeling approaches, each contributing to distinct analytical perspectives: one emphasizing long-term, strategic system transitions and actor-oriented insights using the TIMES model; and the other focusing on technically detailed and high-resolution city energy system optimization using a model developed in this work. The chapter is structured into three subsections. Subsection 3.1 describes the application of the TIMES modeling framework, highlighting its suitability for long-term scenario analysis and participatory planning.. Subsection 3.2 presents the internally developed optimization model, emphasizing the technical details, spatial representation, and electricity system integration. Finally, in Subsection 3.3, a comparative analysis summarizes the strengths and limitations of both modeling approaches, offering reflections on how they complement each other and contribute to a more- comprehensive understanding of urban energy system transitions.

3.1 Spatially explicit participatory methodology – Papers I – III

This section provides a summary of the methodology developed using the TIMES modeling framework. Each step of the methodology is explained, followed by a detailed description of the modeling procedure and the cases to which the methodology is applied.

3.1.1 Spatially explicit participatory modeling methodology

Figure 2.1 outlines the aims, approaches, and outputs of the five modeling steps that incorporate stakeholder dialogues as an integral part of the methodology applied in **Papers I – III**. Throughout the process, municipal stakeholders (i.e.,energy and urban planners) contribute inputs, feedback, and contextual knowledge relevant to their local setting. Their participation was facilitated through semi-structured interviews, email correspondence, online meetings, and workshops. An overview of the conducted interviews, including anonymized identifiers (Interviewee A, B, etc.), the interviewees' roles, and the dates of the interviews, is provided in Appendix A. As such, the successful application of the participatory approach depends on the engagement and active involvement of these key 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 2.1. Steps used in the methodology. EP, Energy planning; UP, Urban planning.

Step 1 (Reviewing the planning processes) is a preparatory step that aims to explore and clarify the linkages between urban spatial planning and heat planning within the context of a municipality. To gain insights into how these two planning domains are practiced and whether, or how, they intersect at the municipal level, a series of planning-related questions were posed to municipal planners. The interviewees consisted of municipal staff who were directly involved in energy, heat, and urban planning processes[1]. **Step 2** (Inclusion of spatial features) divides the municipality into smaller geographic units, referred to as 'districts[2]', so as to enable spatially detailed energy system modeling. The division is based on heat demand density, building characteristics (e.g., type, size, age), urban spatial plans, and inputs from municipal planners. These factors influence the energy performance and heating technology suitability. Spatial plans, construction projections, and heating technology statistics were used as inputs. Stakeholders also identified their information needs and preferred types of model outputs to support decision-making. **Step 3** (Scenario formulation) is a central component of this work, shaping the modeling context to align with municipal plans and priorities. Multiple heating transition scenarios were developed based on discussions with municipal planners through interviews, workshops, and email exchanges. These dialogues addressed local climate targets, technology preferences, national policies, investment plans, and spatial constraints. A scenario structure was provided to guide these discussions (see Appendix D). The outcomes, which included CO_2 targets and the technological pathways identified during the participatory process, were translated into model inputs, including constraints, parameter settings, and selectable scenario elements.

[1] For the interview materials including questionnaires used in the interviews, see Appendix C.

[2] In this methodology, the term 'districts' is used interchangeably with the 'new districts', '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.

The methodology requires a model that captures long-term energy system development in line with municipal emissions targets. In **Step 4** (Energy systems modeling), key input data and assumptions were reviewed and adjusted through dialogue with energy and urban planners. The TIMES (The Integrated MARKAL-EFOM System) optimization model is adopted and executed in this methodology (see Section 3.1.2 for modeling description). The aim was to enhance the transparency, legitimacy, and practical relevance of the spatially explicit results for municipal planning. Finally, in **Step 5** (Evaluation of modeling outcome), the modeling results, such as the generation and capacity mixes across the scenarios, were presented to municipal planners for feedback. Their inputs were used to refine the model in an iterative manner, ensuring good alignment with local needs and priorities.

3.1.2 Cost optimization and the spatial dimension in participatory modeling

Energy systems optimization modeling provides valuable insights into how energy systems can transition to meet different targets under varying assumptions, making it a key tool for analyzing system dynamics and policy impacts [147]. These models use decision variables such as generation capacities and dispatch, while the constraints reflect technical, environmental, and economic limitations, as well as policy goals. Figure 3.2 presents a conceptual diagram of the modeled heating system, highlighting the main parameters and distinguishing between individual and DH technologies.

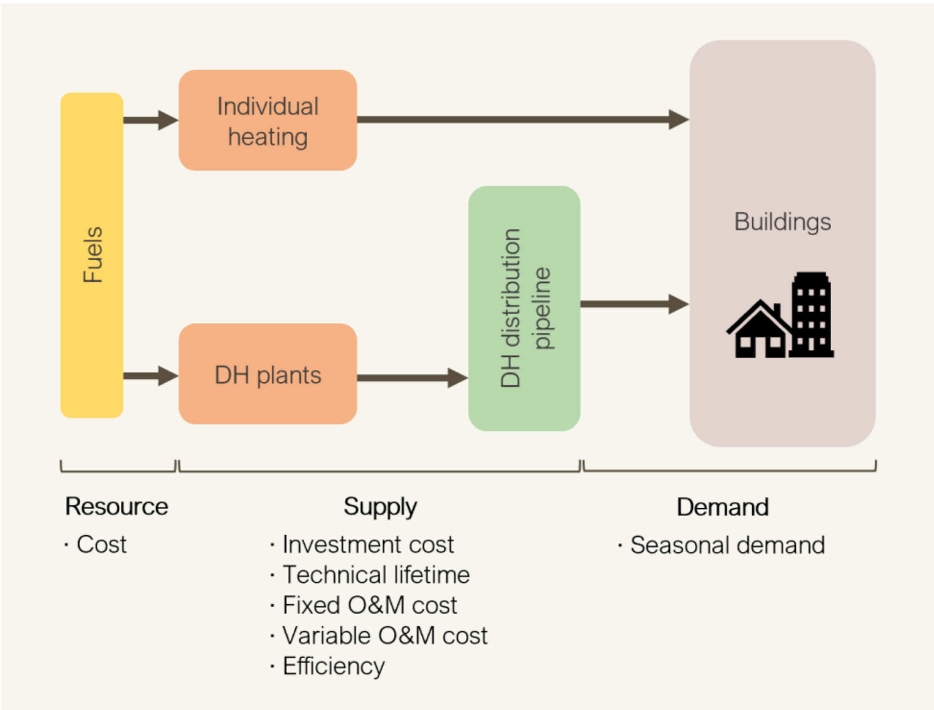

Figure 3.2. Schematic of the heating system and related model parameters in this methodology. DH, district heating; O&M, operation and maintenance. Individual heating directly supplies heat to buildings, while DH systems require insulated pipeline systems to distribute heat using water as the medium. The investment cost for DH distribution pipelines increases with distances from the heat generation and existing pipelines to the heat demand in the buildings

This thesis employs the TIMES (The Integrated MARKAL-EFOM System) model and an internally developed optimization model. The TIMES model is a linear programming framework designed to minimize total system costs over a defined time horizon [148]. TIMES operates with perfect foresight and is demand-driven, such that it ensures that the exogenous electricity and heat demands are met in each modeled time-slice. Although TIMES can represent both electricity and heating systems, this study focuses exclusively on the heating system, entailing modeling heat demands and heating technologies, while treating electricity as an externally supplied input. Electricity produced by CHP plants is assumed to be sold to the national grid and included as an economic benefit. Scenario constraints, such as net-zero CO_2 targets, are also incorporated. The model outputs include the dispatch of heating technologies, optimal investment strategies, total system cost, and emissions.

To account for spatial variation, the model incorporates district-specific pipeline investment costs that reflect the distance from each demand point to the existing DH network. The notation 'r (region)' in the objective function represents the 'districts' defined in Step 2, enabling the modeling of spatially distinct sub-systems. The input data include techno-economic parameters for technologies, commodities, and resources, along with time-resolved heat demand data. These inputs are specified separately for each district, ensuring that the heat demand profiles, technology options, and cost parameters reflect local conditions. Consequently, the objective function [Eq. (1)], which minimizes the total system cost over the modeled time horizon, is expressed as the aggregate cost across all districts.

$$OBJ(t) = \sum_{r} \sum_{y} \left(1 + d_{r,y}\right)^{REFY-y} \cdot \left[\begin{array}{c} (c_p^{inv} + c_p^{fixOM}) \cdot \sum_{p} C_{p,v,r} \\ + (c_p^{varOM} + c_p^{fuel}) \cdot \sum_{p} G_{r,t,p} + c^{other} \end{array} \right] \quad (1)$$

The term $d_{r,y}$ represents the discount factor applied for each region r and year y, relative to the reference year ($REFY$). The capital investment costs and fixed operation and maintenance (O&M) costs are calculated per unit of installed capacity $C_{p,v,r}$, weighted by the corresponding unit costs c_p^{inv} and c_p^{fixOM}. The variable costs are determined by the amount of heat generated $G_{r,t,p}$ multiplied by the variable O&M cost c_p^{varOM} and fuel cost c_p^{fuel}. A general cost term c^{other} accounts for additional system-level costs, such as taxes, subsidies, and revenues from electricity export. In addition to the main system constraints [Eqs. (2) and (3)], the model includes specific constraints related to emissions targets, a prohibition on natural gas use, a carbon dioxide (CO_2) tax, and, in selected scenarios, a subsidy for HPs[3]. The subsidy is applied only in scenarios where policy support for HP adoption is explicitly assumed, reflecting the existing national scheme.

$$\sum_{p} G_{r,t,p} \geq D_{t,r} \quad (2)$$

$$G_{r,t,p} \leq C_{p,v,r} \quad (3)$$

In Eq. (2), $D_{t,r}$ denotes the heat demand in time-slice t for region r. A key aspect of integrating spatial considerations into the modeling framework is the use of linear heat density, which represents the annual heat demand per meter of DH pipeline. As proposed previously [36], linear heat density can be estimated using demographic indicators, such as population density and specific building floor area. This insight motivated the use of a plot ratio in the calculation of DH expansion investment costs in this study. The plot ratio, alongside the proximity to existing infrastructure and the linear heat demand density, is incorporated into the model by assigning differentiated investment costs for pipeline construction. These

[3] There is a central government subsidy scheme for 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 [173].

costs vary by heat transmission distance and the heat demand density characteristics of each district. A schematic of this spatial cost differentiation approach is shown in Figure 3.3.

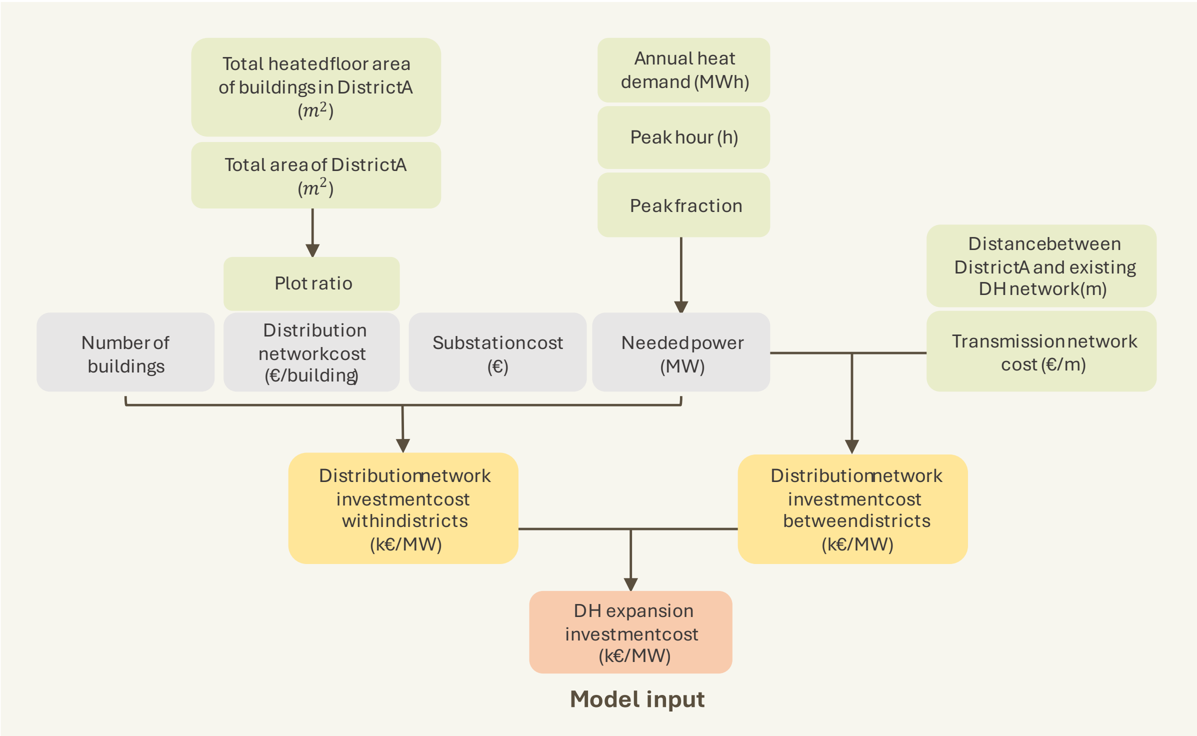

Figure 3.3. Investment costs for DH network expansion for District A. The cost components are used to calculate the investment costs for location-specific DH expansion.

3.1.3 Case studies

In the participatory modeling (**Papers I-III**), scenarios were co-developed with local stakeholders and thus constitute part of the research outcome. These scenarios reflect locally grounded priorities and were derived through an iterative engagement process, making them an integral component of the results.

The spatially explicit participatory modeling methodology is applied to two contextually different municipalities in Denmark: Lyngby-Taarbæk (LTK) Municipality, as an urban case and Holbæk (HK) Municipality, as a semi-rural case. Table 3.1 shows an overview of the settings and assumptions used in the model for the two 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 3.1. Summary of the model assumptions applied for the two cases investigated.

	Urban setting (Paper I-II) **LTK Municipality**	**Semi-rural setting (Paper III)** **HK Municipality**
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 (DH)	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.

3.2 Multi-node city energy system optimization – Paper IV

To explore the role of DH in future energy systems with potential industry electrification and and aging DH infrasturctures, **Paper IV** builds upon and further develops the city-level energy system optimization model originally developed by Heinisch et al. [12,13]. The present work contributes additional developments, namely: (1) the spatial disaggregation of the electricity and heating sectors through a multi-nodal representation and inter-nodal heat transport; (2) the inclusion of individual HPs as an alternative to DH; and (3) a physical representation of the DH network. For a detailed description of the modeling approach and scenarios, see the appended **Paper IV**.

3.2.1 Spatial disaggregation

Similar to the other studies in this thesis using the TIMES model, the city is subdivided into multiple regions, to enable a spatially resolved analysis of the heating system. This subdivision allows the model to account for differences in infrastructure, heat demand density, proximity to existing DH networks, and access to local energy resources. The limitations of the electricity and DH networks are captured using the spatial subdivisions of the modeled region. In this study, the focus is on a region encompassing the Swedish cities of Gothenburg and Mölndal, which share a connected DH system. As illustrated in Figure 3.4, heating nodes h1 to h6 correspond to areas within Gothenburg, while h7 represents the Mölndal heating node. The electricity system in the modeled region is represented by four electricity nodes, each corresponding to a transformer substation that links the 130-kV grid to the lower-voltage distribution levels.

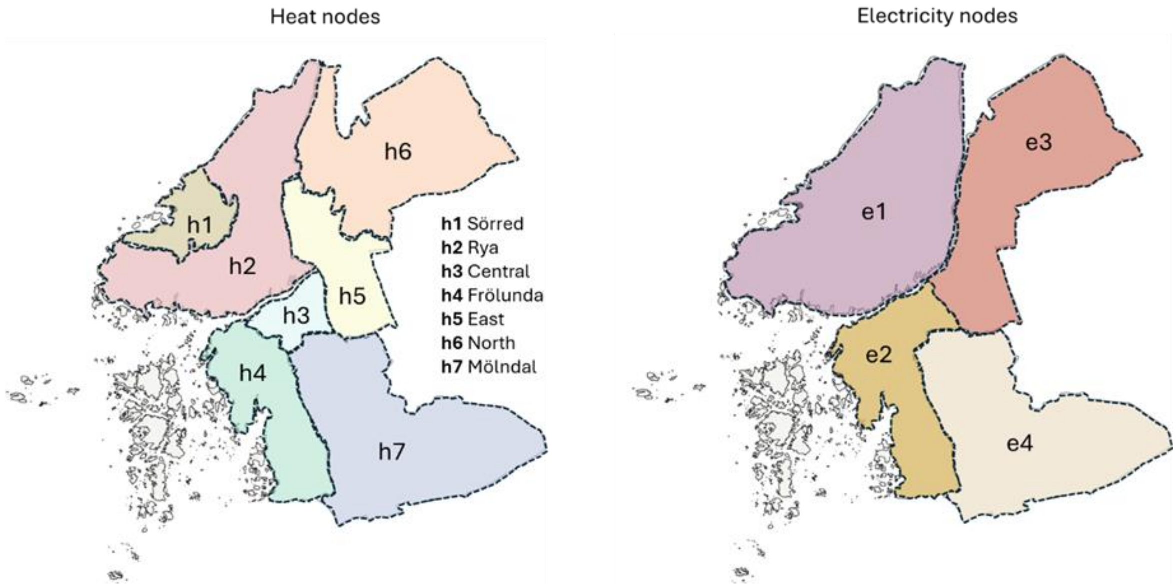

Figure 3.4. Spatial layout of the model's heat and electricity nodes for the Gothenburg and Mölndal region from **Paper IV**. The map on the left illustrates the DH network, with nodes h1 to h6 representing distinct areas within Gothenburg, and h7 corresponding to Mölndal. The map on the right shows the electricity network, where nodes e1 to e4 reflect the aggregated zones of electricity demand and supply across both cities.

Each node has hourly electricity, heat, and hydrogen demands, with interconnections allowing heat exchange between the heating nodes that is constrained by DH transmission capacities. Technologies that link electricity and heat, such as HPs and electric boilers, can only draw electricity from their corresponding electricity nodes. Electricity imports from the regional grid are allowed up to the local grid capacity. The heat demand in each heating node is disaggregated by building type into single-family houses (SFH) and multi-family houses (MFH) and can be met by either DH, which includes costs for transmission, distribution, and substations, or individual HPs, which include reinforcement costs for the electricity network. This building-level breakdown enables the evaluation of heating options while capturing the differing demand profiles. For both individual and large-scale HPs, the model uses temperature-dependent coefficients of performance (COP). The COPs of air- and ground-source HPs vary with heat source temperature, with higher temperatures yielding better efficiency. Daily air temperature data of Year 2019 for Gothenburg, obtained using Renewables.ninja web tool [149] are used to estimate dynamic COPs, following the functions descrbied by Staffel et al. [150].

The DH network is split into transmission and distribution pipes: transmission pipes link heating nodes, while distribution pipes deliver heat to end-users within each node. Each node's distributed heat includes both locally produced heat and heat that is imported via the transmission network. The model incorporates the current age structure of both the pipelines and production units. Refurbishment is applied only to the distribution network, as transmission lines are relatively new and are not expected to require upgrades by Year 2050. However, parts of the distribution network will have reached their technical lifetime by then, making refurbishment a key consideration in long-term DH planning. The existing capacities for transmission pipelines and production units shown in Figure 3.5 and Appendix E, are assumed to be still in place in Year 2050, aligning with realistic infrastructure lifetimes rather than favoring DH.

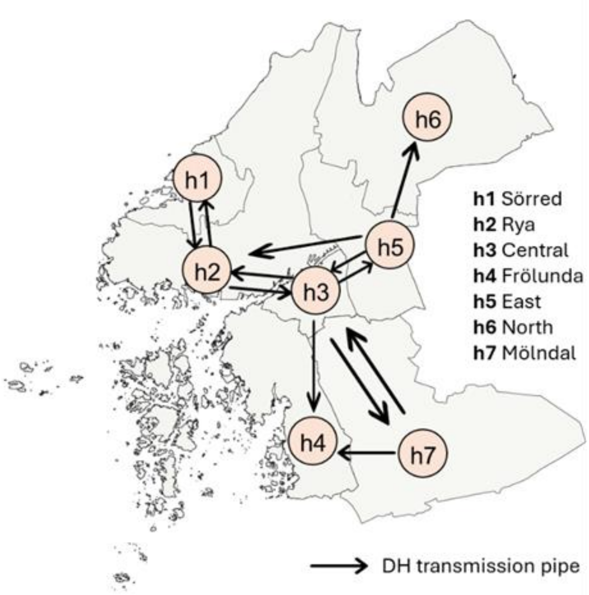

Figure 3.5. Spatial layout of the seven heating nodes, from **Paper IV**, for the subdivision of Gothenburg and Mölndal. The arrows indicate the DH transmission pipes connecting the nodes, illustrating the directions of potential heat flows in the modeled network.

Based on these assumptions, the model allows investment in new DH units while considering existing ones that are still functional by Year 2050. These existing units are included in the optimization, so the model may either continue using them or reduce their operational levels if better alternatives becomes available. This brownfield modeling approach, which accounts for infrastructure age, offers more realistic scenarios than greenfield approaches. It enables assessment of the economic viability of refurbishing aging DH distribution networks. Where DH is not cost-competitive, the model can instead invest in individual HPs, supporting disconnection from the DH network when economically justified.

3.2.2 City energy system optimization model

The model is formulated as a linear programming problem that aims to minimize the total system cost C_{tot}, which includes the costs of generating and importing electricity and heat, as well as investments in energy technologies and infrastructure, over a one-year time horizon, as expressed in Eq. (4):

$$C_{tot} = \sum_{p \in P} \left[\begin{array}{l} \left(C_p^{inv} + C_p^{OM_{fix}}\right) \cdot \left(\sum_{e \in N} I_{e,p}^{elec} + \sum_{h \in N} I_{h,p}^{heat} + \sum_{e \in N} \sum_{h \in N} I_{e,h,p}^{comb}\right) \\ + \sum_{t \in T} C_{p,t}^{var} \cdot \left(\sum_{e \in N} g_{e,p,t}^{elec} + \sum_{h \in N} g_{h,p,t}^{heat} + \sum_{e \in N} \sum_{h \in N} g_{e,h,p,t}^{comb}\right) \end{array} \right] + \sum_{t \in T} E_{e,t}^{imp} \cdot C_t^{el} + \sum_{h \in N} DHN_h^{dist} \cdot I_h^{dist} \quad (4)$$

where C_p^{inv} represents the investment cost of technology p, and $C_p^{OM\_fix}$ denotes its fixed O&M cost. The model considers the full set of time-steps T, nodes N (including electricity and heating nodes e and h), and technologies p. Installed capacities are defined as $I_{e,p}^{elec}$ for electricity generation technologies in electricity node e, $I_{h,p}^{heat}$ for heat generation technologies in heating node h, and $I_{e,h,p}^{comb}$ for technologies that relate to both heat and electricity (e.g., HPs, CHP plants, electric boilers). The variable generation costs at each time-step t are represented by $C_{p,t}^{var}$. Generation levels are constrained by installed capacities: $g^{elec}_{e,p,t}$ for electricity generation in node e; $g^{heat}_{h,p,t}$ for heat generation in node h; and $g^{comb}_{e,h,p,t}$ for combined generation across nodes e and h.

The model includes costs for electricity imports, DH network capacity, and investments in heat technologies. For individual HPs, electricity distribution reinforcements such as transformer upgrades are included in their investment costs [69]. Heat balances are maintained at every node and time-step, linking demand to local production, WH recovery, thermal storage, and heat exchanges between nodes. Individual HPs are modeled as decentralized solutions serving only local demand, with no possibility of network interaction, while DH technologies are connected through a multi-node structure that enables spatial interactions such as heat exports and imports. Thermal energy storage is represented with charging and discharging variables, allowing for temporal shifting of heat. Heat demand is further disaggregated by building type, and the model is solved at hourly resolution for a full year (2050). A full mathematical formulation of the cost terms, balance constraints, and technology sets is provided in the appended manuscript of **Paper IV**.

3.2.3 Transmission pipeline representation

The DH transmission system is represented as a network of interconnected heating nodes, where heat is exchanged via transmission pipelines. At each node, a heat balance is enforced to ensure that all inflows and outflows of heat are tracked consistently [(see Eq. (2)]. This nodal balance regulates the heat distribution within the system and links to the overall system-wide heat equilibrium. The flow of heat through the pipelines is subject to certain technical constraints, including pipe diameter, temperature levels, and mass flow rates. The amount of heat transported between nodes is determined by the calculated mass flow, which is based on the physical characteristicsThe heat transfer equation in the pipeline includes the product of two variables, mass flow rate and temperature difference, which results in a nonlinear expression. To maintain the model's linear structure and computational tractability, this relationship is linearized. This is achieved by splitting the heat transfer variable $Q_{pipe,t}$ into two separate variables, $Q1_{pipe,t}$ and $Q2_{pipe,t}$, as illustrated in Figure 3.6.

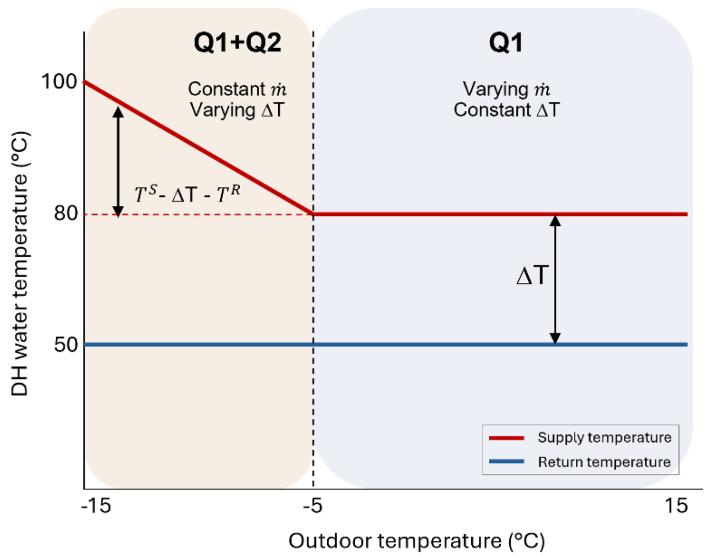

Figure 3.6. Schematic illustration of the linearization of the transferred heat variable $Q_{pipe,t}$ (from **Paper IV**), which is divided into two variables: $Q1_{pipe,t}$ and $Q2_{pipe,t}$. The division is based on outdoor temperature intervals, indirectly represented through the heat demand profiles in the model. $Q1_{pipe,t}$ corresponds to periods that are

associated with moderate demand (typically linked to outdoor temperatures between -5°C and 15°C), while $Q2_{pipe,t}$ corresponds to high demand periods (typically linked to outdoor temperatures between -15°C and -5°C).

In this formulation, *Q1* captures the portion of heat transfer where the water mass flow rate is treated as a variable and the temperature difference ΔT is held constant, defined by a fixed supply temperature (T^Sat 80°C) and return temperature (T^Rat 50°C). In contrast, *Q2* accounts for heat transfer under the assumption of a fixed mass flow rate, which is determined by the maximum velocity limit (v_{max} at 3 m/s), while allowing the supply temperature $T^S_{pipe,t}$ to vary within the range of 80C°–100°C. Figure 3.7 provides a schematic representation of the heat transfer computation for DH transmission lines that connect heating nodes *h_n* and *h_m*.

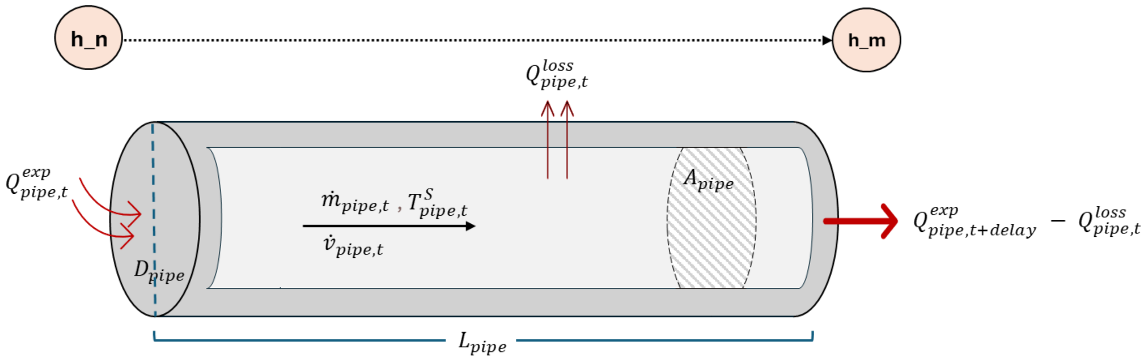

Figure 3.7. Illustration of the heat transfer from heating node h_n to h_m through a DH transmission pipe from **Paper IV**.

Eqs. (5) and (6) describe how the two components of total heat transfer, $Q1_{pipe,t}$ and $Q2_{pipe,t}$, are calculated. These quantities represent the heat conveyed through the DH transmission pipe from heating node *h_n* to *h_m*, where *cp* denotes the specific heat capacity of water.

$$Q1_{pipe,t} = \dot{v}_{pipe,t} \cdot \rho \cdot A_{pipe} \cdot cp \cdot \Delta T \quad (5)$$

$$Q2_{pipe,t} = v_{max} \cdot \rho \cdot A_{pipe} \cdot cp \cdot \left(T^S_{pipe,t} - \Delta T - T^R\right) \quad (6)$$

To ensure realistic and technically feasible heat transfer within the network, further constraints are applied. These include upper and lower bounds being imposed on the flow velocity and supply temperature, as well as energy balance requirements that must hold across all interconnected heating nodes. The full mathematical formulation, including the linearization procedure and loss functions, is provided in the appended manuscript of **Paper IV**.

3.2.4 Scenarios

In contrast to the participatory modeling approach in Section 3.1, the optimization-based approach applied in **Paper IV** relies on pre-defined scenarios formulated by the authors, which is standard practice in techno-economic energy systems modeling studies. Here, the scenarios serve as input assumptions to explore system behaviors under different future conditions and are therefore presented in the methodology section.

To explore the effects of different distribution network refurbishment rates and levels of WH availability, three WH availability levels are combined with three annual refurbishment rates, along with a reference case that assumes no refurbishment. Each scenario refers to a set of three refurbishment cases under the same WH availability assumptions. The WH sources include excess heat from the St1 and Preem refineries in Rya, and the Renova waste incineration plant in East. These facilities supply heat either as industrial byproducts or from waste combustion processes. Table 3.2 presents an overview of the modeled scenarios.

Table 3.2. The scenarios used in the modeling of this work from **Paper IV**. The WH availabilities from the refineries refer to contributions from both the St1 and Preem refineries.

Scenarios (**Paper IV**)	Waste heat availability (GWh/y)	DH pipe refurbishment rate (%)
Reference case	Refineries 1112 Waste incineration 1375	No refurbishment
Current WH level	Refineries 1112 Waste incineration 1375	0.2 0.4 0.6
No refinery WH	Refineries 0 Waste incineration 1375	0.2 0.4 0.6
Reduced WH level	Refineries 376 Waste incineration 797	0.2 0.4 0.6

The reference case represents Year 2050, assuming no need for DH network refurbishment and maintaining the current level of WH availability. For all the other scenarios, three levels of WH availability, reflecting potential changes in supply from refineries and the waste incineration plant, form the scenario basis.

In the Current WH level scenario, the WH supply from the St1 and Preem refineries remains unchanged, contributing 595 GWh/yr and 517 GWh/yr (68 MW and 59 MW at peak capacity), respectively. The Renova incineration plant supplies 1,375 GWh/year witht a peak capacity of 157 MW. In the No refinery WH scenario, both refineries are assumed to shut down to meet carbon-neutrality goals. Only the Renova plant remains, still providing 1,375 GWh/year (157 MW at peak). This results in a 45% reduction in the total WH supply. The Reduced WH level scenario reflects future reductions in the levels of WH from both refineries and waste incineration due to increased electrification and hydrogen production (5 TWh/year). Waste heat levels from the St1 and Preem refineries drop to 175 GWh and 201 GWh (20 MW and 23 MW at peak), while Renova's supply decreases to 797 GWh (91 MW), assuming that plastic waste is diverted to a recycling plant in Stenungsund. Overall, this scenario reflects a 53% reduction of WH.

Each WH scenario is combined with three annual DH refurbishment rates of 0.2%, 0.4%, and 0.6%, corresponding to replacing approximately 5%, 10%, and 15%, respectively, of the network by Year 2050. These rates represent increasing levels of infrastructure reinvestment, replacing the oldest pipes (aged 90, 85, and 80+ years, respectively) and enabling assessments of long-term refurbishment strategies for DH system evolution.

3.3 Comparison of the two methodological approaches

The modeling work carried out in this thesis builds upon two distinct, yet complementary methodological approaches. By employing both the TIMES framework and an internally developed city model, the research captures different dimensions of energy system planning: strategic long-term development combined with actor-oriented insights; and detailed technical modeling with high spatial and temporal resolutions. To summarize the key differences and the added values accured from the two approaches, Table 3.3 provides a comparative overview of the TIMES and the city model developed in this work.

Table 3.3. Overview of key differences between the TIMES model (**Papers I–III**) and the city energy system model (**Paper IV**) in terms of objectives, scope, resolution, and system representation.

	TIMES model (Papers I-III)	City model (Paper IV)
Objective	Minimize societal cost to meet the demand for heating	Minimize societal cost to meet demand for electricity and heating
Modeling approach	Actor-oriented participatory approach	Technically detailed approach
Spatial resolution	District or Building-type level	Building-type level
Temporal resolution	Multi-year, seasonal resolution	Single year, Hourly resolution
Sector representation	Heating system	Heating and electricity system
Actor perspective	Integrated through participatory modeling	N/A
Optimization type	Linear programming, cost minimization	Linear programming, cost minimization
Cases	Denmark, urban and semi-rural cases	Sweden, urban case
Electricity system representation	Electricity is an imported/exported commodity	Co-optimized in parallel
DH network	Simplified representation	Physical representation
Heat transport between districts	N/A	Heat import/export through network

The TIMES modeling approach primarily focuses on long-term heating system transitions, emphasizing the importance of strategic decision-making over multiple decades and supporting the exploration of diverse future pathways through scenario analysis. The scenarios are developed in collaboration with local actors such as municipal planners and utilities using participatory modeling processes. In this way, the model captures locally relevant assumptions and priorities, even though the scenarios themselves are externally specified rather than endogenously generated by the model. This approach allows for the exploration of potential path dependencies and lock-in effects, highlighting how early technology or infrastructure choices might constrain future options. In contrast, the city model focuses more on the technical and operational aspects of urban energy systems. It integrates physical representations of the DH networks into a multi-node model, and resolves on an hourly basis for a single year system operation. This enables the capture of system flexibility needs, and the interactions between heating and electricity sectors. While the city model is less centered on actors' perspectives or long-term pathways, its technical granularity offers valuable insights into how infrastructure aging and operational flexibility influence the future urban energy system.

Reflecting on the combination of these two approaches, it is clear that both perspectives are necessary to understand city-level energy transitions, in thatthe TIMES model highlights how strategic and actor-driven decisions shape long-term outcomes, while the city model shows the operational realities and technical system dynamics that such decisions must consider. However, each approach also has limitations. The TIMES participatory modeling, while valuable for grounding scenarios in local knowledge and institutional priorities, may risk locking into what is currently perceived as likely or acceptable despite the fact that these perceptions can change rapidly. On the other hand, the technically-detailed city model may overlook important social, political, or institutional factors, and thus propose cost-optimal solutions that are difficult or impossible to implement in practice.

4. Main results

This chapter presents the main results of the thesis, drawing on the two complementary methodological approaches applied across different geographic and institutional contexts as described in Chapter 3. The first approach is the participatory energy systems modeling framework based on the TIMES model, applied to two Danish municipalities, one urban (**Papers I** and **II**) and one semi-rural (**Paper III**). The second approach is the technically detailed city energy system optimization model implemented for the Swedish city of Gothenburg (**Paper IV**).

Although the two approaches differ in terms of structure, purpose, and level of detail, in that one focuses on stakeholder engagement and long-term planning processes, while the other involves high-resolution techno-economic modeling, together they investigate cost-effective and spatially resolved heating transition strategies. While the participatory modeling method comprises five steps (see Section 3.1.1), the results are not presented according to this stepwise structure. Instead, to facilitate comparisons and synthesis, the results are organized across shared analytical dimensions, namely, system-level outcomes, spatial variations, and building-type-specific insights. This structure enables a more-cohesive narrative and facilitates the integration of findings from both methodological approaches. This section is structured as follows:

· Results from participatory modeling (Urban case, **Papers I** and **II**)
· Results from participatory modeling (Semi-rural case, **Paper III**)
· Results from city energy system optimization model (Urban case, **Paper IV**)

4.1 Results from participatory modeling – Urban case (Papers I, II)

The interviews with municipal planners in the Danish case municipalities revealed weak integration between the actors dealing with urban spatial planning and those involved in heat planning. Both urban and heat planners noted a lack of effective tools and processes for exchanging information across departments, which they viewed as a barrier to strategic, coordinated planning (see Section 3.2 in **Paper I**). This lack of integration hinders their ability to engage effectively with building developers. The discussions with urban planner and heat planners from the case municipality in **Papers I** and **II**, further revealed that urban planners currently lack the tools that would allow them to integrate energy considerations into urban development processes. Given the strategic importance of DH in Denmark's energy landscape, one planner (Interviewee B) emphasized the need to divide the municipal territory into designated zones, that align with the spatial planning, so as to support the identification of priority areas for DH expansion within the municipality.

Interviewees B and D also emphasized that equipping urban planners with knowledge about appropriate heating options for different zones would improve communication with developers and enable more informed choices during the planning process. This issue has gained new urgency following a Year 2019 change to national policy that removed municipalities' authority to mandate DH connections for new buildings. As a consequence of this change, municipalities can only advise developers on available heating solutions. As Interviewee C noted, this shift increases the need for accessible and actionable information about heating options to guide such recommendations. In their professional role, municipal planners are generally expected to provide technology-neutral guidance, although individual preferences were not explicitly discussed in the interview. Recognizing this gap between planning domains motivated the formulation of criteria later applied in the present study to define the district boundaries for spatial heat planning.

4.1.1 Spatial mapping and scenarios

In this section, the spatial mapping process carried out in **Paper I** is described. The methodology for combining multiple spatial datasets and municipal input is outlined, and the resulting district structure is presented in relation to its role in the modeling framework. To enable implementation in the spatially resolved model in **Paper II**, as shown in Figure 4.1, the LTK municipality was subdivided into districts based on an overlay of three data sources: (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) the current heating supply technologies (see Appendix B).

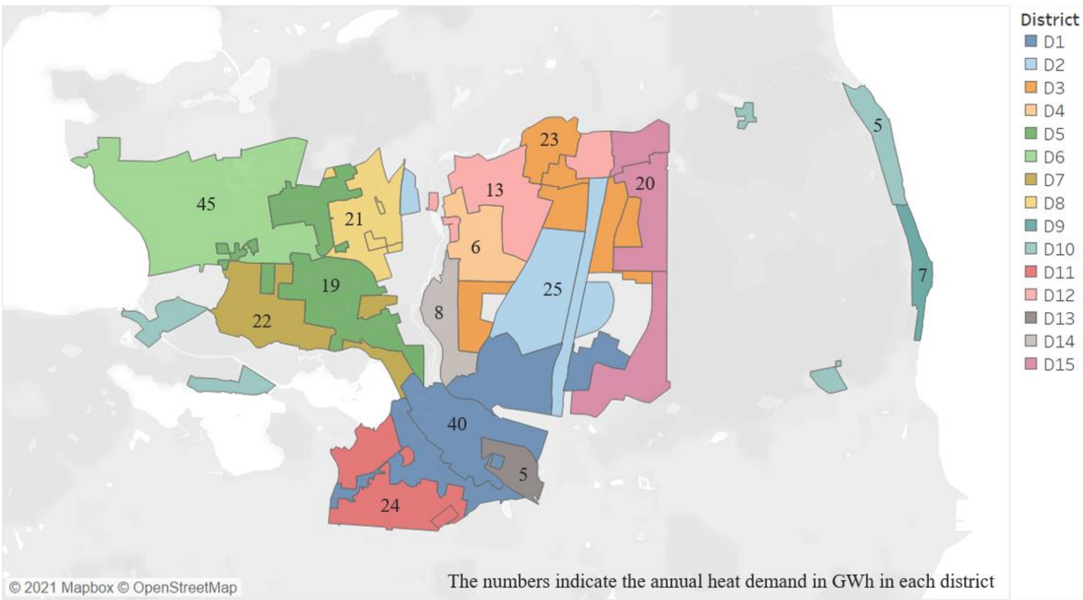

Figure 4.1. The districts identified in Step 2 from **Paper I**. The various colors indicate the different districts (D1–D15) identified by applying Step 1 to 3. The numbers on the map indicate the annual heat demand of buildings in GWh in each district. Districts D1–D5 are connected to DH, and districts D6–D15 use natural gas for heating.

The boundaries were overlaid to identify all unique intersections, representing the smallest possible spatial units given the three data sources. Next, adjacent areas with the same neighborhood and the same heating supply type were merged to form larger, coherent districts suitable for modeling. Merging was necessary to avoid impractically small zones and to ensure each district had a consistent heating supply profile for modeling purposes. In parallel, inputs from municipal planners were used to align the number of districts and the division criteria with local planning preferences. This process was carried out in **Paper I**, resulting in the delineation of 15 districts, representing both administrative and heating supply characteristics, as illustrated in Figure 4.1.

The participatory approach played a significant role in shaping the technology choices applied in the scenarios, ensuring that the modeling work reflected the local context. Notably, bio-based heating technologies were excluded from the model in response to the municipality's concerns regarding local air pollution levels.

Table 4.1 provides an overview of the investment options and parameters in the scenarios. All six scenarios are designed to meet the municipality's climate targets: a 25% reduction in CO_2 emissions by Year 2025 (relative to Year 2018 levels) and net-zero emissions by Year 2050. As of Year 2023, the most recent available data indicate that CO_2 emissions from the energy sector have already decreased by approximately 57% compared to Year 2018 levels, exceeding the municipality's 2025 interim target [151]. It is important to note that carbon capture and storage (CCS) on MSW incineration was not considered in this study, although it could, in principle, mitigate fossil CO_2 emissions. The exclusion reflects both the current uncertainty regarding its economic feasibility and the lack of concrete deployment plans in the case study context. In addition, heating technologies based on natural gas and oil are to be phased out by Year 2035.

To support these goals, four deterministic parameters were defined, namely, HP subsidy; building renovation rate; electricity price; and individual heating investment. The Government of Denmark, through Danish Energy Agency, offers a HP subsidy that covers approximately 15% (up to a maximum of 20%) of the market price. The impacts of this subsidy are tested in the Scenarios HP expansion 1 and 2, where individual HP investment costs are reduced accordingly. The building renovation rate is represented by two parameters: the EU average renovation rate, reflecting a 1% annual reduction in heat consumption based on current practice; and the EU Renovation Wave, which targets an 18% reduction in heat consumption by Year 2030 relative to Year 2015 levels [152]. Three electricity price levels are modeled to account for their influences on both electricity-based heat production (e.g., CHP plants and electric boilers) and electricity-consumping technologies (e.g., HPs). Lastly, individual heating investments are assumed to be limited outside DH-designated areas over the next 5 years. This constraint is applied in the DH expansion and Combined scenarios, to model heat supply options during the period preceding DH connection (see Table 4.1).

Table 4.1. Overview of the scenarios developed through the participatory process for the urban case study from **Paper II**. The municipal solid waste (MSW) incineration plant is located near Copenhagen, and its DH network supplies several surrounding municipalities. According to Interviewee C, the plant has sufficient capacity to meet the entire heat demand of the LTK. Consequently, no investment cost is assigned to this facility in the model.

Scenario	Parameters/assumptions defining scenarios	Investigated technology	
		Individual heating	DH
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 ·Limiting individual heating investment options in certain areas for the first 5 years ·EU Renovation Wave rate ·Low electricity price		

HP, Heat pump; MSW, municipal solid waste.

4.1.2 System-level results

The six scenarios developed differ as to which of the defined parameters are applied, while the same set of technologies is available under both individual heating and DH options. Emission constraints and the phasing out of natural gas and oil heating by Year 2035 are binding across all scenarios. The scenarios were implemented using a cost-optimization model, and the results are shown in Figures 4.2–4.4. Figure 4.2 illustrates heat generation mixes over time for four selected scenarios (DH expansion, Renovation 2, HP expansion 1, and Combined).

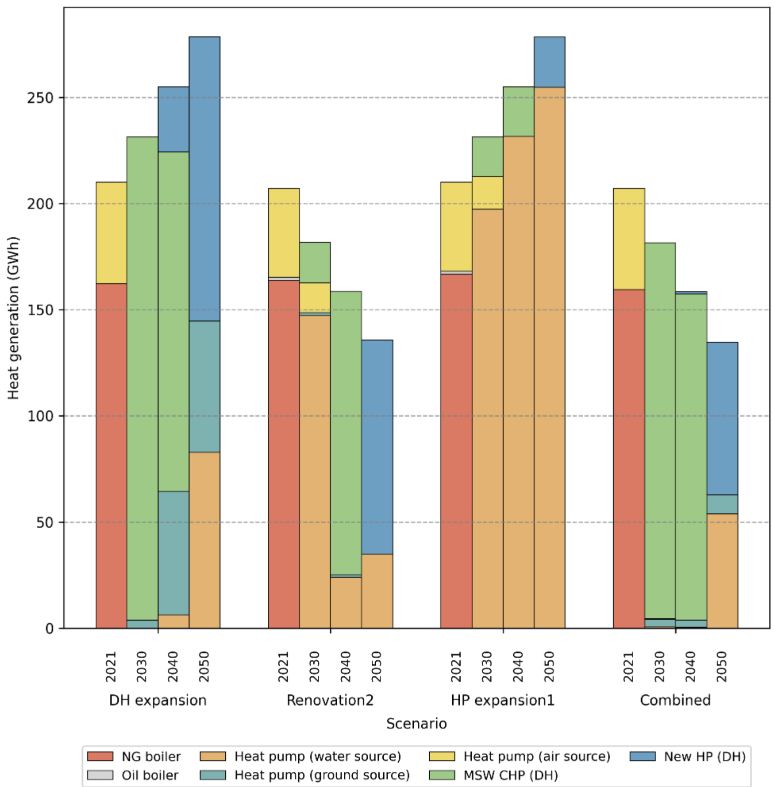

Figure 4.2. Heat generation level by technology for the selected scenarios at 10-year intervals from **Paper II**. HP, Heat pump; DH, district heating; NG, natural gas.

The Renovation 1 and HP expansion 2 scenarios are excluded, as their results were similar to those of their corresponding paired scenarios. In this section, the results presented in **Paper II** are summarized and discussed. Key findings are highlighted, and their implications are examined in relation to the study's objectives and the broader research context.

In the DH expansion scenario, the heat supply is initially dominated by the existing MSW incineration plant, which provides low-cost heat. District heating meets most of the heat demand until around Year 2040, after which the DH gradually declines. It is replaced by individual ground-source HPs in areas where DH expansion is not cost-competitive, while within the DH system, a large-scale water-source HP replaces MSW incineration. By Year 2050, the heat demand is met entirely by HPs, both individual and large-scale units, driven by the requirement to achieve carbon neutrality. This development reflects a transitional role for the existing MSW incineration plant, which enables cost-effective heat supply in the near term but is phased out to meet carbon neutrality targets. The gradual replacement of DH with individual HPs reflects the decreasing cost competitiveness of DH over time, while the shift to a large-scale HP within the DH system illustrates the integration of renewable electricity into centralised heat supply. By 2050, the full reliance on HPs highlights the growing importance of electrification, but also signals increased dependency on the electricity system's capacity and stability. The expansion of the DH system over time in this scenario is depicted in Figure 4.3.

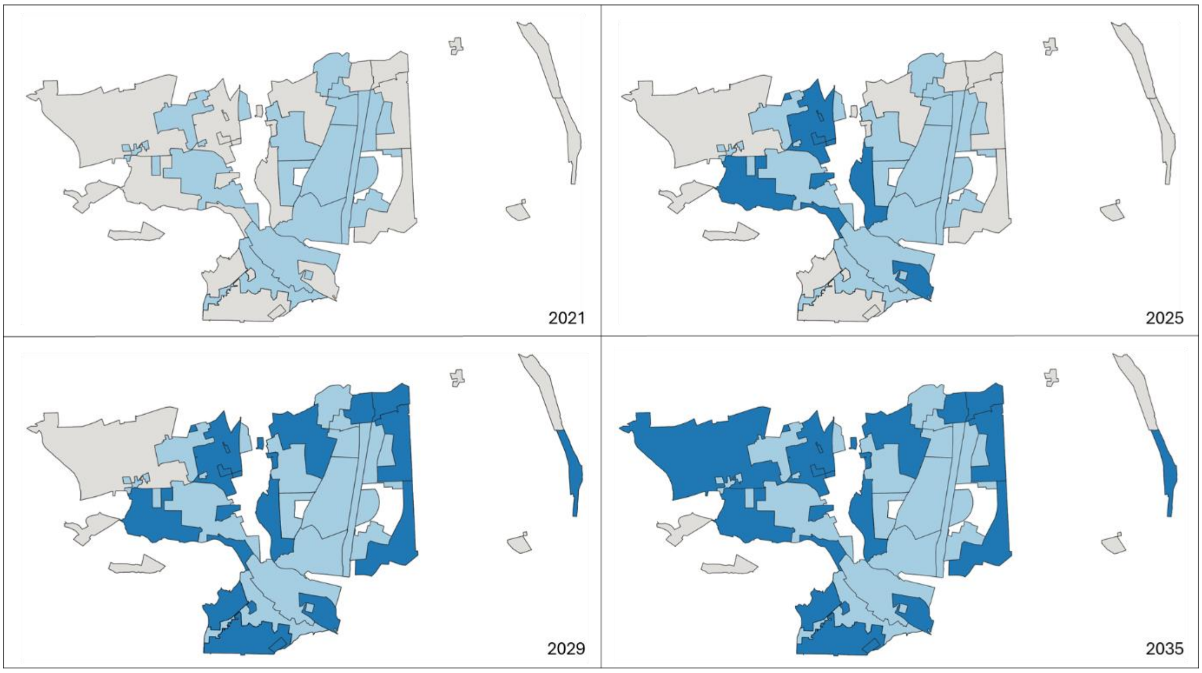

Figure 4.3. District heating expansion over time in the DH expansion scenario for the LTK Municipality from **Paper II**. The districts depicted in light-blue represent the current DH supply area and the areas in dark-blue indicate new connections to the existing DH network.

In the Renovation 2 scenario, natural gas boilers are largely replaced by individual HPs. By Year 2030, DH connections are no longer cost-effective due to a reduced heat demand from building renovations. However, once the initial wave of HPs reaches the end of their technical lifetime in Year 2035 (not shown in Figure 4.2), MSW-based DH becomes the dominant heat source, covering 85% of demand. Towards Year 2050, this is gradually replaced by a large-sacle HP in the DH system, so as to comply with emissions constraints. The results show that the reduced heat demand due to the extensive building renovations makes DH connections uneconomical in the early years and leading to widespread adoption of individual HPs. However, when these individual HPs reach the end of their lifetime, DH expansion into previously unconnected areas becomes cost-effective, with MSW incineration playing a central role. It should be noted, however, that the future availability and sustainability of MSW incineration is uncertain, which could affect the long-term feasibility of this pathway. The eventual replacement of MSW with a large-scale HP within the DH system reflects the shift toward fully renewable, low-emission heat supply in line with carbon neutrality targets.

In the HP expansion 1 scenario, individual HPs outcompete DH due to the introduced subsidy. Water-source HPs are significantly invested, while ground-source HP remains economically unattractive, even with the 15% subsidy of the market price. Although individual solutions predominate, district-level results (e.g., Figure 4.4) show that DH continues to serve parts of the multi-family housing stock. The district-level results are addressed in the next section. The results highlight the strong impact of subsidies in favouring individual HPs over DH, leading to high investment in water-source units while ground-source options remain uncompetitive.

In the Combined scenario, in which extensive building renovations reduces the overall heat demand. The reduced heat demand is reflected in decreased investments in a large-scale HP for DH and individual ground-source HPs, as compared with the DH expansion scenario. Towards Year 2050, the heat demand is met entirely by HPs, both individual and large-scale, to comply with the model's carbon-neutrality constraint. Since MSW contains fossil carbon, the model phases out MSW-based CHP plants in later years. However, in the absence of carbon emission constraints, MSW-based DH would remain the most cost-effective option for the municipality.

4.1.3 District and building-type levels results

Beyond the system-level results presented in Figure 4.2, the methodology also allows for analyses at the district and building-type levels. Buildings are grouped into six categories: detached houses; terraced/semi-detached houses; apartments; student/community housing; non-residential buildings; and commercial buildings. Figure 4.4 presents the results for Districts 6 and 11, which are selected to illustrate how, under identical investment conditions, heat generation levels vary depending on various factors, such as building composition, proximity to the existing DH network, and heat demand density.

In District 6, Non-residential and Commercial buildings primarily invest in individual HPs, whereas the same building types in District 11 are more heavily reliant on the DH system for their heat supply. This difference is driven by district-specific characteristics, including proximity to the existing DH network, building composition, and heat demand density. Notably, District 11 has a 10% higher heat demand density and is located closer to the existing DH network than District 6. This contrast between District 6 and District 11 illustrates how local infrastructure conditions and building type composition shape the cost-effectiveness of heating options. It reinforces the study's central point that spatial context influences technology choice and the optimal balance between centralized and decentralised heat supply. Such variation underlines the importance of integrating district-level data into energy system modeling studies to ensure strategies are tailored to local conditions.

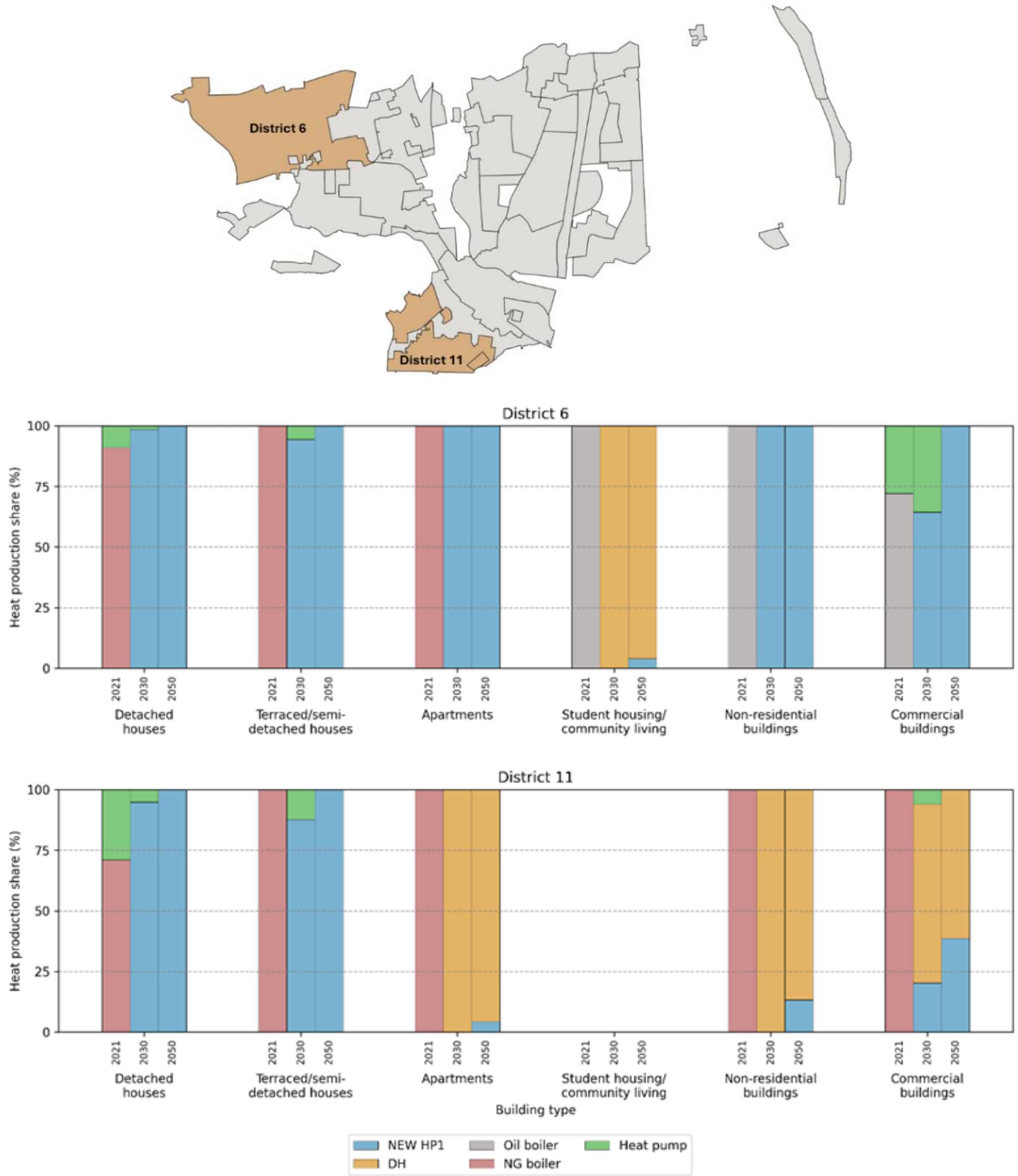

Figure 4.4. Heating technology shares by building type in Districts 6 and 11 in the HP expansion2 scenario from **Paper II**.

Table 4.2 summarizes the key properties of the districts currently without DH connections and DH share in each scenario from the model results. The pie charts in Table 4.2 show the different building type composition and the bar charts indicate the percentage of DH in each district. According to a socio-economic evaluation for DH connection conducted by the LTK municipality, Stage 1 areas, Districts 7, 8, 13, and 14, are scheduled to receive DH connections between Year 2023 and 2027, while Stage 2 areas, Districts 6, 9, 11, 12, and 15, are planned for DH connection between Year 2027 and 2030 [144]. However, further prioritization within these stages would benefit from a techno-economic assessment with higher spatial resolution in prioritizing the ares to be connected to DH. The methodology applied in this study enables such granular analysis by capturing transitions over time at both district and building-type levels. This time-based breakdown of Stages 1 and 2 areas can complement and enrich the municipality's existing evaluation.

Table 4.2. District properties and DH supply shares (%) in Year 2050 for each scenario based on **Paper II**. The remaining share (%) is supplied by individual heating technologies.

	Building type distribution	Distance to existing DH network (m)	Heat demand density (GWh/km²)	DH share (%) DH_expansion	DH share (%) Renovation	DH share (%) HP_expansion	DH share (%) Combined
D6		687	59				
D7		659	64				
D8		1,622	71				
D9		600	59				
D11		502	66				
D12		621	58				
D13		1,090	65				
D14		409	61				
D15		447	55				

The modeling framework used in this thesis enables time-resolved, spatially explicit analyses at both the district and building-type levels. This can complement the municipality's existing evaluations by highlighting intra-stage variations and technology transitions that occur over time. In the feedback discussions, municipal planners emphasized the value of such disaggregated results, particularly with respect to distinguishing between detached housing (governed by national rules) and semi-detached housing (under local planning authority), which has important implications for heat planning.

The results from the DH expansion scenario (Table 4.2) suggest that in districts with heat demand densities above 60,000 MWh/km², connecting to DH represents a cost-effective solution. Overall, this aligns with LTK Municipality's broader planning direction, which prioritizes DH as a key pathway to achieving carbon neutrality. While the case study thus provides insights that support more targeted and informed DH expansion planning, the spatial division used in this study differs somewhat from the municipality's internal zoning, e.g., District 11 in this model representing a combination of three separate municipal subdivisions, the general trend of prioritizing densely built-up areas is consistent. However, some differences appear at the district level, where the model proposes alternative priorities for DH connection. These variations can be attributed to differences in criteria and assumptions: this study applies a techno-economic optimization based on heat demand density and infrastructure costs, whereas municipal planning also consider factors such as conservation values, protected areas, and gas boiler ages [144]. Identifying the most cost-efficient expansion pathway remains important, as these insights can inform discussions on how to best meet local objectives while compensating for other values or constraints through complementary measures. The model therefore provides an independent, system-level perspective that can support and complement local strategies.

4.2 Results from participatory modeling – Semi-rural case (Paper III)

As the participatory modeling applied in the semi-rural case mirrors that of the urban case presented in Section 4.1, a review of the planning process (Step 1) is not undertaken here. This section presents the modeling results specific to the semi-rural municipality, beginning with the spatial mapping and the formulation of scenarios developed through the participatory approach.

4.2.1 Spatial mapping and scenarios

The HK Municipality was divided into districts to apply the spatially resolved modeling. This division was based on current heating technologies, proximity to the existing DH network, and heat demand density (see Appendix B). The discussion with the municipal planners revealed their preferences regarding the division of the districts and, as a result, 11 districts are defined for the modeling, as shown in Figure 4.5.

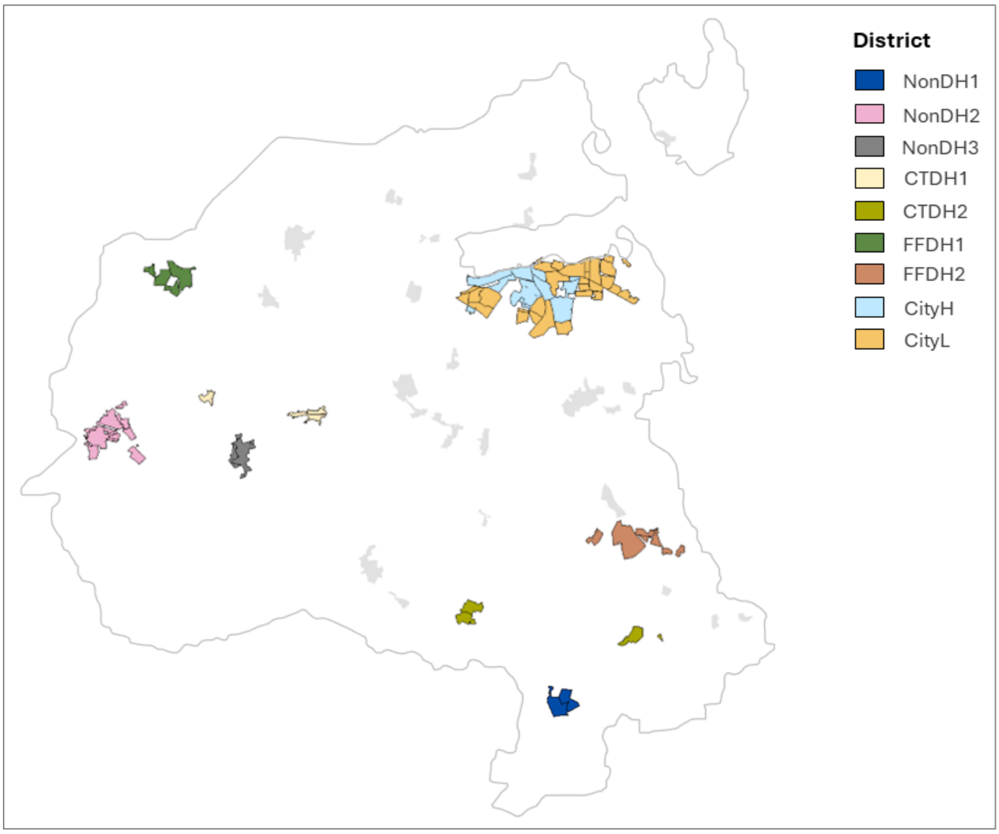

Figure 4.5. Division of the districts for the modeling based on **Paper III**. DH1-3 areas are partially connected to DH, meaning that part of the areas do not have the connection to the existing DH network; CTDH indicates districts locaed close to the existing DH network; LCTDH for districts that are less-close in proximity to the existing DH network; CityH is Holbæk City with high heat demand density; and CityL is Holbæk City with low heat demand density.

Four decarbonization scenarios were developed for the case study, as outlined in Table 4.3. These scenarios were shaped through a combination of insights from previous research on rural heat decarbonization [153–155] and iterative engagement with energy planners in Holbæk. The ongoing dialogue with the planners throughout the study led to several refinements of the initial scenario concepts, incorporating local climate goals, technology preferences, policy directions, planned investments, and resource limitations (for an overview of topics discussed with the energy planners of HK municipality in **Paper III**, see Appendix D). For instance, based on the planners' inputs, specific technology options were included, such as utilizing biogas in the existing gas grid and recovering excess heat from the wastewater treatment plant (WWTP) and nearby industries. To avoid constraining the model to those technologies favored by municipal planners, the Mixed-Integrated scenario was designed to include all available options, including technologies not explicitly proposed during the discussions, such as biomass-based DH units.

Table 4.3. Heating technology options included in the model. All scenarios optimize the total system cost from **Paper III**.

		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 HP Solar heating		DH network	EH1 EH2
	Decentralized-Local	Biomass boilers Electric boiler HP Solar heating	Biogas	HP Electric boiler Solar DH with TES	
Mix of local resources and electrification in heating	*Electrification*	Electric boiler Heat pump		HP Electric boiler Solar DH with TES DH network	
	Mixed-Integrated	Biomass boilers Electric boiler HP Solar heating	Biogas	HP 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 stoRAGEE; HOB, heat-only boiler; CHP, combined heat and power.

4.2.2 System-level results

This section summarize and discuss the system-level results from **Paper III**, as illustrated in Figure 4.6, which shows the heat generation levels by technology for 10-year intervals. In the Centralized-Local scenario, individual biomass boilers meet approximately 80% of heat demand up to Year 2029 (not shown in Figure 4.6), primarily in response to a forthcoming natural gas ban taking effect in Year 2030. From Year 2027 onwards, DH expands with the introduction of excess heat from the municipal WWTP and from Kalundborg Symbiosis in Year 2030. These sources are integrated into a growing DH network, which gradually connects more users and displaces the use of individual biomass boilers. By Year 2044, when these biomass boilers reach the end of their technical lifetime, most are replaced by the DH system. From Year 2045 onward, more than 90% of the heat in the DH system is supplied by excess heat, with the remainder provided by individual solar thermal systems and biomass boilers. These results demonstrate how policy measures, such as the natural gas ban, can trigger rapid shifts in heating technologies, while the integration of excess heat enables a gradual transition toward centralized, low-carbon heat supply. The displacement of biomass boilers by DH shows the role of infrastructure expansion in reducing reliance on individual combustion-based systems.

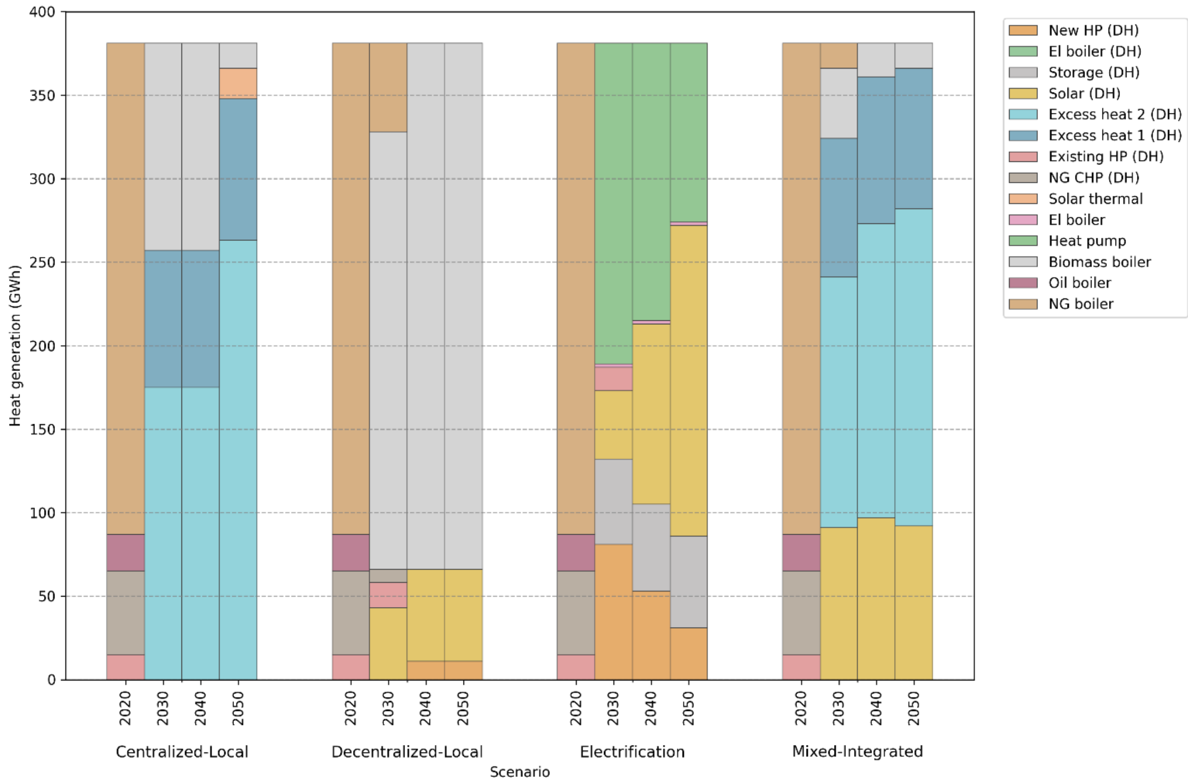

Figure 4.6. Heat generation by technology in each scenario for the 10-year intervals from **Paper III**. Excess heat 1 is heat from the municipal wastewater treatment plant, and Excess heat 2 is heat from the Kalundborg Symbiosis industrial site.

In the Decentralized-Local scenario, biogas begins to replace natural gas in individual boilers from Year 2023, as existing boilers require only minimal modification for the replacement of fuel. This shift makes Year 2023 the feasible year for adoption of the biogas recovery from WWTP. Biogas continues to supply heat until Year 2030, driven by the natural gas ban and a tightening CO_2 emissions cap in the model. Despite its high current cost, biogas injected into the existing gas grid could be viable under supportive financial schemes. The results highlight the potential of biogas as a transitional fuel, leveraging existing gas infrastructure to enable rapid fuel switching ahead of stricter carbon limits. The DH sources change over time, with the solar heat gradually replacing natural gas. By Year 2050, solar DH provides up to 83% of total DH supply. When the existing DH HPs reaches the their end-of-lifetime, a new one is installed in Year 2040 to complement the solar DH.

In the Electrification scenario (see Figure 4.6), HPs and electric boilers reduce fossil fuel use significantly, covering 51% of the total heat demand by Year 2030, with DH covering the remainder. District heating expands steadily, reaching 71% by Year 2050, while individual electric boilers decline as low-cost DH from excess heat becomes dominant. Solar thermal and seasonal heat storage significantly increase (by more than four-fold) the district heat output by Year 2050, with the storage covering around 20% of the demand. Large-scale HPs are crucial in the early phase, supplying 43% of DH in Year 2030, although their share drops as solar and excess heat become more dominant. These results show how electrification, combined with low-cost excess heat and thermal storage, can drive a steady shift toward DH dominance. The success of this pathway will be however, closely linked to decarbonization progress in the power and industrial sectors.

In the Mixed-Integrated scenario, DH becomes the dominant heat source starting in Year 2028, replacing individual natural gas and biomass boilers. After Year 2030, the most cost-effective source becomes excess heat from the municipal WWTP (see Figure 4.6), which is fully utilized. About 73% of the available excess heat from Kalundborg Symbiosis is also used, though it is not entirely carbon-neutral. Solar heat accounts for 25% of the DH generation by Year 2050, with investments beginning in Year 2025. However, access to Kalundborg's excess heat becomes possible only from Year 2030 onward. The results illustrate how integrating multiple local heat sources can rapidly shift supply away from fossil fuels, with excess heat playing a central role in DH system's dominance.

It is important to highlight that the modeled scenarios reflect the technology preferences expressed by municipal planners. As such, each scenario can be interpreted as a potential pathway to achieve local climate goals with specific technologies. The Mixed-Integrated scenario, which allowed a broad range of technologies without excluding options based on stakeholder preferences, produced a different system configuration compared to the more restricted scenarios. Notably, even under these broader assumptions, the model did not invest in biomass-based DH units. This indicates that their absence in the results is not only due to stakeholder preferences but also to their limited cost-competitiveness in the modeled context.

4.2.3 District-level results

Similar to the urban case, this case presents results at the district level in addition to the overall system level. Figure 4.7 presents the DH supply shares in Year 2030 and 2050 for each scenario and district.

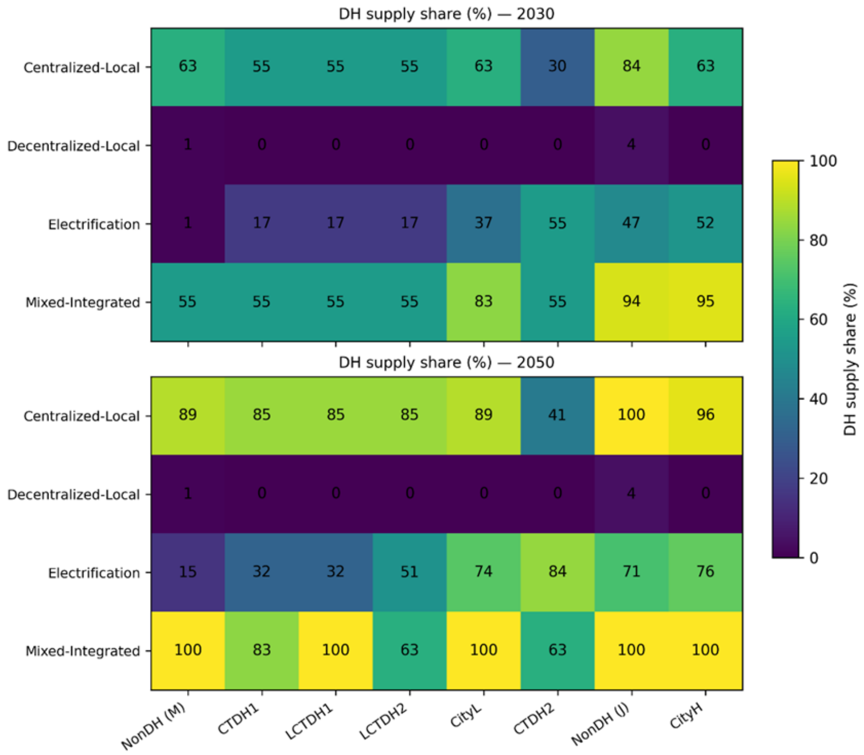

Figure 4.7. District heating supply shares (%) in different districts in Year 2030 and Year 2050 based on **Paper III**. The districts in the x-axis are ranked according to the heat demand density, i.e., NonDH(M) has the lowest heat demand density and CityH has the highest.

Variations in the DH share reflect differences in district characteristics, such as heat demand density and proximity to the existing DH network. As a result, the DH expansion patterns differ between the three scenarios: the Centralized-Local, Mixed-Integrated, and Electrification scenarios.In the Centralized-Local scenario, the DH supply is widespread by Year 2050, with high-density districts, such as CityH, reaching nearly 100%, and lower-density districts reaching moderate shares up to around 80%. The Decentralized-Local scenario shows minimal DH supply across all districts, reflecting a focus on individual heating solutions, as DH was not an option in this scenario. The Electrification scenario shows moderate expansion of DH supply, up to 84%, in high-density districts by Year 2050. Overall, the Mixed-Integrated scenario has the highest DH shares, with five districts reaching 100% and low-density districts exceeding 60%. In this scenario, DH is supplied by excess heat sources from WWTP and Kalundborg industrial site, and solar thermal. However, excess heat from Kalundborg is used less than in the Centralized-Local scenario, with 25% replaced by solar heat. This shows that even when broad technology options are available, the model still selects similar technologies as in the other scenarios mainly because excess heat is more cost-effective than the alternatives. Figure 4.8 shows the results from the CTDH1 and CityH districts across scenarios. Two districts were selected to illustrate contrasting conditions: one with high heat demand density but located far from the existing DH network (CityH), and the other with lower demand density but situated close to the existing DH network (CTDH1).

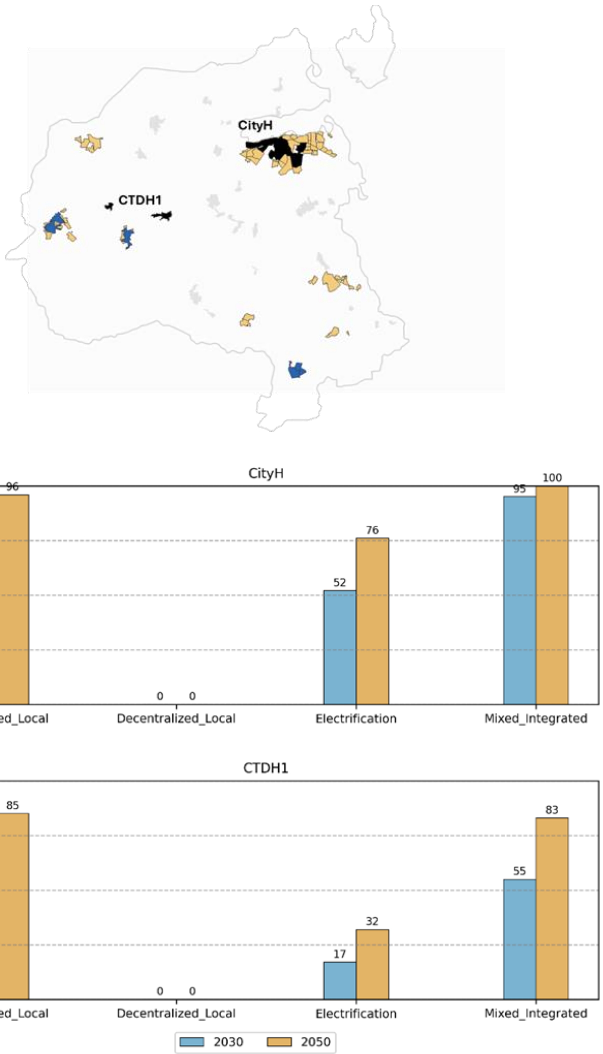

Figure 4.8. District heating supply shares for the selected districts (CTDH1 and CityH) in Year 2030 and Year 2050 from **Paper III**.

In the Centralized-Local scenario, DH supplies 96% of the heat demand in CityH and 85% in CTDH1 by Year 2050 demonstrating that DH can remain competitive even in lower-density areas when supported by centralized and low-cost heat sources. In contrast, in the Electrification scenario, the DH share in CityH reaches 76% in Year 2050, while CTDH1 reaches only 32% of the DH shares in Year 2050. This results highlightshow supply conditions and system design influence DH's viability in less-dense areas. The district characteristics and DH supply shares are detailed in in Appendix F. As expected, heat demand density is the key factor for DH expansion, while access to excess heat sources significantly improves the feasibility of connecting areas with lower heat demand densities.

4.2.4 Cost analysis

Figure 4.9 presents the total undiscounted annual costs, which include the investment, fuel, and variable operational costs, over the modeling period, shown relative to the Mixed-Integrated scenario, which yields the lowest system cost. The Electrification scenario shows significantly higher costs due to combined investments in individual HPs and DH expansion, indicating that widespread electrification can be capital-intensive despite the long-term emission benefits. In contrast, the Decentralized-Local scenario has the lowest investment costs because it relies on existing gas infrastructure and local biomass, although it faces higher fuel costs and substantial biogas upgrading expenses. This result shows that minimising the upfront costs can lead to higher operating expenses over time. The Centralized-Local scenario ranks the second in cost efficiency, with a cost profile that is similar to that of the Mixed-Integrated scenario but with higher O&M costs driven by the use of individual biomass boilers, highlighting that technology mix choices can shift cost burdens from investment to O&M costs. Both of these scenarios demonstrate that while industrial excess heat use can increase costs due to DH expansion, integrating it with renewable heat sources offers a cost-effective pathways to reducing fossil fuel dependence and supporting long-term savings.

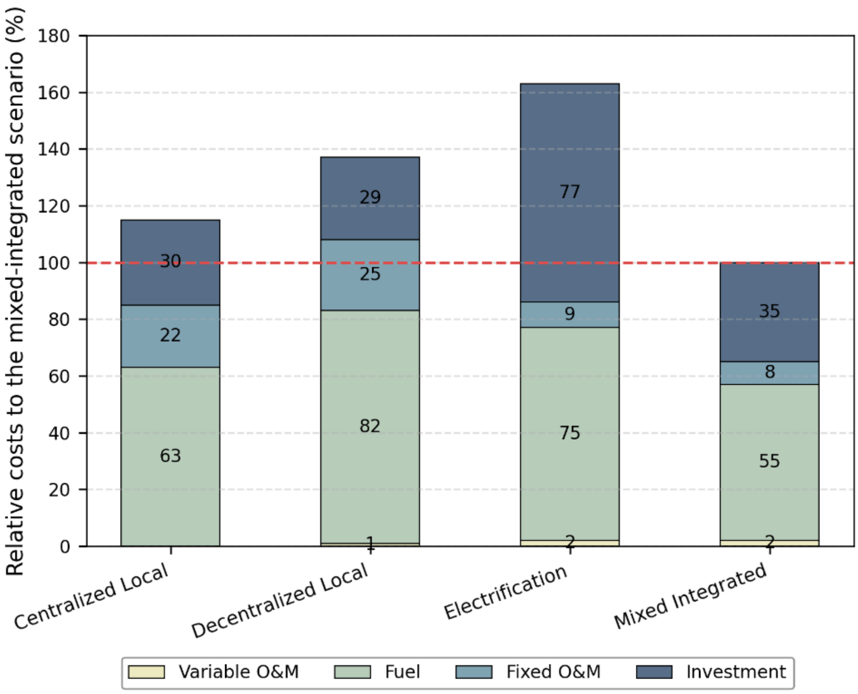

Figure 4.9. Overview of the cost elements for each scenario from **Paper III**. The red dashed line represents the Mixed-Integrated scenario, which has the lowest total system cost.

While the model settings differ, some parallels can be drawn with the cost optimization results from **Paper IV** (discussed in the Section 4.3). In both modeling approaches, scenarios that rely more heavily on electrification or require replacing the lost WH sources tend to incur higher total system costs (for the cost structure of scenarios in **Paper IV**, see Appendix G). However, in **Paper IV**, the impacts of adding the cost of the DH network refurbishment on the total system cost are small, and the distribution of the cost components remains relatively the same across scenarios. This differs from the results of **Papers III**, where expanding the DH network and integrating industrial excess heat can shift the cost balance more visibly between investment and O&M costs. These differences largely reflect the scope of each model: **Paper III** examines heating systems in isolation with strong spatial constraints, while **Paper IV** co-optimizes the heat and electricity sectors, allowing for greater flexibility in cost redistribution across the system.

The modeling results were presented to the municipal planners to gather feedback aimed at refining the model to better reflect their specific needs and preferences, and to improve the practical relevance of the outcomes. The feedback from the planners on the modeling results focused primarily on verifying whether key assumptions and constraints. Stakeholders also questioned the realism of certain constraints, such as assumed biogas prices, and stressed the importance of representing the O&M costs of both DH and natural gas networks to better reflect real-life cost drivers. In some cases, preferences diverged from a purely cost-optimal pathway, reflecting political priorities (e.g., retaining use of the existing gas infrastructure) and interest in specific “local resource” solutions, even when these might be less economical. As a result, the Mixed-Integrated scenario balanced cost-optimal and stakeholder-preferred configurations, enabling exploration of both technically efficient and politically/practically feasible transition pathways.

Overall, the planners’ engagement ensured that scenario narratives were grounded in the municipality’s context, and the reception of the results indicated that they were seen as a useful complement to internal planning processes, particularly as a way to test alternative options and challenge existing assumptions. In this way, the chapter’s findings demonstrate how spatially explicit participatory modeling can serve both as a technical decision-support tool and as a platform for dialogue between modelers and local stakeholders.

4.3 Results from the city energy system optimization model (Paper IV)

This section summarizes and discusses the results from the second methodological approach in this study, thecity energy system optimization model in **Paper IV**. For a full description of the results, see appended **Paper IV**. Unlike the previous case studies, the scenarios in this model are predefined and not developed through a participatory process. Instead, they were established based on a methodological design developed with the aim to assess systematically the impacts of varying WH availability and DH pipe refurbishment strategies on long-term heating system development. The model captures the spatial and temporal dynamics of the heat supply and demand across multiple urban regions, allowing for a detailed analysis of cost-optimal decarbonization pathways. As in previous sections, the results are presented at three levels (system-wide, regional, and building type), in order to understand how spatial characteristics and infrastructure conditions influence the choice of heating technology. The results are presented at three levels, system-wide, regional, and building type, to examine how spatial characteristics and infrastructure conditions influence the choice of heating technologies.

4.3.1 System-level results

Figure 4.10 presents the shares of the different heating technologies across the modeled region in Year 2050 across the scenarios. District heating remains the dominant heat supply in all the scenarios, covering at least 70% of the total demand. This reflects the cost-efficiency of maintaining the existing DH infrastructure under the given assumptions, even when refurbishment costs are introduced. Waste heat utilization plays a central role, complemented by existing biomass CHP and large-scale HPs. While individual HP deployment increases with higher refurbishment rates, it does not exceed 30% of the total demand. Refurbishment rates exert a weakinfluence on technology choice, as refurbishment costs remain low compared with other cost components. Only the aged DH distribution pipeline sections that are reaching the end of their technical lifetimes are assumed to be either refurbished or dismantled, with different refurbishment rates representing varying assumed lifespans.

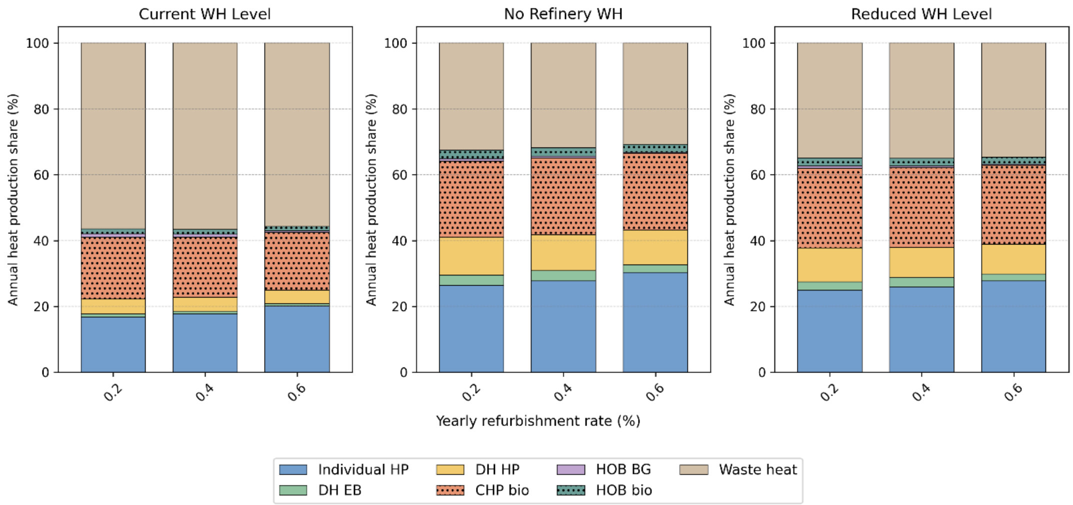

Figure 4.10. The production mixes of the heating systems for the three WH level scenarios and the three different annual refurbishment levels from **Paper IV**. With the exception of the individual HP, all the technologies are used in the DH systems. CHP bio and HOB bio represent existing plants (indicated by dotted bars), while DH HP includes both existing and newly invested units. DH electric boilers (EB) represent newly invested capacity only.

In the Current WH level scenario, the DH system continues to dominate despite the rising costs for refurbishments. A slight decrease in biomass CHP reflects a modest reduction in the DH share from 83% to 80%, as some buildings shift to individual HPs. Waste heat accounts for approximately 69% of the DH production, reinforcing its competitiveness given its low assumed cost (modeled as free, reflecting its low market value as a by-product with limited alternative uses), in the model. These results indicate that the abundant andlow-cost WH can stabilise DH's role in the heating mix, even with higher refurbishment costs, by offsetting the need for more expensive supply options. The limited shift toward individual HPs suggests that the network-based solutions remain economically robust when anchored by competitively-priced local resources.

In the No Refinery WH scenario, in which WH from the Rya refinery is removed, the DH supply decreases by 10% compared to the Current WH level scenario. Thecontribution of WH to the DH drops to 44%, and the shortfall is primarily offset by increased generation from large-scale HPs, electric boilers, and biomass-based technologies. As refurbishment rates increase, individual HP use increases by 5% (at the rate of 0.4%) and 15% (at the rate of 0.6%), while centralized electricity-based heating solutions decline accordingly. This suggests that individual HPs primarily compete with centralized electricity-based heating, and that the balance between centralized and decentralized solutions is dictated by refurbishment rates. In addition, the reduction in DH share when refinery WH is unavailable underscores the importance of diversified local heat sources for maintaining network competitiveness.

In the Reduced WH level scenario, in which the WH from both the refineries in Rya and the waste incineration plant in East is reduced, the DH share falls by 8% relative to the Current WH level scenario. Despite this being a larger WH reduction (53%) than that observed in the No Refinery WH scenario (45%), the decline in DH share declines is less-pronounced. The impact of refurbishment rates on the overall system is weak, but the placement of WH emerges as a more decisive factor for DH performance under constrained WH conditions. Despite slightly higher WH availability in the No refinery WH scenario (7% more than in the Reduced WH level scenario), its more concentrated spatial distribution leads to a greater decline in DH integration, emphasizing the need to consider location-specific accessibility in planning low-carbon heat supply. In addition, hydrogen production increases electricity demand, reducing the competitiveness of electricity-based heat generation. The capacity factors for large-scale and individual HPs drop to 22% and 40%, respectively, compared to 34% and 48% in the No refinery WH scenario. This points to an overall decline in electricity-based heating under rising system-wide electricity loads. However, these average values mask important spatial operational variations, which are explored further in the next section.

4.3.2 Node-level results

The results indicate that there are regional variations in heat supply and inter-nodal heat exchange, which are driven by differences in WH availability and DH pipe refurbishment rates. Figure 4.11 illustrates the extent of DH pipe refurbishment required by Year 2050 in each node, based on the technical lifetime assumptions outlined in Section 3.2.4.

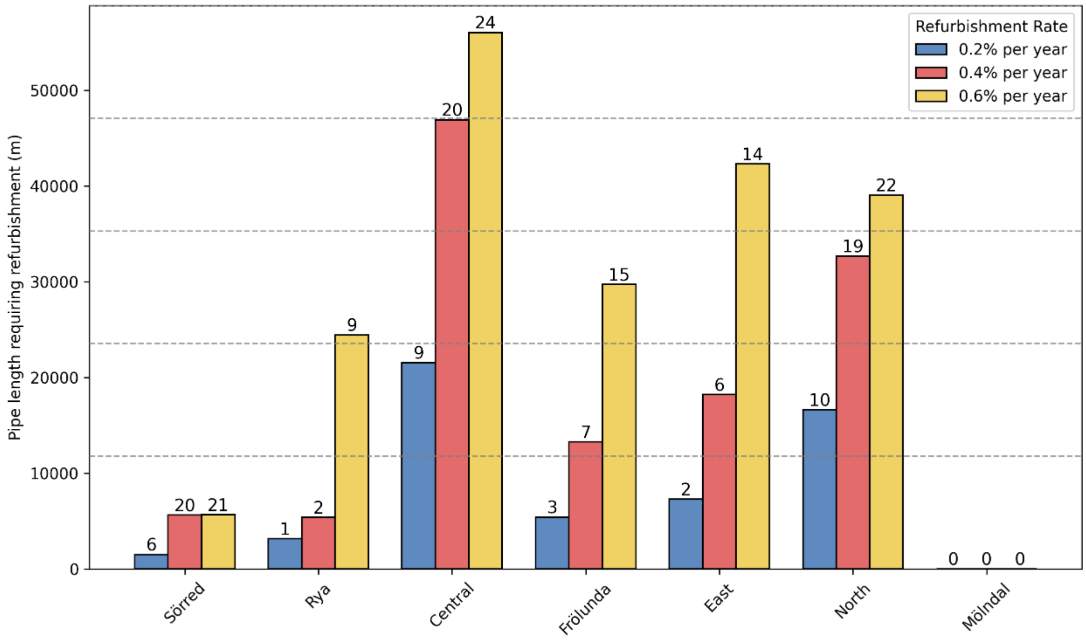

Figure 4.11. District heating pipe lengths (in meters) that require refurbishment by Year 2050 in each region for three annual refurbishment rates from **Paper IV**. The variation in refurbished pipe length reflect differences in the age structure of the DH networks across the city. The values shown on top of each bar indicate the share (%) of refurbished pipe length relative to the total pipe length within each respective region.

Across the seven heating nodes, the percentages of pipes that require refurbishment vary significantly in line with the assumed annual refurbishment rates. The Mölndal node consistently shows no pipe refurbishment needs, reflecting its relatively recently installed DH infrastructure. In contrast, the Central node exhibits the highest pipe refurbishment requirements across all the rates. Figure 4.12 presents the annual heat production mix (GWh) for four nodes, Sörred (S), Frölunda (F), Mölndal (M), and North (N), which are each characterized by a high percentage of individual HP adoption. The figure covers all three refurbishment rates (0.2%, 0.4%, and 0.6%) across the three scenarios: Current WH level, No Refinery WH, and Reduced WH level. The stacked bars in Figure 4.12 indicate the contributions of the different heat supply technologies, including imports and exports between nodes.

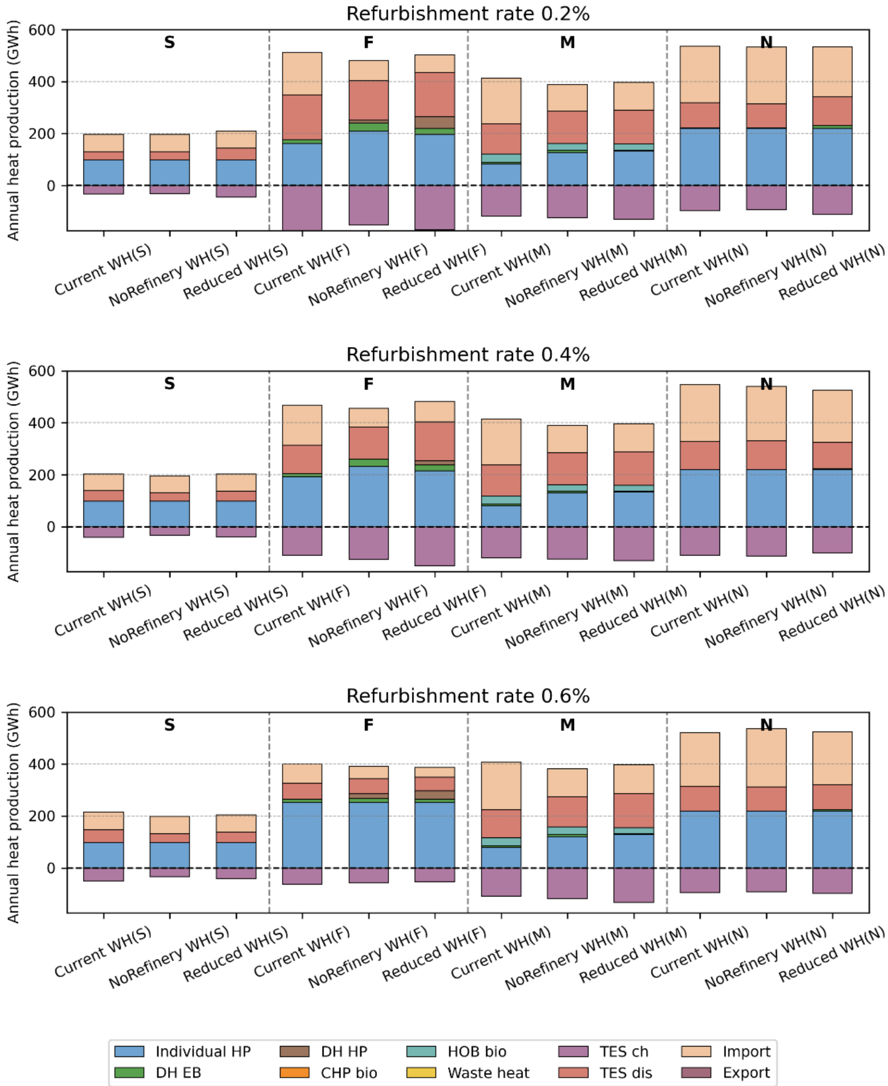

Figure 4.12. Annual heat production (GWh) for the Sörred (S), Frölunda (F), Mölndal (M), and North (N) nodes from **Paper IV**. TES ch and TES dis represent the charging and discharging of thermal energy storage, respectively. Exports and TES ch are shown as negative values.

With regards to the Sörred, Mölndal, and North nodes, the impact of the refurbishment rates has a limited influence and WH availability has little effect on the supply mix in the Sörred and North nodes, indicating a low level of reliance on imported WH. In contrast, the Mölndal node shows a significant shift when WH availability is reduced – individual HP adoption increases by 61%–66% compared with the Current WH level scenario. This is driven by Mölndal's reliance (up to 60%) on imported heat from the Central node, which itself depends on WH from Rya and East. When upstream WH is curtailed, Mölndal compensates with decentralized heating with individual HP adoption.

Frölunda exhibits greater variability across both scenarios and refurbishment rates. At the highest pipe refurbishment rate, individual HPs supply up to 75% of the node's heat. Despite also importing heat from the Central node, Frölunda shows greater adoption of HP than Mölndal. This difference is attributed to infrastructure age: Frölunda's DH system is older (average age, 52 years), making reinvestment less-viable compared with Mölndal, where newer infrastructure and the presence of a biomass HOB support DH system retention.

The high level of adoption of individual HPs in these four nodes reflect both technical and spatial factors. These areas have a larger share of SFH, which typically aligns better with individual solutions due to the lower heat demand density. Although DH remains dominant system-wide (covering ~70% of the total demand), these four nodes account for only 36% of the total demand. Thus, shifts toward decentralization in these areas have a limited impact at the system level but are important for understanding spatially differentiated transitions. The current findings suggest that in areas with aging infrastructure, low demand density, and higher shares of SFH, decentralized heating is the more-viable alternative, even within a predominantly DH-based system. Figure 4.13 presents the annual heat production mix in GWh for the Rya (R), Central (C), and East (E) nodes across three refurbishment rates and three scenarios.

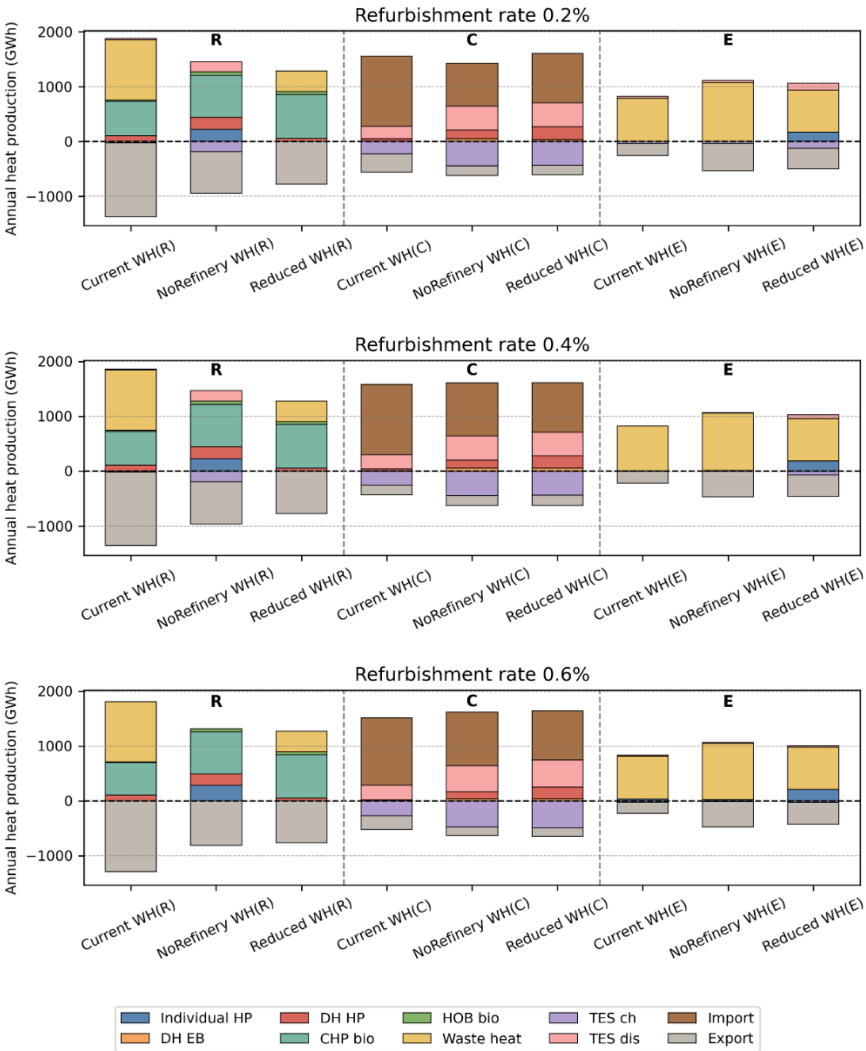

Figure 4.13. Annual heat production (GWh) in Rya (R), Central (C), and East (E) from **Paper IV**. TES ch and TES dis represent the charging and discharging of thermal energy storage, respectively. Exports and TES ch are shown as negative values.

Each node plays a distinct role within the system: Rya primarily exports heat; East focuses on supplying local demand with its WH; and Central relies heavily on imported heat. This suggests that while the highest refurbishment rate of 0.6% has minimal system-wide effects due to its low cost, it influences the local outcomes.

Rya remains a major heat exporter across all scenarios. Even in situations of reduced WH availability, it continues to export up to 800 GWh using the existing biomass CHP and large-scale HP capacity, indicating it remains more cost-effective for the Central node to import heat than to invest in local capacity. Although refurbishment has a limited impact on the overall system cost, it affects regional investment patterns. At the highest refurbishment rate (0.6%), thermal energy storage (TES) investments in Rya are no longer observed, likely due to an improved supply-demand balance that is enabled by the higher refurbishment rate. As a result, local pipeline refurbishment increases from 1%–2% to 9%, illustrating how refurbishment can reduce the need for TES locally.

The Central node depends heavily on imported heat, up to 82% of its supply, primarily from Rya, while also exporting heat to Frölunda and Mölndal. Its reliance on imports reflects the high local demand, lack of direct WH sources, and the availability of a cost-effective supply from adjacent nodes. When WH availability is reduced, imports decline and are partially replaced by local large-scale HPs. However, the Central node continues to prioritize imports, driven by economic efficiency. Marginal heat costs support this pattern: the Central node has the highest cost (10.28 €/MWh), followed by Rya (8.08 €/MWh), and East (5.36 €/MWh), thereby reinforcing the economic preference for importing heat from Rya and East.

The East node, which hosts a waste incineration plant, meets the local demand with WH under the Current WH level scenario. As WH from Rya declines, East increasingly supplies other nodes, particularly Central. When WH is reduced in both Rya and East (Reduced WH level scenario), East still exports heat by compensating with individual HPs. This underscores East's flexibility and strategic role in balancing the heat supply under constrained WH conditions.

4.3.3 Building-type level results

Disaggregating the node-level results by building type reveals important differences in the heating solutions between SFHs and MFHs. The relative shares of these building types within each node significantly influence the dominant heating technologies and their sensitivities to scenario assumptions. The Rya and East nodes are used here to illustrate these differences, as they represent contrasting urban compositions. In the Rya node, the SFH-to-MFH ratio is approximately 20, while in the East node it is around 1, indicating a more-balanced distribution. Figure 4.14 shows the shares of DH in SFH and MFH across the three scenarios and refurbishment rates. District heating consistently supplies nearly 100% of the MFH demand in both nodes, reflecting a high heat demand density and the cost-effectiveness of the centralized supply. In contrast, the shares of DH in SFH vary significantly, influenced by WH availability and the refurbishment rates. Under the Current WH level scenario, the DH shares in SFHs decline slightly as the refurbishment rates increase, with a more-pronounced reduction seen in the East node due to its older DH infrastructure (average ages: 49 years in East vs. 44 years in Rya).

In the No Refinery WH scenario, the DH supply to SFHs in the Rya node drops from 55% to 41%, as WH becomes unavailable and individual HPs become more cost-efficient for low-density areas. In the Reduced WH level scenario, DH continues to serve both building types in the Rya node, supported by its excess generation capacity.

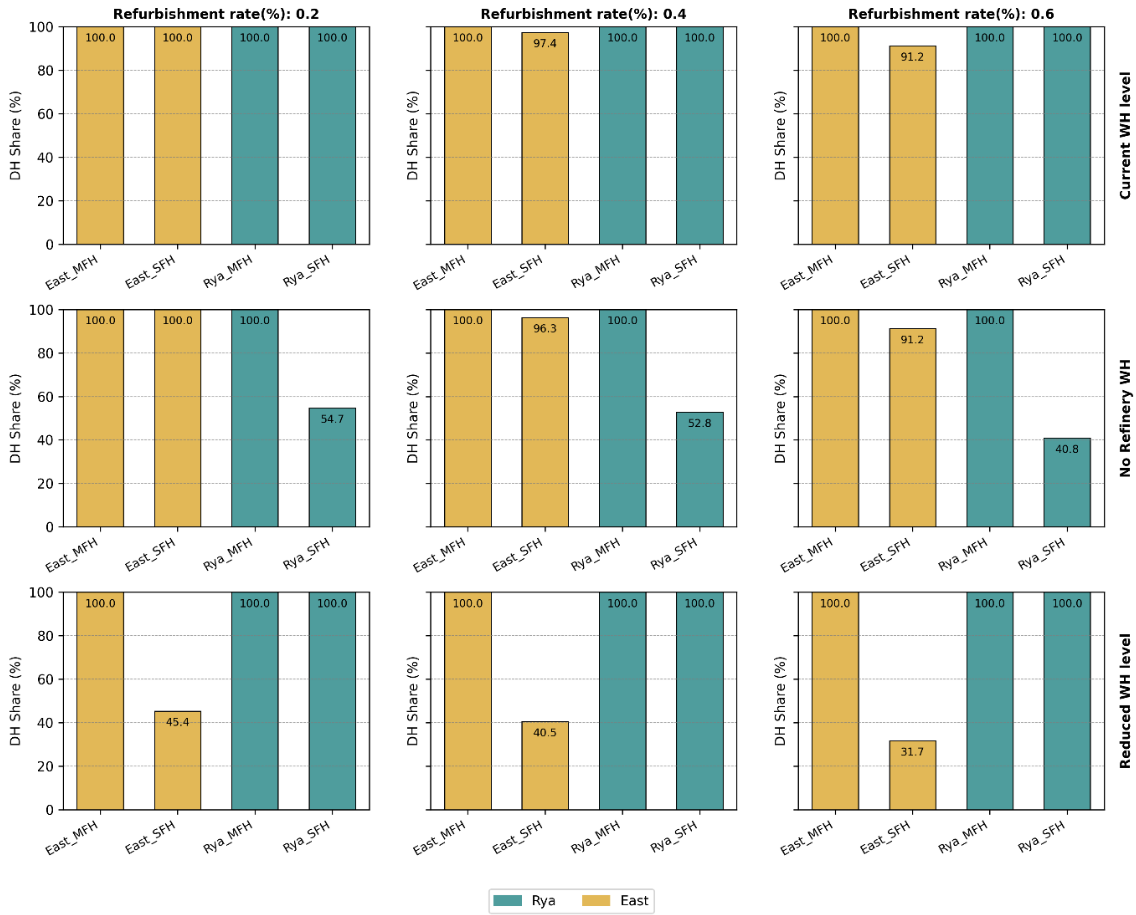

Figure 4.14. DH shares (%) of the total heat supply in the Rya and East nodes from **Paper IV** broken down according to building type: Single-family house (SFH) and Multi-family house (MFH).

However, in the East node, WH is prioritized for MFHs, leading to a notable shift towards individual HPs for SFHs. These patterns highlight how the urban structure and building composition shape heating transitions. The Rya node, with dispersed demand and surplus heat generation, remains a net exporter of DH, while the East node, with denser development and concentrated MFH demand, must allocate limited WH resources more selectively. While the shift from DH to individual HPs in SFHs is observed system-wide as WH availability decreases, the extent of this transition varies according to local conditions.

4.4 The role of district heating versus individual heating

A recurring theme across the studies in this thesis is the interplay between DH and individual heating solutions, particularly HPs. While each study applies a distinct methodological lens, their combined findings provide deeper insights into the conditions under which DH continues to play a central role, and when individual heating becomes more prominent. This section compares the results across studies and analyzes how the methodological differences, particularly in terms of the spatial system representation, treatment of WH, electricity system modeling, temporal scope, and actor involvement, help explain why DH or individual heating becomes more favorable in different contexts. By comparing how these modeling dimensions are handled in **Papers I–IV**, the analysis discusses differences in results between the papers, and the underlying assumptions that drive them

The central insight across the studies is that spatial heterogeneity within the urban area, particularly in terms of heat demand density, building typology, distance to DH infrastructure, and excess heat availability significantly shapes the feasibility of heating technology mix. In **Paper II**, districts with high heat density and compact building structures are more likely to retain or expand DH, whereas detached housing concentrated and located farther from existing DH pipelines tend to favor individual solutions such as HP. **Paper IV** reinforces this by incorporating a representation of the DH transmission pipeline network, which enables the model to capture nodal heat exchanges between interconnected nodes. The model includes temperature,velocity, and pipe diameter parameters in the calculation of heat transfer, providing a more physically grounded estimate of flow dynamics compared to simplified energy-only representations. The inclusion of the pipeline network allows for observation of how the role of specific nodes shifts depending on their ability to import or export heat efficiently, and adds a dynamic spatial layer to the analysis that is not captured in more aggregated models in **Papers II** and **III**.

Including these network constraints in the modeling influences the interplay between DH and individual heating technologies and shows where and how heat can be cost effectively distributed across the system. It reveals that DH can remain competitive in nodes that are either well-connected to centralized WH sources or capable of efficiently exporting or importing heat via the transmission pipes. In contrast, in nodes located far from WH sources and where pipeline is costly, i.e., due to age of pipes, individual solutions like HPs become more favorable. It is important to note that while refineries and the incineration process emit CO_2, and there is a risk that incineration may not be sustainable in the long run, these aspects are not reflected in the modeling. Without this level of spatial-infrastructural resolution, models may either overestimate the competitiveness of DH by assuming unrestricted access to waste heat across all nodes, or prematurely predict its decline across the entire system if a high enough cost is assumed for aggregated DH infrastructure.

In models without physical representation of DH transmission pipelines, the straight-line distance between heating sources, i.e., location of industries, heat generation plant, and demand centers often becomes the main determinant of DH viability. This reflects a greenfield planning approach, where new transmission pipelines are assumed to be built, with transmission costs typically scaled by distance. In contrast, the model in **Paper IV** incorporates an existing transmission network with fixed heat transfer capacities between nodes, allowing the model to account for current infrastructure constraints. However, it does not allow for investment in new or expanded transmission capacity, which limits the model's ability to explore long-term infrastructure development pathways. Nontheless, with the transmission network explicitly modeled in **Paper IV**, it becomes possible to identify intermediate or transit nodes that facilitate heat transfer across the system. Their strategic position within the network allows them to efficiently relay heat from heating sources to more distant demand areas at relatively low cost. As a result, the model may find DH to be viable in locations that would otherwise be excluded in more simplified DH system representations. This highlights how incorporating physical infrastructure details can lead to more favorable and geographically nuanced outcomes for DH feasibility, especially in systems with spatially distributed heating sources.

Another important factor influencing the interplay between DH and individual heating is the treatment of the electricity system within the modeling framework. In **Papers II** and **III**, which apply a participatory TIMES-based model, the electricity system is not explicitly modeled in parallel. Electricity is treated as an externally supplied energy carrier with fixed, seasonal average prices, and no endogenous electricity generation or temporal dynamics are included. This simplification means that the model does not account for hourly electricity price variations or system-level interactions between electricity and heat. As a result, the competitiveness of electric heating technologies, such as individual and centralized HPs, is assessed under static electricity price assumptions, and their ability to respond to short-term electricity market dynamics is not captured. In contrast, **Paper IV** includes a fully coupled representation of the electricity and heating systems within an hourly-resolved optimization framework. This allows the model to reflect dynamic electricity prices with flexibility measures, variability of renewable electricity generation, and electricity supply constraints, such as grid capacity limit and peak demand hours.

In the model, large-scale HPs are modeled with operational flexibility and can be supported by investment in TES, whereas individual HPs operate primatily on demand and therefore offer limited temporal flexibility. The cost of this flexibility is reflected in the investment and operating costs of TES and the capital cost of the large-scale HPs themselves, which must be sized to allow for this dynamic operation. On the other hand, individual HPs are modeled without associated thermal storage, i.e., their operation is driven directly by heat demand and electricity prices, but without the ability to shift load over time. Consequently, the role of individual electric heating technologies becomes highly sensitive to the temporal cost and availability of electricity. The implications of these different assumptions regarding electricity system are substantial. In the TIMES-based model (**Papers II** and **III**), individual heating technologies may appear more stable and predictable due to the lack of operational cost variability, while DH options are evaluated more on infrastructure and fuel costs. In the coupled model (**Paper IV**), however, the dynamic nature of electricity prices can both enhance and constrain the feasibility of individual solutions, depending on the broader system context.

This is also reflected in the consumption-weighted electricity prices faced by the two technologies in the coupled model. For example, in the Current WH level scenarios in **Paper IV** with the annual refurbishment rate of 0.2%, individual HPs pay a higher average electricity price of 62 €/MWh, compared to 55 €/MWh for large-scale HPs in the DH system. In reality, individual HPs may have some temporal flexibility using the the thermal inertia of the building as an energy storage. However, previous work has shown that on cold days, HP load can be shifted by building thermal inertia by 3–4 hours , while TES in DH system can be sized to shift load over much longer timescales to multi-day horizon, allowing it to more efficiently avoid high electricity price periods [156–158]. Thus, incorporating the electricity side account for an important difference between individual and large-scale HP athough the difference may be slightly exaggerated due to thermal inertia not being represented in the modeling. The simplified electricity price representation in **Papers I–III**, where both large-scale and individual HPs face the same seasonal average price, likely favours individual HPs by removing the economic advantage that large-scale HPs gain from TES-enabled flexibility. In the coupled model of **Paper IV**, this advantage is visible as lower consumption-weighted electricity prices for large-scale HPs.

Another methodological difference that influences the results across the studies is the temporal scope and resolution of the models. In **Papers II** and **III**, the TIMES-based model adopts a multi-year time horizon from the present such as Year 2021 and 2022 to Year 2050, at seasonal time resolution, to represent intra-annual variation. This structure is well-suited for exploring long-term investment decisions and technology transitions over time, but it does not reflect hourly system behavior. Consequently, the model emphasizes how investment decisions change over time, over hourly variation in system performance. Technologies are therefore assessed based on their long-run costs and static seasonal assumptions, which may overlook timing mismatches between supply and demand. The multi-year, seasonal models may favor solutions that perform well on average across seasons and over time, often reinforcing strategic infrastructure investments like DH in dense areas or widespread adoption of individual HPs in less connected districts. In contrast, **Paper IV** takes a one-year snapshot approach for Year 2050, modeled at hourly resolution. This one-year snapshot limits the analysis of temporal scope, and therefore does not account for investment pathways, technology ramp-up, or infrastructure lock-ins that can influence long-term system development. For example, while DH may not appear cost-competitive in certain nodes in Year 2050, it might have been economically viable if investments had been made earlier. Similarly, widespread adoption of individual HPs in earlier periods may lead to lock-ins that reduce the feasibility of DH expansion later, even where it could be more efficient.

Moreover, in the multi-year models (**Papers II** and **III**), several key parameters change over time reflecting assumptions about how technology costs, fuel prices, and emissions policies evolve over time. These include declining technology investment costs, increasing CO_2 tax imposed on fuels, changes in electricity prices, and heat demand driven by building stock renovation and efficiency improvements. These changes are applied at selected milestone years in **Papers II** and **III**, primarily Years 2021, 2030, and 2050 (**Paper II** applies Year 2022 as starting year), rather than annual basis, reflecting broader policy and planning timeframes. The results clearly show shifts in cost-competitiveness over time as these parameters change. For example, in **Paper II**, natural gas boilers dominate in 2021 when CO_2 taxes are low and investment costs for HPs remain high. By 2050, higher CO_2 taxes and lower HP investment costs lead to a transition towards HPs. Including multiple years captures such transitions, which would be missed in a single-year model where all parameters are fixed. As such, the seasonal multi-year model highlights long-term structural pathways and strategic infrastructure choices, while the hourly snapshot model offers detailed operational insights for a single year. Together, these approaches offer complementary perspectives: the former emphasizes transitional dynamics and strategic planning, while the latter provides operational dynamics and highlights the temporal variation of heating technology performance.

A further important distinction across the studies lies in whether or not actors participate in and influence the modeling process, which significantly shapes how the problem is framed and, ultimately, the role assigned to DH versus individual heating. **Papers II** and **III** are unique in their participatory modeling approach, where municipal stakeholders were directly involved in defining problems and scenarios, and provided feedback during the iteration of results presentation. For example, in **Paper II**, technologies involving biomass combustion such as biomass boilers and biomass CHP were excluded from the modeling based on local concerns or contextual constraints raised by the stakeholders, despite their potential cost-effectiveness. In contrast, **Paper III** did not include such restrictions, and **Paper IV**, which adopts a more conventional techno-economic optimization framework without explicit representation of institutional preferences, includes biomass-based options where they are cost-competitive. In this context, DH is retained primarily where it is the most cost-effective solution from a systems perspective, and not necessarily where it might serve broader public planning goals. This divergence in actor involvement has clear implications for the modeled feasibility and desirability of DH and individual heatings, and it is further discussed in Section 5.3.

5. Discussion

This chapter synthesizes the key findings from the four studies and reflects on how spatial and infrastructural factors shape municipal heat transition pathways. Drawing on both participatory and technical-oriented modeling approaches, the discussion examines the robustness and implications of the key findings. The chapter is structured into four parts: 1) a summary of the main results, focusing on spatial variation and stakeholder knowledge, infrastructure, and future uncertainties (Section 5.1); 2) a methodologic reflection on the development and application of the two modeling approaches (Section 5.2); 3) a discussion of the results and methods in relation to existing literature and their broader implications (Section 5.3); 4) a consideration of the limitations of the research (Section 5.4). Together, these reflections place the thesis contributions within the wider context of urban energy systems research and planning practices.

5.1 Summary of results

This thesis demonstrates that municipal heating transitions are shaped by complex interactions between spatial, infrastructural, and systemic factors. The modeling results derived from diverse contexts, urban and semi-rural, reveal that spatial heterogeneity is not merely a boundary condition but a defining feature of energy system transformation. The results also show that aging infrastructures and uncertainties related to WH and decarbonization pathways in other sectors (e.g., industry and electricity) interact in non-trivial ways with local conditions to determine the long-term feasibility of future heating solutions. This suggests that robust municipal strategies must anticipate changes beyond the heating sector, such as industrial restructuring or decarbonisation, rather than treating these as fixed externalities.

5.1.1 Influences of local spatial characteristics and stakeholder knowledge

Local spatial characteristics, such as building density, typology, and proximity to existing infrastructure, are primary determinants of cost-optimal heating configurations. In the semi-rural case, a low heat demand density and scattered settlement patterns make decentralized options, such as individual HPs, biomass boilers, and solar heating, more attractive. In contrast, the urban case benefits from economies of scale and an existing infrastructure that support further expansion and densification of DH systems.

This mirrors previous studies from other European contexts [98,159] and aligns with practical planning intuition: dense, infrastructure-rich areas are more suitable for networked solutions. It is evident from the cases that spatial planning decisions and heating system strategies are closely interconnected. For example, the spatial overlap between high-density and aging DH infrastructures influenced the modeled outcomes for Gothenburg's nodes, where DH pipelines refurbishment was either economically viable or strategically justified. Conversely, areas with a predominance of SFH, such as the Frölunda and the Rya node, leaned more towards decentralized transitions, especially when facing constraints such as WH scarcity or outdated pipelines. Stakeholder knowledge was instrumental in refining these insights. Participatory modeling in the Danish municipalities revealed that local planners' inputs, such as preferences in favor of or against biomass, the perceived potential of biogas substitution for natural gas, and future land-use plans, substantially altered both the scenario design and outcomes. While the modeling framework remained techno-economically driven, these inputs directed attention to particular assumptions and contextual factors, thereby shaping how the results were understood in the local planning setting.

5.1.2 Roles of refurbishment strategies in the aging infrastructure

The Gothenburg case explores how varying DH pipe refurbishment rates influence spatially differentiated heating system outcomes, revealing distinct nodal responses that are dependent upon infrastructure age, heat demand density, and proximity to WH sources. While the city-wide modeling suggests that DH remains a resilient backbone of the urban heat supply, even under higher refurbishment rates, the local-level dynamics reveal more variations across areas. These differentiated outcomes highlight that refurbishment decisions cannot be made based on uniform assumptions. Instead, they should be informed by node-specific indicators such as pipeline age, the marginal cost of heat supply, connection densities, and the existing capacities of DH units. Similar lessons have been drawn in infrastructure asset management literature, where localized condition data leads to more cost-effective investment sequencing [160]. The results show that refurbishment costs constitute a relatively small share of overall system costs and have a limited influence on overall system performance and the total system cost. This suggests that refurbishment efforts can be scaled up without significantly reducing the cost-competitiveness of DH. However, the impact of DH pipe refurbishment is not uniform across the city, as its value depends on local infrastructure conditions and the spatial system dynamics.

5.1.3 Impact of waste heat availability

A central finding of **Paper IV** is the sensitivity of future DH configurations to the availability and location of WH. The modeling demonstrates that WH is not just a supplementary resource, but a structuring element of the heating system that shapes the flows of energy between nodes and the composition of heat supply technologies. The withdrawal or reduction of WH from the refineries at a specific node (Rya), results in cascading, system-wide effects. However, the total quantity of WH is not the only relevant factor, as its spatial distribution and connection to a transmission infrastructure determine its systemic value. For example, the removal of refinery WH in one node has more-severe consequences than a system-wide reduction of WH availability across the two nodes. This is due to the node of refinery WH's centrality in heat exports and the strong dependency of the Central node on this supply route. For example, the full loss of refinery WH supply (No refinery WH scenario) leads to greater system impacts, than a distributed reduction scenario (Reduced WH level scenario) where the total reduction in WH availability is greater in the latter scenario (by 53%) than in the former (by 45%)

relative to the Current WH level scenario, the corresponding decline in the DH share is slightly less pronounced in the Reduced WH level scenario.

These phenomena are observed also in the semi-rural case study in **Paper III**, which investigated the potential of integrating WH from the local wastewater treatment plant and neighboring industrial site into a DH system. The results highlight how proximity to industrial WH and existing infrastructure enables economically viable DH expansion in semi-rural contexts with a dispersed heat demand. However, a potential vulnerability should also be taken into account: while industrial WH can support DH expansion in the near term, the long-term system resilience may be compromised if these sources diminish or disappear due to changes in industrial activity. As such, while the geographic and infrastructural co-location of WH sources and heat demand can offer near-term benefits, it should not be seen as a permanent solution for DH systems in the absence of contingency planning. Therefore, both cases illustrate the importance of designing systems that are both spatially optimized and robust to industrial uncertainty.

These findings reinforce the importance of geographic flexibility and system redundancy. Future WH integration strategies should be based not only on projected volumes, but also on siting decisions, co-location with transmission capacity. The vulnerability to changes in industrial operations should also be considered. As industrial decarbonization proceeds, potentially reducing the availability of WH , cities will have to prepare for scenarios in which the supply of WH is less-predictable, more-distributed or subject to commercial and regulatory uncertainties.

5.2 Methodologic reflection

This thesis develops and applies two complementary modeling approaches: a spatially explicit participatory modeling framework and a technically-detailed optimization model. Together, these approaches provide a multi-layered response to the following research question: How can a spatially detailed techno-economic optimization methodology be developed and applied to support municipalities in identifying cost-efficient heat decarbonization pathways?

5.2.1 Participatory modeling (Papers I - III): embedded in long-term local planning

The participatory modeling approach creates a methodology by involving municipal stakeholders in all phases of the modeling process. Through collaborative scenario development, local data validation, and feedback sessions, the modeling framework is shaped by the institutional realities, planning norms, and technical knowledge of municipalities. This fosters local ownership and increase the usability of the model results, as the model incorporate geospatial data on the building stock, infrastructure proximity, and planned developments, to capture district-level heterogeneity. By aligning the spatial logic of the model with the administrative and planning rationale of municipalities, it creates a framework that is capable of bridging urban planning and energy planning. The ability to co-produce spatially resolved, policy-relevant scenarios offers a tangible improvement over conventional top-down models, which often lack local relevance. While the municipality has not formally adopted the outputs of this work, the spatial analysis and scenario insights could support future planning by providing a structured, model-based complement to existing evaluations.

However, participatory modeling presents certain challenges. One concern is that scenarios and assumptions often remain constrained by what is considered politically or institutionally feasible [130]. This reflects a trade-off inherent in co-designed scenarios: the benefit of aligning with local stakeholder perspectives and increasing the legitimacy of the results is balanced against the risk of narrowing the technological scope and potentially omitting more radical transition pathways. In **Papers I-III**, the scenario scope is primarily defined in collaboration with stakeholders, in order to support municipal planning under locally acceptable conditions. To balance this with a broader perspective, **Paper III** includes a more open scenario encompassing all technologies, which allows the comparison between stakeholder-aligned futures and the full range of technically feasible options. Maintaining engagement across diverse stakeholders could be another challenge, as group composition is often shaped by resource limitations and facilitation capacity [131,132]. In addition, disciplinary divides and model complexity can hinder active participation, underscoring the need for careful facilitation to ensure meaningful input [133].

5.2.2 City model (Paper IV): infrastructure representation and a 1-year snapshot

The technically detailed city model contributes a spatially grounded representation of physical infrastructure, complementing the participatory approach by adding analytical depth. Its hourly resolution allows for the assessments of temporal flexibility, an aspect that participatory approaches generally cannot capture due to their more qualitative or aggregated structure [84,161]. Likewise, the model's multi-node structure facilitates an explicit representation of spatial interactions, including the heat exports, inter-node dependencies, and the marginal cost dynamics, addressing limitations of single-node or spatially aggregated optimization models.

Importantly, the model enables the systematic testing of the key uncertainties such as WH availability and refurbishment strategies, which are difficult to explore in stakeholder-led processes without computational support. By structuring such uncertainties within an optimization framework, the method facilitates the exploration of alternative transition pathways, highlighting the trade-offs such as centralization versus decentralization, reinvestment versus dismantling, and electrification versus WH use. In this sense, the model illustrates how high-resolution, spatially explicit optimization can complement participatory methods, by making visible the system-level consequences of local choices, and by clarifying the techno-economic boundaries within which the planning discussions unfold.

5.2.3 Complementarity of the two approaches

The integration of the two modeling approaches in this thesis, one participatory and the other technically detailed, demonstrates the value of methodological complementarity in urban energy system research. Both models are optimization-based, yet their purposes and design rationales differ. The participatory model embeds local knowledge, institutional constraints, and planning visions into a long term transition framework, while the latter model provides a techno-economically rigorous representation of physical infrastructures and system-wide dynamics with an hourly resolution under various future conditions.

The complementarity highlights that techno-economic optimaztion can provide important, unbiased information on cost efficient pathways, which should serve as a basis for energy planners. Yet, integrating local spatial context and stakeholder perspectives is essential to capture additional aspects that enhance the relevance and legitimacy of the modeling results. The participatory method ensures that model outputs reflect stakeholder priorities, real-world constraints, and local spatial context, factors often underrepresented in conventional system models. Yet, unbiased information on cost efficient pathways may be lacking. Meanwhile, the technically detailed model (**Paper IV**) offers scenario-based clarity in relation to infrastructure and regional interdependencies, particularly in complex urban environments, albeit with higher computational requirements. The two approaches are not mutually exclusive but are instead mutually reinforcing, and the participatory modeling could be done using a model with higher technical detail. Had the city-scale model also incorporated actor input more directly, such as local constraints on certain technologies, or district-specific political and planning priorities, the resulting outcomes might have shifted, especially in those areas in which the techno-economic optimization diverges from the planning feasibility. At the same time, more unconventional solutions might have been missed.

With the two approaches of participatory modeling and a physically detailed system representation, this thesis contributes a more holistic and practice-relevant approach to planning decarbonized urban heating systems, one that future research can extend to integrate further dimensions of uncertainty. In principle, combining the two approaches into a single framework could be highly beneficial, as it would allow the technical rigor of the city-scale model to be complemented by the contextual knowledge and legitimacy provided through participatory engagement. At the same time, keeping the models separate can also be advantageous, since it enables each to be tailored to its primary purpose: one to engage planners and integrate local knowledge, and the other to analyze system-level trade-offs with technical detail. In this sense, the choice is not about superiority of one approach over the other, but about how they can be combined or applied in parallel depending on research objectives and planning needs.

5.3 Discussion of results and methods

This thesis focuses on how spatial differentiation, infrastructure dynamics, and institutional factors influence municipal heating transitions, thereby contributing to an evolving body of research on local energy system planning [97,162–165]. While many national or regional energy system studies rely on aggregated data or assume uniform transition pathways, this work provides empirical evidence that the spatial heterogeneity is not merely a modeling detail, but a determinant of viable decarbonization strategies. Across both urban and semi-rural contexts, the results show that, as expected, factors such as distance to the heating infrastructure, building typology, demand density, and infrastructure age influence the cost effectiveness and feasibility of various heating options. This supports earlier studies emphasizing that the spatial distribution of heat demand is critical to planning cost-effective collective heating systems, as infrastructure costs are highly sensitive to factors, such as linear heat density, distance to the heat sources, and network length [98–100,166].

The novelty of this work lies in incorporating and quantifying explicitly the spatial and infrastructural characteristics within the modeling framework, thereby extending how such factors are represented and highlighting their implications for the long-term heating strategies. In particular, in the semi-rural case, the availability of locally accessible energy sources such as biomass or WH can make DH a viable and strategic option even in rural settings with low heat demand density and dispersed settlement patterns. These findings align with several studies on rural heating transitions which highlight leveraging locally available renewable resources and the spatial proximity to them for using in the centralized heating systems in low-density areas [167,168]. As such, rural areas should not be excluded from DH considerations solely based on population or building density. Instead, planning approaches must account for the spatial distribution of local energy resources, industrial WH, or wastewater heat as these can shift the balance in favor of centralized solutions even in dispersed settings. This finding challenges the common assumptions in national or regional models that typically categorize rural areas as unsuitable for DH and instead default to individual heating technologies. It suggests that the need for spatially resolved assessments in rural heat planning, especially where renewable or excess heat sources are within feasible proximity.

In the case of the urban municipalities investigated in **Papers II** and **IV**, the works demonstrate the continued value of DH, particularly when supported by existing infrastructures and spatially concentrated heat demands. This aligns with earlier studies [98,159], as mentioned above, which emphasize the efficiency and climate benefits of DH in dense urban settings. However, **Paper IV** adds further granularity by showing how DH distribution pipeline refurbishment affects the distribution of heating supply choices across the city. **Paper IV** shows that refurbishment in dense andhigh-demand zones can be carried out without major system-level disruption and high expenses, but in lower-density areas with aging infrastructure or limited access to WH, decentralized alternatives may be more appropriate. This highlights the need for node-level assessments and spatially targeted reinvestment strategies within urban DH systems, rather than city-wide assumptions about DH viability.

Stakeholder engagement further shapes the results in critical ways. Participatory modeling in the Danish municipalities in **Papers II** and **III** reveals that local planners' preferences such as avoidance of biomass combustion, interest in biogas, and the alignment with the spatial plans have a tangible impact on both the scenarios considered and the resulting system configurations. This aligns with the findings from McGookin et al. [129] and Süsser et al. [119], who stress that stakeholder inputs can substantially reshape energy modeling outputs by introducing context-specific constraints and priorities. Importantly, this thesis suggets that when stakeholder knowledge is integrated into technically grounded modeling, the resulting insights tend to be more relevant for real-world decision-making, as they reflect planning priorities and context-specific feasibility. When the local priorities are integrated, modeling becomes a tool for dialogues and negotiation rather than a purely technical exercise. In this way, participatory approaches can bridge the gap between technical feasibility and planning legitimacy, ultimately increasing the likelihood that the decarbonization pathways are both actionable and supported by those who are responsible for implementation [169].

Both spatial conditions and institutional priorities are crucial for ensuring locally relevant results, but this creates a trade-off: findings become more context-specific and less easily generalized. Tailoring the analyses to the local circumstances enhances practical usefulness and legitimacy, yet it reduces comparability and broad applicability. This tension is not a weakness but a central challenge in energy system research – balancing generalizable insights with actionable, place-specific knowledge. This thesis demonstrates how spatial and institutional factors can be systematically integrated into modeling, offering a path toward approaches that are both rigorous and locally grounded.

The treatment of WH as a spatially embedded factor that shapes system configuration and development, rather than as a static input is another contribution of this thesis. While many optimization studies incorporate WH as a single input parameter, such as in [170] and in [171], the findings in **Papers III** and **IV** show that the availability and location of WH, and network connectivity have non-linear and sometimes counterintuitive impacts on system configurations. The removal of WH from the refineries (the Rya node) in **Paper IV**, for instance, has more severe implications for DH viability than a larger but geographically distributed reduction in WH availability. This observation aligns with recent work [106] showing that the proximity, integration conditions, and system connectivity must be considered alongside the total volume when evaluating the potential of WH utilization. This calls for a shift from static modeling assumptions towards more dynamic and geographically resolved approaches.

In terms of implications for policy and practice, the findings point to the need for planning tools that can simultaneously reflect localized decision logics and broader system-wide interactions. As municipalities take on greater responsibility in climate action, including heating transitions, the ability to co-produce actionable and spatially grounded scenarios will be critical. Moreover, the uncertain future of WH, especially in the face of industrial decarbonization, calls for planning approaches that prioritize flexibility and geographic diversity in system design. These findings offer practical insights for cities like Gothenburg and other European municipalities that are seeking to align the long-term infrastructures reinvestment with carbon-neutrality goals under various conditions with spatial diversity and systemic uncertainty.

5.4 Limitations

While the thesis develops and contributes to the methodologic understanding of spatially explicit and participatory energy system modeling for municipal heat transitions, certain limitations must bt considered. The participatory modeling process focuses primarily on municipal planners, who have critical knowledge regarding the local infrastructure, planning procedures, and policy ambitions. However, the non-inclusion of other relevant actors, such as energy utilities, building owners, industrial stakeholders, and civil society representatives, constrains the representativeness of the insights generated. These actors might offer additional perspectives on the practical feasibility, behavioral dynamics, and acceptance barriers associated with different heating technologies. Their absence potentially narrows the scopes of the identified pathways and underrepresents the socio-technical complexity of heating transitions.

In addition, the modeling approaches used in this thesis rely on a set of assumptions that simplify certain features of the real-world systems that they aim to represent. The technically-detailed city model assumes static DH transmission pipeline capacities and does not allow for endogenous investments in transmission expansion, which may underestimate the system's adaptability under shifting demand or supply conditions. The building stock is represented through aggregated typologies while being necessary for tractability, limit the ability to analyze micro-level variations such as intra-district differences in socioeconomic characteristics, building form, or ownership structure. Moreover, the model assumes universal deployability of technologies such as individual HPs, without accounting for potential spatial or regulatory constraints enough, such as space limitations in apartment buildings, heritage protection policies, or resident preferences, which might significantly impact real-world adoption.

The generalizability and transferability of the proposed modeling methodologies are also subject to limitations. The participatory modeling relies on access to spatially detailed building stock data (e.g., from the Danish building registry BBR) and presupposes the existence of institutional capacity for sustained stakeholder involvement. These prerequisites may not be met in all planning contexts, particularly in regions with data scarcity, limited institutional resources, or fragmented planning structures. Applying the approach in different countries or cities would require tailoring to local data standards, governance frameworks, and planning cultures. Furthermore, the stakeholder engagement process is resource- and time-intensive, which may challenge its feasibility in municipalities with constrained planning capacity or with limited institutional support for cross-sectoral collaboration.

Lastly, the structuring of the scenario space in both modeling approaches raises important methodological issues. In the participatory model, scenario development is guided mainly by stakeholder inputs, ensuring contextual relevance and local ownership. However, this reliance on institutional perspectives may limit the inclusion of more-exploratory or disruptive futures, particularly those that challenge existing policy trajectories or institutional paradigms. Conversely, in the city model, the scenarios are defined externally by the researcher and explored through systematic parameter variation, which may overlook locally relevant constraints, opportunities, and values. Both approaches, while valuable in their own right, highlight the tension between contextual specificity and exploratory breadth. Future studies could benefit from hybrid scenario-building processes that integrate stakeholder co-design with structured critical reflection, enabling the exploration of both preferred and disruptive futures within a coherent modeling framework.

6. Conclusions and future research

This thesis has develops and applies a spatially explicit, participatory, and scenario-based energy system modeling approach to examine heat decarbonization in urban and semi-rural municipalities. By engaging local stakeholders, incorporating spatial and infrastructural characteristics, and exploring future uncertainties, such as DH refurbishment strategies and WH availability, the work contributes both methodologically and empirically to the field of municipal energy system planning.

A central finding of these studies is that heat decarbonization of the heating sector is inherently place-specific. The cost-effective configuration of future heating systems is not only shaped by technology costs and emissions targets but also by local spatial attributes, including building typology, heat demand density, existing infrastructure, and geographic proximity to WH sources. These factors determine not only the technical feasibility of options such as DH and HPs but also their levels of economic attractiveness under various conditions.

The participatory modeling applied in the urban and semi-rural case studies emphasizes that stakeholder involvement significantly enhances the legitimacy, contextual relevance, and usability of the model outcomes. Municipal planners provided critical insights into spatial zoning, technology preferences, and infrastructure priorities, which directly influenced the scenario formulation and model interpretation. By aligning energy modeling with local planning knowledge and needs, this approach supports more-grounded and actionable decision-making at the municipal level. The methodology is flexible and adaptable, offering a valuable tool for other municipalities that are aiming to develop long-term heating transition strategies.

This thesis further contributes to the understanding of infrastructure-related decision-making, particularly in the context of aging DH networks. In **Paper IV**, the system-level impact of varying DH refurbishment rates was relatively limited. However, localized impacts were substantial, shaping investment needs, reinforcing or undermining DH viability in specific districts, and influencing the competitiveness of decentralized heating solutions. These results highlight the importance of accounting for infrastructure age and refurbishment costs not only in aggregated cost models, but also through disaggregated spatial modeling that captures local variations. Similarly, WH availability emerges as a decisive factor in shaping heating transitions. The analysis shows that the location and accessibility of WH sources are often more important than their total volumes. The scenarios with a constrained WH supply illustrate how the loss of WH in one node can cascade through the system, undermining DH viability, increasing the electricity demand, and prompting shifts in import-export patterns between districts. This highlights the sensitivity of future DH strategies to industrial decarbonization trajectories and underlines the need for system flexibility in WH sourcing.

While **Paper IV** primarily focuses on technical and economic optimization, the findings carry broader planning implications. Municipalities must manage long-lived infrastructure investments under conditions of uncertainty, balancing short-term cost efficiency with long-term robustness. **Papers II** and III also reveal that rural and urban heating transitions require differentiated strategies. Semi-rural areas with dispersed heat demand benefit from using locally available resources, such as biomass or wastewater heat, while urban areas with high heat demand densities and existing DH infrastructure can justify reinvestments and the integration of new technologies, such as large-scale HPs or power-to-heat solutions.

This thesis opens up several avenues for further research. While it demonstrates the value of stakeholder participation, future studies should compare in a systemativ way participatory and non-participatory modeling outcomes, so as to understand how actor involvement shapes scenario design, assumptions, and decision relevance. Incorporating a higher temporal resolution and greater flexibility in electricity use, particularly for power-to-heat technologies, should capture more effectively the interactions between heating demand and renewable electricity variability. Further work is also needed to address social equity. While the current modeling emphasizes cost-effectiveness, future studies should assess the distributional impacts of heating strategies across different income groups and neighborhoods. This could support more-inclusive and just transitions.

As industries decarbonize or relocate, the availability of WH will become increasingly uncertain. This highlights the need for contingency planning in DH system design, ensuring that networks can adapt to potential disruptions in industrial heat supply, whether due to decarbonization, economic shifts, or infrastructural changes. While this was not explicitly modeled here, recent studies underline its importance: Marx et al. [172] quantify the economic risks of uncertain WH availability, while Moser and Jauschnik [53] emphasize institutional vulnerabilities linked to industrial partner changes. These findings suggest that WH should be treated as a strategic but uncertain component of the urban energy system, requiring both spatial optimization and institutional foresight.

Research studies should also explore strategies to reduce dependency on individual WH sources, such as those involving diversification, storages, and hybrid systems. The transferability of the participatory modeling approach to municipalities with limited data or institutional capacities also deserves attention. Adapting the methodology to different planning contexts would expand its relevance and usability. Finally, future research could strengthen the integration of heating system modeling with other urban domains, such as transport, land use, and climate adaptation, through improved tools and cross-departmental coordination. Building on this thesis, future work can help to ensure that heating transitions are not only technically robust and economically viable but also socially equitable and aligned with institutional realities.

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Appendix

Appendix A. Interviewees

Table A1. 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

Appendix B. Sources used for the Districts

1. Urban case (Papers I and II)

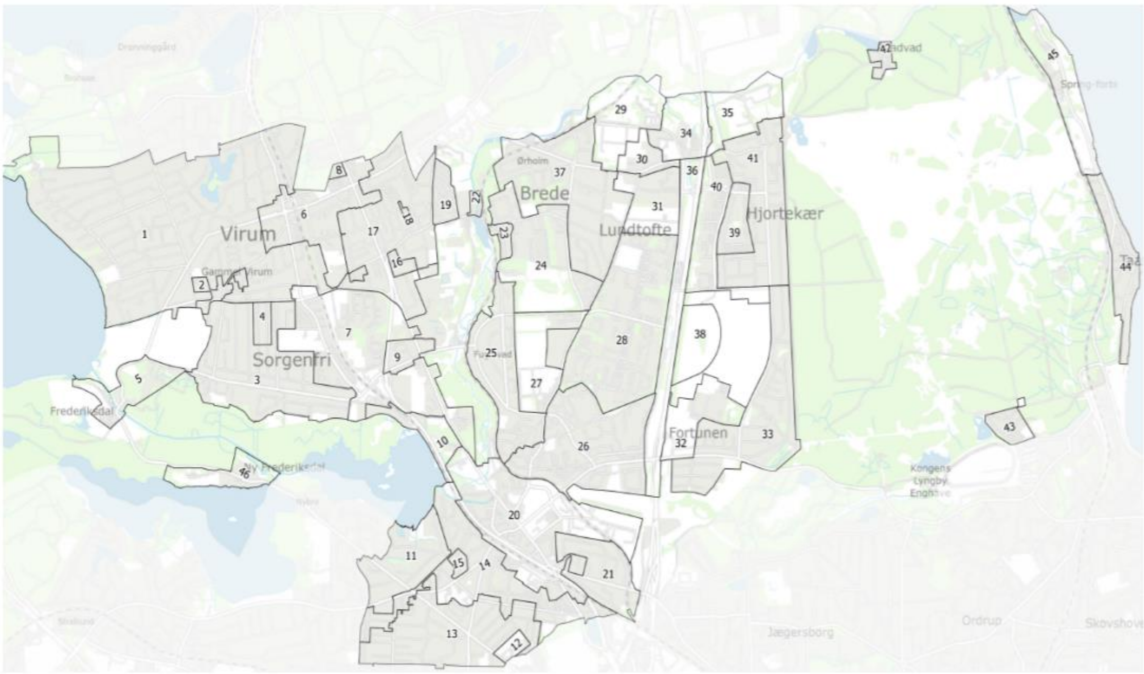

Figure B1. Existing geographic divisions of the municipality available in the national building and dwelling registry (BBR).

Figure B2. Municipality's official urban quarter divisions.

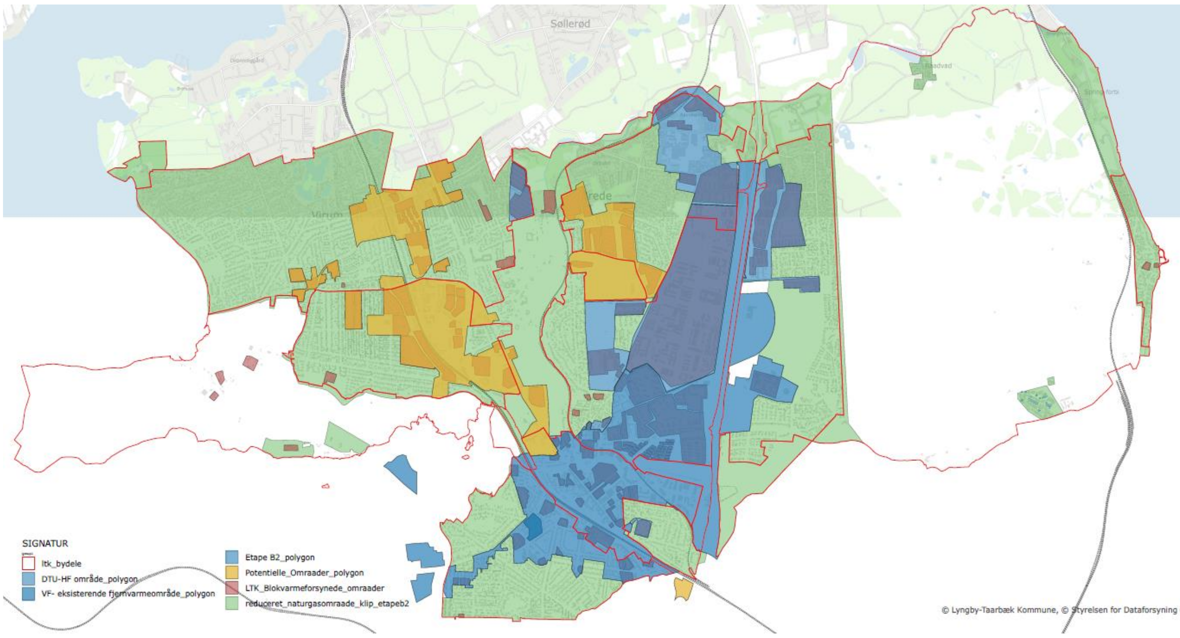

Figure B3. Current heating supply technologies in Lyngby-Taarbaek Municipality.

2. Semi-rural case (Paper III)

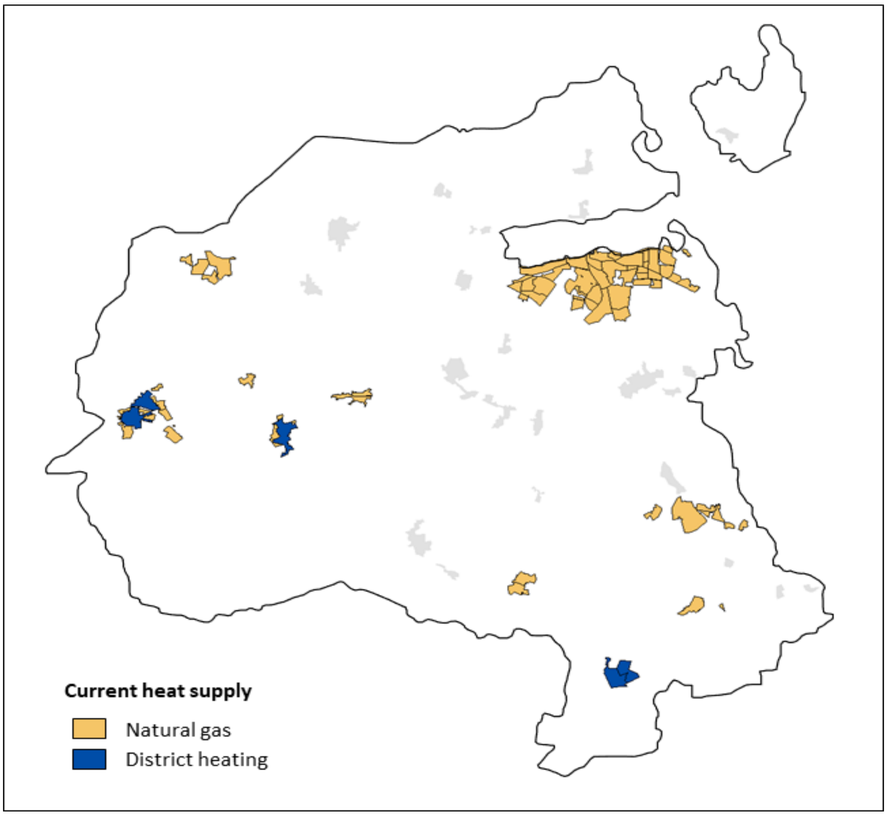

Figure B4. Current heating technologies in HK Municipality.

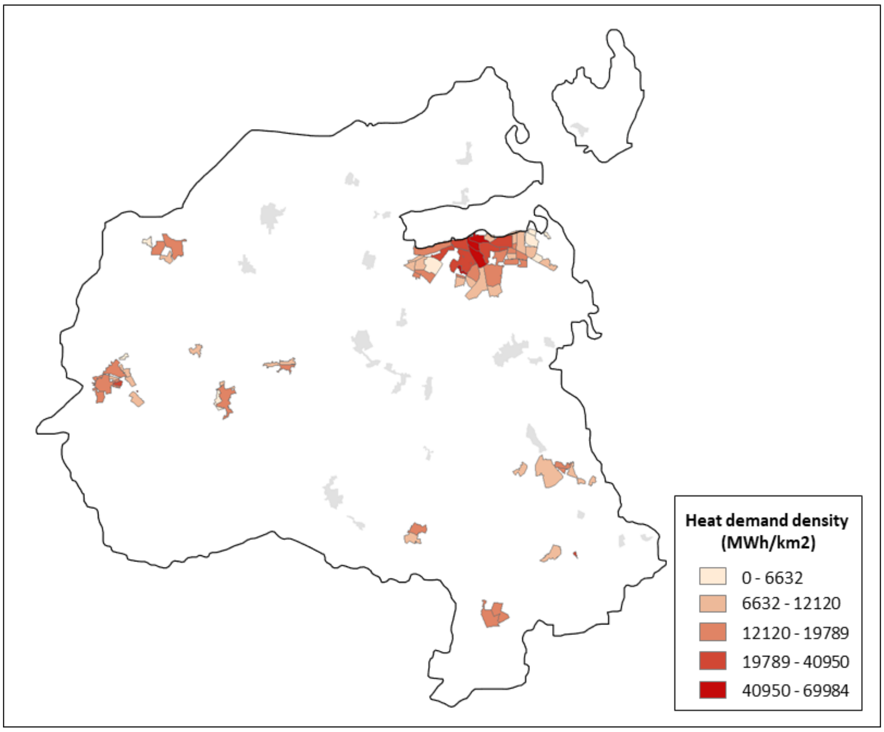

Figure B5. Heat demand densities in HK Municipality.

Appendix C. 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

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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?

Appendix D. Material for Scenario Discussion

1. Urban case (Papers I and II)

Table D1. 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 CO_2 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
CO_2 cap of 25% reduction by 2025	X	X	X	X	X
CO_2 cap of 50% reduction by 2030	X	X	X	X	X
CO_2 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
CO_2 tax increase		X			X
Ban on NG by 2035		X	X	X	X

Table D2. 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.

Scenario	Constraints included in the model run	Potential slider in the web-based platform
Reference scenario	No new investment	-
	CO_2 cap (Climate goal) 2025, 2030, 2050: 25, 50, 100%	-
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.		
Scen1: Environmental Scenario	New investment options	-
	Natural gas ban by 2035	-
	Stricter CO_2 cap 2025, 2030, 2050: 30, 55, 100%	-
	Biomass tax	0,24 / 0,12 / 0,48 DKK/kwh
	CO_2 tax 2021, 2030, 2050 (0,024 / 0,2 / 0,4 DKK/ton CO_2)	-
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.		
Scen2: HP expansion	New investment options allowed	-
	HP subsidy	15 / 20 / 25% (of HP investment cost)
	Natural gas ban by 2035	-
	Stricter CO_2 cap 2025, 2030, 2050: 30, 55, 100%	-
	CO_2 tax 2021, 2030, 2050 (0,024 / 0,2 / 0,4 DKK/ton CO_2)	-

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%?
	CO_2 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 CO_2 cap	Same as above
	Natural gas ban by 2035	Same as above
	Biomass tax	Same as above
	CO_2 tax	Same as above

2. Semi-rural case (Paper III)

Table D3. 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)

Appendix E. Existing capacity of transmission and DH units

Table E1. The transmission capacities between heating nodes (table on the left side) and DH production units and their capacities[4] that will be still operating in the future modelled year of 2050 (table on the right side). The first column in the left table indicates the direction of transmission pipes between heating nodes. h1: Sörred, h2: Rya, h3: Central, h4: Frölunda, h5: East, h6: North, h7: Mölndal.

Transmission pipe	Transmission capacity (GW)	Heating node	Existing DH production unit in 2050	Capacity (GW)
h1→h2	0.030	h1	N/A	
h2→h1	0.045	h2	Biomass HOB	0.124
h2→h3	0.500		Biomass CHP	0.039
h3→h2	0.200		Heat pump	0.050
h3→h4	0.075	h3	N/A	
h3→h5	0.060	h4	N/A	
h5→h3	0.045	h5	N/A	
h5→h2	0.025	h6	N/A	
h3→h7	0.037	h7	Biomass HOB	0.047
h7→h3	0.030			
h5→h6	0.135			
h7→h4	0.055			

[4] Biomass HOB in the Rya node (h2) has been in operation since around 2023. CHP plant in the Rya node is expected to be commissioned around 2026. Heat pump in the Rya node is also expected to be commissioned around 2027. Biomass HOB located in the Mölndal node (h7) is planned for commissioning around 2027 (Göteborg Energi, 2024).

Appendix F. District-level results in Paper III

Table F1. District properties.

District	Heat demand density (MWh/ km²)	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.

Appendix G. Cost structure of scenarios in Paper IV

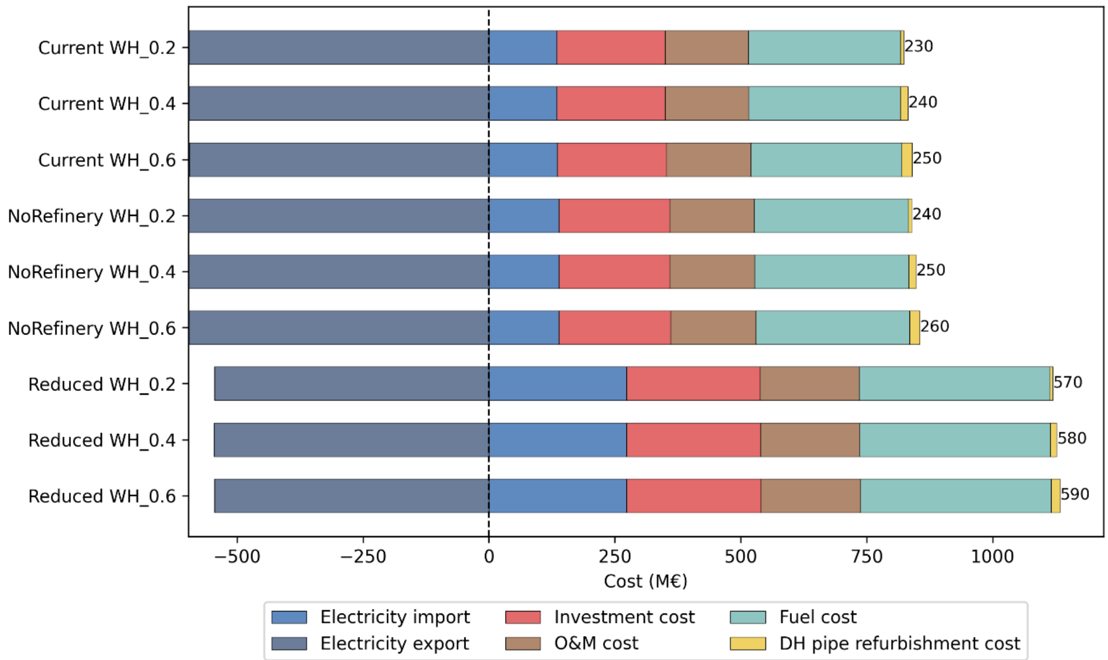

Figure G1. Cost structure of the total system cost across the three scenarios. Electricity exports are represented as negative values, reflecting economic gains in total system cost calculation. Operation and maintenance (O&M) costs include both fixed and variable components. The values displayed on the right of each bar represent the total system cost, calculated as the sum of all cost components.