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Policy-driven City Energy Systems Planning

- Spatially Explicit Technology Deployment and Co-Benefits Distribution

Kushagra Gupta

Department of Environmental and Energy Sciences

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Department of Environmental and Energy Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)73-492 0950

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Kushagra Gupta
Division of Energy Technology
Department of Environmental and Energy Sciences
Chalmers University of Technology

Abstract

Cities account for more than 75% of the global energy use and 70% of the total emissions, making urban climate action essential for decarbonization efforts and to achieve national climate objectives. Implementing emission reduction measures allows cities to realize a wide range of social, environmental, and economic co-benefits. Policy-driven decarbonization measures and their benefits are not always equitably distributed across urban areas, as socioeconomic and demographic disparities can lead to different levels of technological deployments. Taking into account consumer heterogeneity at high spatial resolution is therefore essential to understand how mitigation measures and their benefits are distributed. This thesis investigates the impacts of city energy plans on future cost-optimal system design, assessing their alignment with national climate objectives, and quantifies the delivery of co-benefits from urban climate action.

An integrated approach is employed, encompassing inter-connected demand-side and supply-side dynamics. The long-term decarbonization targets and policy measures are incorporated using a cost optimization model. The TIMES model generator is used to develop the TIMES Northern European city model, characterised by high heating and transportation demands and Gothenburg is selected as a suitable case. With the implementation of policy-driven scenarios based on City Energy Plan (CEP), and National Energy and Climate Plan (NECP) and sensitivity analyses, long-term sectoral developments of the buildings and transportation sectors and their impacts on local air pollution, resource efficiency and economic efficiency are evaluated. Cross-sectoral interactions are analyzed through the allocation electrification and bio-based resources, under varying assumptions on future fuel prices. The city is divided into 5 sub-regions to represent consumer heterogeneity based on socioeconomic and demographic characteristics and to quantify the distribution of co-benefits. Co-benefits delivery and distribution are assessed under different assumptions of income-dependent, technology-specific hurdle rates for residential consumers.

The city's heating system is already largely decarbonized, with only a small share of natural gas-based production remaining. The fossil fuel ban under the city's energy plan ensures complete phase-out of the remaining fossil-fuel use. The modelling results show that under the NECP scenario, district heating production is reduced by approximately 15% compared to the CEP scenario, as biomass use is constrained by territorial emission reduction targets. Heating supply options for residential buildings emphasize the declining cost-effectiveness of district heating with time, as the primary heating option for new apartments changes from district heating to heat pumps. Cost-efficient transport sector developments show a rapid deployment of biofuel-driven vehicles, followed by a gradual increase in electrification to meet emissions reduction targets. For passenger cars, the results indicate eventual 100% penetration of electric vehicles, with timelines that vary according to policy interventions and sub-regional factors.

The modelling results on grid infrastructure for electrification of residential heating and passenger vehicles emphasize the need for gradual investments in low-voltage distribution grid. Further, grid capacity investments are expected to reduce, with the deployment of distributed solar photovoltaic systems and battery storages. Bioresources are expected to have a transitory role in the transportation sector decarbonization, supporting the journey towards eventual electrification. The use of bioresources in the heating sector is expected to evolve to meet district heating demands; however, additional measures would be necessary to continue the use of biomass while complying with the national territorial emission reduction targets.

With a fully electrified passenger car fleet, exhaust emissions from passenger cars would be completely eliminated. However, because approximately 60% of the population belongs to consumer groups facing

delayed electrification, the overall air quality benefits are expected to materialize more slowly. On the other hand, particulate-matter emissions from non-exhaust sources (road, brake, tyre) are expected to persist long-term until measures to reduce the use of cars are applied. When assessing the impacts of climate policy on energy affordability, more than 15% of the population is projected to experience elevated energy burdens (more than 3% of income allocation to energy services) under high hurdle rate assumptions, compared to 4% in the base year. In contrast, under low hurdle rate assumptions, the share of the population facing such burdens remains at approximately 4% in 2045. These results highlight the significant long-term operational benefits of decarbonization measures once barriers related to upfront investment costs are reduced.

This study presents the impacts of local energy plans and their alignment with long-term national climate targets. Aligning short-term city plans with long-term national decarbonization targets is crucial to achieving significant and rapid emissions reductions that are sustainable in the long term. Furthermore, quantification of co-benefits in energy systems planning can enable cities to assess the most appropriate actions while accounting for equitable distribution of benefits and burdens. The findings also emphasise the importance of integrated energy systems modelling to capture the interplay between supply-side and demand-side dynamics at the city and sub-regional levels, while accounting for sectoral interactions in their development pathways.

Keywords: *City energy systems; Sectoral integration; Spatial characterization; Cost-optimization; TIMES, Co-benefits, Distributional impacts*

List of publications

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

I. K. Gupta, E.O. Ahlgren, Analysis of City Energy Systems Modeling Case Studies: A Systematic Review, International Journal of Sustainable Energy Planning and Management 43 (2025) 123–139. https://doi.org/10.54337/ijsepm.9335.

II. K. Gupta, K. Karlsson, E.O. Ahlgren, City energy planning: Modeling long-term strategies under system uncertainties, Energy Strategy Reviews 56 (2024). https://doi.org/10.1016/j.esr.2024.101564.

III. K. Gupta, K. Karlsson, E.O. Ahlgren, City energy transitions: Modelling policy alignments with sectoral integration at sub-city levels, Energy (2025) 139659. https://doi.org/10.1016/j.energy.2025.139659.

IV. Gupta, K., Karlsson, K., & Ahlgren, E. O. (2026). Co-benefits of urban climate action: Leveraging high spatial resolution of cities (Manuscript under review)

Author contributions

Kushagra Gupta is the principal author of Papers **I–IV** and performed the literature review, modeling, analysis, and draft writing for all four papers. Kenneth Karlsson contributed with method development, editing and discussions to Paper **II**, **III and IV**. Erik Ahlgren contributed with initial idea and concept of the project. He also contributed with the method development, editing and discussions to all the papers, along with funding acquisition for the project.

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Kushagra Gupta
Gothenburg, May 2026

List of abbreviations

CEP	City energy plan scenario
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
DH	District heatin
ESP	Energy systems planning
ESM	Energy systems modelling
GHG	Greenhouse gases
HC	Hydro carbons
HP	Heat pumps
LV	Low-voltage
MFH	Multi-family housing
NECP	National energy and climate plan scenario
PM	Particulate Mattter
PV	Photovoltaic
RegSO	Regionala statistikområden: Regional statistical areas
REF	Reference scenario
SFH	Single-family housing

Declaration on the use of Artificial Intelligence

This thesis employed AI-assited tools (ChatGPT, M365 Copilot) to support language refinement, and code-structuring for automating visualization developments. All outputs on language refinements were critically reviewed, verified, and adapted by the authors. AI tools were not used to generate any form of original work, research findings, analyses, or conclusions.

1 Introduction and background

Energy systems are the largest emitters of anthropogenic greenhouse gas (GHG) emissions, accounting for more than 70% of the global emissions [1]. To limit global warming to well below 2 °C by the end of the century, as set out in the Paris Agreement, a rapid transformation in the global energy system is required, and many countries have committed to achieve climate neutrality by 2050 [2]. In the European Union, the European Climate Law binds its member nations to reach net-zero GHG emissions by 2050, with intermediary targets [3]. Cities account for more than 75% of global energy use, and 70% of global GHG emissions, making them key players in climate mitigation efforts and municipal action and regional initiatives are key to national climate action [4,5]. With the introduction of initiatives such as C40 Cities, Covenant of Mayors, and Viable Cities, cities are identified as central parts of climate change mitigation strategies through local energy systems planning.

The built environment and transportation are the main contributors to energy use and emissions in cities. The buildings sector accounts for 30 % of the total final energy consumption (TFEC), of which half is used for space heating and hot water [6]. In colder climates, the share of heating in TFEC could reach up to 80 % [7]. In Europe, the transport sector is responsible for a quarter of the GHG emissions, with road transport contributing more than 72 % of the total transport sector emissions [8]. Given the important role of the buildings and transportation sectors, urban energy system analyses have largely concentrated on decarbonizing these key areas. In cities, decarbonization of the buildings and transportation sectors is driven by increasing shares of renewable energy, electrification across sectors, demand-side measures and alternative transportation modes. However, the uptake of such transition measures is highly dependent on factors such as socioeconomic status, housing composition, and population density [9]. Hence, it is important to account for differences in socioeconomic and demographic characteristics within city energy systems planning.

Biomass and electrification are identified as the primary resources in the transition to climate neutral energy systems [10]. Rapidly increasing demand for bioresources could surpass sustainable supplies, thus undermining climate mitigation efforts and harming biodiversity unless the use of bioresources is carefully prioritized [11]. Furthermore, electricity has been the fastest-growing form of final energy in recent years. Rapid electrification could lead to higher peaks, creating challenges for distribution grid operators. Grid upgrades will be significant at the city level and delays in grid development could hinder clean energy transitions, raise costs, and heighten security concerns [12]. Investigating how resources are allocated among competing sectors within their transition pathways is thus crucial to consider.

By taking action to reduce GHG emissions cities can gain multiple co-benefits [13]. Integrating co-benefits into climate action planning at the city level enables cities to address multiple challenges, encourage support from key stakeholders and enhance public acceptance [14]. However, such measures can have unintended negative consequences, while also leading to unfair distribution of climate action co-benefits, with some parts of society reaping the benefits while others bear the burdens of mitigation actions [15]. Quantification of co-benefits can firstly support transitioning towards a decarbonized energy system while ensuring fair distribution of climate action co-benefits.

Given the importance of urban energy systems for overall climate mitigation goals, they have become a central focus for researchers and policymakers, and many initiatives have been started to support long-term decarbonization of city energy systems. However, relatively few studies have examined the critical interactions between sectors when analyzing their transition pathways over long-term planning horizons in cities. Moreover, variations in demographic and socioeconomic characteristics warrant further investigation into how such differences particularly at high spatial resolution influence the adoption of transition measures, and to what extent they affect the equitable distribution of climate action co-benefits among different population groups within cities.

1.1 Aim and Research Scope

The overarching aim of this thesis is to develop and apply a comprehensive methodological approach to support long-term energy systems planning in cities, with emphasis on the impact of energy policies and decarbonization targets on the cost-efficient energy system development pathways. This work places particular emphasis on consumer heterogeneity by representing the city's socioeconomic and demographic characteristics at high spatial resolution. This enables the investigation on how such differences influence the adoption of decarbonization measures and allows for an assessment of the extent to which urban climate action co-benefits are equitably distributed across different population groups. This approach is applied to a case study city to address the following research questions focused on analysing city energy systems' long-term planning objectives:

I. How do short-term energy plans and policy targets influence the future cost-optimal design of city energy systems at city and sub-city levels, and to what extent do local-level energy plans align with national climate objectives in the long term?
II. In their optimal pathways, how are the limited resources allocated among the competing sectors?
III. What are the co-benefits of urban climate action, and how do spatial differences in socioeconomic and demographic characteristics influence the equitable distribution of their co-benefits?

This thesis comprises of the four appended papers and a summary essay. Brief summary of the contribution from the appended papers is described below:

Paper I presents a review of the existing literature on city energy systems modeling, focusing on how current studies represent the complexity of urban energy systems and on the key research objectives that underpin city energy system modeling efforts.

Papers II, **III,** and **IV** adopt an integrated energy systems modelling approach, including inter-related demand- and supply-side energy systems for multiple sectors. Energy systems optimization technique is incorporated into the studies to investigate policy-driven, long-term development pathways for city energy system. The energy system includes the supply- and demand-side representations of the buildings and road transportation, with the overall aim of identifying inter- and intra-sectoral interactions with the implementation of energy policies and plans. Special emphasis has been placed on spatial representation of socioeconomic and demographic characteristics in **Papers III** and **IV**.

Paper II evaluates the impacts of city energy plan and short-term targets on the future cost-optimal energy system in the long-term perspective. **Paper III** further explores the

effectiveness of city energy plan and evaluates how the city energy plan aligns with the national and regional climate objectives. In **Paper IV**, the impact of urban climate action on the distribution of co-benefits is investigated.

Guiding the long-term, policy-driven energy system's developments, model-based studies included in this thesis emphasize on inter-sectoral interactions through allocation of resources, impact of spatial characterization on deployment of decarbonization measures and the distribution of climate action co-benefits and unintended negative consequences.

1.2 Outline of the thesis

This thesis outlines key findings of the four papers within the context of the overall aim of the thesis and is structured as follows. Building upon the Introduction, Section 2 presents a literature review regarding urban energy systems and energy systems modelling to guide energy planning at the city level. Section 3 describes the methodological approach that is developed and incorporated into this work. Section 4 presents the main results of this work, along with their analysis. Section 5 presents reflections on the adopted methodology, followed by thesis contributions and findings, and suggestions of areas for future work.

2 Literature review

Energy Systems Planning (ESP) can be defined as the process of developing long-term strategies for local, national, multi-regional and global energy systems to inform decarbonization targets, policies, investment and operational strategies [16]. ESP encompasses three competing objectives referred to as the energy trilemma: Environmental sustainability; Energy Security; and Energy Equity. Environmental sustainability aims at reducing GHG emissions and environmental impacts of the energy system, which is inevitable to limit global warming to well below 2°C, in line with international climate goals [1]. Energy security ensures a reliable and uninterrupted energy supply, particularly challenging during geopolitical disruptions. Energy equity aims at providing affordable and accessible energy to all, critical for addressing socioeconomic inequalities and ensuring access to the capabilities enabling a sustainable and prosperous society built on just principles [17].

Cities play a central role in climate mitigation efforts due to their substantial contributions to the global energy use and GHG emissions, while ensuring reliable, affordable and accessible energy to all. These energy systems are complex and involve intricate interactions between various sectors, such as transportation, industry, and buildings, all of which are significant sources of urban GHG emissions. A key aspect of climate change mitigation at the city level is the integration of mitigation measures across sectors, which can produce cascading benefits across transportation, energy, land use, and behavioural patterns [2]. Urban energy systems are socio-technical systems, meaning they have not only technological components, but also comprise social, economic, and institutional factors. These systems are influenced by multiple scales (spatial and temporal) and intersect with various sectors [18,19]. In this context, decision-making involves considering a wide range of factors, including investments, operational decisions, environmental and social concerns, and institutional frameworks, thereby highlighting the need for local energy system planning to support urban decision-making.

Local energy planning was first introduced in the Scandinavian region. In Sweden, the municipalities are required to have a municipal energy plan according to the Act on Municipal Energy Planning from 1977 [20]. In 2010, Strategic energy planning was introduced among the Danish Municipalities. In the context of this thesis, energy planning is referred to as a long-term strategy for the development of energy systems while accounting for supply and demand-side dynamics [21].

The complexity of these systems necessitates advanced tools and methodologies for city-level energy planning. Cities worldwide are increasing adopting energy system models (ESMs) to inform decision-making [22]. These models support energy transitions planning by simulating alternative scenarios, evaluating trade-offs, and identifying the most effective pathways to reduce GHG emissions while maintaining economic and social feasibilities. Through these models, cities are better equipped to navigate the complexities of their energy systems and implement strategies aligning with national and global climate efforts.

The following subsections present key aspects of urban energy systems incorporated into energy system modeling, drawing on the literature review in Paper I and relevant research found in the literature regarding the main topics included in this thesis that are aimed at supporting long-term energy systems planning in cities.

2.1 Modelling to support energy planning in cities

Energy models have been extensively used to support energy planning aimed at supporting evidence-based policymaking and to provide solutions to energy and environmental problems. With increasing attention being paid to energy planning at the local level, researchers and practitioners are using ESMs to replicate the complexities of local energy systems. Studies have used several modelling approaches to replicate the local contexts, aimed at identifying transition pathways that support energy systems transformations at the city level.

To support various aspects of city energy system planning, a range of computational models has been developed and applied. Models based on optimization and simulation techniques are widely used to inform urban energy planning and guide policy decisions. **TIMES (The Integrated MARKAL-EFOM System)** is an economic model generator providing a technology-rich basis for the representation of complex energy system dynamics over a multi-period time horizon, supporting local, national, multi-regional and global energy systems planning [23]. TIMES based model for the city of Evora was developed to increase capacity of city energy modelling, while aiming to investigate optimal solutions to municipal low-carbon energy systems [24]. Technology-rich optimization models were used to analyze cost-optimal transition to low-carbon cities for Oslo and Basel [22,25]. **LEAP** is an integrated planning tool used to track energy consumption, production, and resource extraction across sectors, while accounting for GHG sources and sinks, intended at medium to long-term planning [26]. Based on LEAP modelling framework, medium and long-term energy supply, demand and energy flow processes were determined for a Chinese city [27]. Combining LEAP based energy systems analysis with marginal abatement cost curve, future projections for energy generation and consumption were analyzed [28]. Assessment on the integration of energy and urban planning solutions were conducted using LEAP based energy simulation model for the city of Sao Paolo [29]. **Balmorel** is an open-source energy systems model designed to analyze and optimize the production, transmission, and consumption of electricity and district heating [30]. Aimed at achieving a climate neutral energy system, scenarios for sustainable energy and heat supply are evaluated using energy system model Balmorel for Copenhagen [31]. **EnergyPlan** is a specialized simulation tool designed to model integrated energy systems with focus on transitioning towards sustainable renewable energy solutions [32]. EnergyPlan was used to design regional planning strategies based on techno-economic analysis by simulating different energy systems with pre-defined investment decisions [33]. Based on energy requirements of the residential stock, the impact of buildings renovation on the overall energy system was analysed using EnergyPlan [34]. Combining robust simulation using EnergyPlan with multi-criteria decision analysis, methodology for the design of 100% renewable urban energy system is presented [35]. Furthermore, several studies supporting energy planning in cities used modelling platforms independently developed by research institutions. The list of selected literature representing model applications to city energy systems is presented in Paper I.

2.1.1 System aspects and integrated assessments

Modelling studies of city energy planning have attempted to represent the different aspects of the buildings and transportation sectors. Demand-side measures integrated with the decarbonization of the heating supply solution are the key transition pathway for the buildings sector. Transport sector decarbonization is driven by fuel and technology switches, along with a shift towards shared mobility and active transportation modes.

Heating supply solutions have been investigated for municipal energy planning, to identify cost-efficient mix of centralized and decentralized solutions [31,36,37]. Heating system decarbonization has also been investigated at high spatial resolution, to support heat planning at the urban level [38,39]. To incorporate heat supply and heat savings into the planning process, the optimal mix of supply and savings has been investigated in several studies [34,40–42]. Furthermore, studies focused on the buildings sector have introduced a methodology for improved representation of the building demand [18,43]. In transport sector modeling studies, cost-optimal decarbonization pathways and their impacts on local air quality have been examined [44]. Additionally, the role of electric vehicle (EV) promotion policies and their environmental benefits have been investigated for two cities in China. [45,46].

Sectoral integration in energy systems refers to the linking of different energy carriers with various energy end-uses, allowing for the assessment of the overall energy system by including multi-sectoral interactions [47]. At the city level, studies have included multiple demand-side and supply-side measures and their impacts on long-term energy systems planning. Integrated assessment models have been developed to investigate the optimal solutions for achieving future, low-carbon local energy systems [24,48–50]. The results have been presented for energy consumption and emissions levels for the overall energy system, accounting for sectoral integration. These results provide insights into the impacts of applied technological and policy measures on energy use and emissions. Focusing on the roles of national policies and objectives, cost-optimal energy systems pathways have been evaluated using integrated city energy systems models [51,52].

2.1.2 Spatial aspects in energy systems planning

The spatial dimension of the system is important to consider when analyzing energy system transitions driven by increased shares of renewable energy, improvements in energy efficiency, demand-side measures, and consumer participation. Spatial aspects are incorporated into city energy system planning through the disaggregation of systems into zones, spatial mapping of building stocks, and the coupling of energy models with GIS or urban land-use models. Urban features, such as building information and official territorial subdivisions, were identified and integrated into the energy systems model to support urban heat planning [39]. Another study subdivided the city into subregions to improve the representative municipality based on residential building density and characteristics [19]. Spatial distribution for service demands has been identified as the most common approach to incorporating the city's spatial characteristics. Using a GIS based model, city’s building stock energy performance was characterized to assess scenarios through a multi-criteria analysis tool [18]. Aimed at investigating the interactions between building efficiency and heat supply strategies, a spatially resolved building representation was applied to support urban energy planning [40]. Similarly, building aggregation based on geographical location has been used to model heating supply and energy-saving options for a Danish municipality [42]. Another study conducted a spatial analysis to quantify the distribution of reference buildings and estimated energy requirements for the building stock to support urban energy planning strategies [34]. And, future climate variations were integrated into GIS-resolved urban building energy modelling to investigate the impact of climate change on the building energy performance [53]. In addition to mapping the spatial distribution of the building stock, a comprehensive framework was presented to analyze the spatio-temporal distribution of charging load in Shanghai while incorporating EV charging behaviours [54]. Meanwhile, demographic factors including socio-economic status,

housing composition, and population density play a key role in shaping the adoption of decarbonization measures [9]. However, studies focusing on higher spatial resolution have overlooked the spatial representation of demographic characteristics and their impact on sectoral developments.

2.1.3 Scenarios and policy aspects, in energy systems

Investigating future development of city energy systems with the applied models, studies have formulated scenarios to describe possible future developments, and different expected futures. Most studies seem to use explorative scenario types with predefined system measures to evaluate their impact on energy systems. Some studies define measures based on policies, while others implement specific measures to see what can happen if we act in a certain way. The next most used typology is normative, with main targets on emissions but also some with other future targets like targets on renewable energy share. Results from Paper I, on the case studies distribution based on the scenario typology, are shown in Figure 1.

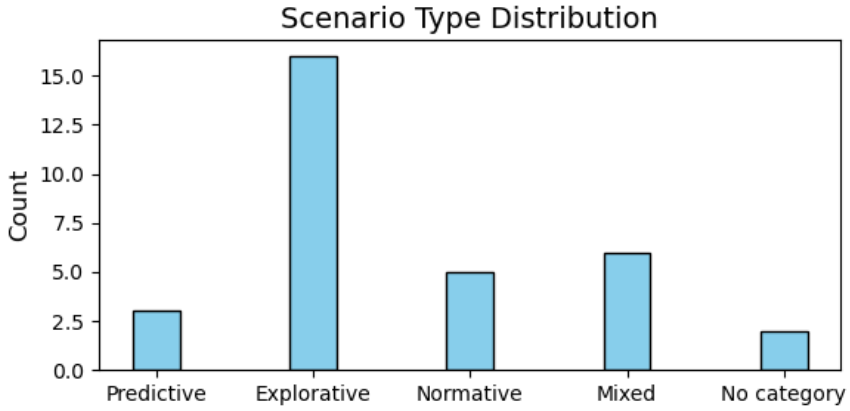


Figure 1: Case studies distribution based on the scenario typology (Paper I).

Focusing on long-term strategies to support energy systems planning, studies have formulated scenarios to represent policy interventions, and gain policy insights to support local decision-making processes. Energy plans and carbon dioxide (CO_2) reduction targets at a municipal level play a significant role in national climate mitigation efforts. When analysing policy-driven scenarios, studies have often applied normative long-term CO_2 emission reduction targets to identify optimal solutions to achieve the decarbonization goals [48,55]. Another study focused on city-level targets, examined scenarios based on municipal CO_2 reduction goals to identify cost-optimal pathways for achieving the city's emission targets [19]. Furthermore, strategic municipal plans were included in the scenario description of a Danish municipality to compare with alternating scenarios [49]. Focusing on the future development of urban heating systems, the authors examined the impact of climate policies such as carbon tax and fossil-fuel ban on future cost-efficient heating systems [56]. In addition, policy-driven scenarios centered on local energy policies and targets have been analyzed to assess their role in guiding energy system transitions. The energy consumption and health environment co-benefits were estimated for the city of Beijing's strict vehicles quota-limit policies [57]. The impacts of Oslo's climate targets on the long-term development energy system and associated emissions were investigated, using a technology-rich optimization model [22]. However, existing urban energy plans are primarily short-term plans and often include independent sectoral initiatives instead of long-term national mitigation plans [40]. Due to the determined

nature of city energy plans, it is vital to investigate the contribution of these short-term plans toward long-term national mitigation targets.

Investigating the role of national policy strategies in long-term city energy planning, scenarios based on national policies are evaluated for Swiss case study Basel [52]. Similarly, scenarios based on the nationally determined contribution targets were applied to a city in Brazil, and cost-optimal pathways identified using an energy model [51]. To further examine the influence of national policies on independent sectors, stringent national policies on electric vehicles (EV) promotion and conventional vehicle bans were examined to investigate the implications of EV penetration [46]. Furthermore, study combining local and national policies assessed the potential impacts of municipal measures and compared with additional policies from higher levels of government in a Canadian city, highlighting the importance of aligning senior-level policies with local strategies to achieve long-term goals [50]. Existing city-level modelling studies have typically assessed the impacts of either local policies, or national energy policies, with limited attention given to the combined effects of policy implementation across multiple levels of governance.

2.2 Allocation of competing resources

The implementation of bio-resource deployment and fossil-free electrification has been identified as crucial for achieving global climate objectives. According to the Swedish Climate Policy Council, these two measures are expected to contribute more than 50% of the required GHG mitigation [10]. At the same time, the Energy Transitions Commission highlights the growing reliance on bioresources, citing the risk of over-utilisation beyond the availability of sustainably sourced resources [11]. When it comes to electrification, electricity has been the fastest-growing form of final energy in recent decades. Increasing electrification leads to higher peak loads, thereby necessitating additional infrastructure for electricity distribution. With increasing electrification in the transportation and heating sectors, the necessary grid upgrades would be significant and would need to be incorporated into the long-term planning process [12,58].

The allocation of bio-resources among various end-users has been investigated using a biomass scenario model for the energy system of United States of America [59]. Another set of studies constrained the availability of biomass, to analyse its roles in the electricity and heating systems [49,60]. The impact of electrification on the distribution grid is driven by the deployment of low-carbon technologies (LCTs). The impact of EV charging on low-voltage grids has been investigated to evaluate violations at the distribution grid level [61,62]. Furthermore, the integration of heat pumps and photovoltaic (PV) systems have been analysed for typical rural and urban grids in Belgium [63]. And, the costs for grid reinforcements linked to the deployment of LCTs have been evaluated for different spatial set-ups with exogenously provided penetration levels [64–66]. While existing studies have examined the systemic impacts of increased bioresource utilization and electrification, there is limited representation of how these resources are allocated across competing sectors within long-term transition pathways.

2.3 Co-benefits and equity considerations in energy systems planning

Climate action co-benefits are the beneficial outcomes of climate change mitigation measures apart from the decarbonization of the energy systems [67]. Quantifying the co-benefits of local

mitigation actions can enable cities to objectively assess most appropriate measures, while emphasizing environmental sustainability, energy security, and energy equity considerations. When analyzing co-benefits, studies are most likely to report the health benefits, specifically from the transportation and agriculture, forestry, and other land-use (AFOLU) sectors [68]. Applying quantitative modelling to assess the benefits of transportation sector decarbonization, studies demonstrated substantial improvements in air-quality and associated health benefits [69–72]. While investigating the co-benefits of physical activity and improved air quality from a macro-economic perspective, substantial decrease in morbidity and mortality with increased physical activity and reduced pollutant exposures are estimated [73]. Additionally, low-carbon passenger transportation actions show further benefits with reduced oil-demands thus increasing energy security of urban systems [74]. Estimations of environmental and social benefits of fleet electrification in the urban areas of Greece indicate that promoting intensive EV adoption deliver benefits such as avoidance of years of life lost, contributing to economic savings as social benefits [75]. Further, co-benefits of reduced transportation demand are estimated to deliver considerable environmental and economic benefits for Chinese cities [76]. More broadly, analyses of cross-sectoral interactions indicate that urban energy exchange strategies coupled with compact urban development can yield significant air-quality related health benefits, with impacts varying across cities in China [77]. While air quality and associated health co-benefits are well documented in the literature, other benefits of urban climate mitigation remain underrepresented. These include improvements in urban resource efficiency and associated system resilience through higher productivity and energy efficiency, as well as enhanced energy affordability and social equity, as mitigation measures are expected to reduce household energy cost burdens.

Furthermore, impacts of the climate mitigation policy and action are often not equally distributed within the city. Socioeconomic disparities and varying demographic characteristics can lead to different levels of technological deployment. It is therefore important to account for equity and fair distribution of co-benefits across socioeconomic and demographic groups within cities.

2.3.1 Equity considerations in energy systems

Energy system transformations aligned to achieve the decarbonization objectives, promises societal benefits, however, climate action policies may have unintended negative consequences. Climate action co-benefits, and its adverse effects are not always uniformly distributed across the population, and some communities/societies are more vulnerable to the negative impacts, while certain population groups are expected to reap greater benefits [15,78].

Just transition refers to the decarbonization of energy systems, while accounting for social justice/equal distribution of co-benefits, and energy systems transformations constitute complex socio-technical systems, particularly when the principles of energy justice are integrated into their design and implementation [79]. Including justice implications in ESM is an opportunity to inform policy makers/wider society, how long-term changes may affect different social groups, and how to minimize inequality and promote justice. Equality principles dominate as the formalized definition of a socially just distribution of benefits and burdens in energy systems studies [80].

When accounting for equity principles, the distribution of benefits should be considered upfront in energy planning, to avoid uneven allocation of the goods and bads. To include energy equity

aspects, indicators addressing issues of affordability, defined by the energy burdens calculated as a ratio of energy expenditure to available budgets (often income) are investigated [81]. Furthermore, ambitious policies may lead to regressive distributional impacts, disproportionately affecting low-income population groups, with results indicating modest increase in energy inequality across income classes [82]. In this context, analyses of urban energy transitions underscore that achieving sustainable and inclusive outcomes depends not only on technological advancements but also on the design of effective policies that explicitly address social equity considerations [83]. Further emphasizing the importance of energy equity, study employed household-level socioeconomic data to assess systemic energy inequities among policy-relevant groups reveal substantial prevalence of energy poverty, with as much as 16% of households affected [17].

A just transition requires an integrated and coordinated approach that explicitly accounts for potential socioeconomic impacts alongside technological and environmental objectives. Such a comprehensive framework is essential to ensure that decarbonization pathways do not exacerbate existing inequalities but instead create opportunities for inclusive and systemic transformation [84]. Inclusive energy policies that simultaneously address environmental and social dimensions are therefore crucial to ensure an equitable distribution of transition co-benefits across society [79]. As urban energy system transformations strengthen interlinkages between sectors, socio-spatial inequalities are likely to become more pronounced, making them a critical priority for future research and policy design [85].

2.3.2 Hurdle rates as a representative of income levels

Hurdle rates, often referred to as individual discount rates or implicit discount rates are employed in energy system modeling to capture private investors' process-specific investment decisions. For residential and commercial users, the willingness to invest in new technologies and thus the cost of capital can be represented through technology-specific hurdle rates [86]. However, the magnitude of the relationship between socioeconomic factors and hurdle rates is not well defined and is shaped by heterogeneous preferences, behavioral responses, and external barriers [87].

A national-level study used income-dependent hurdle rates to represent consumer heterogeneity, presenting insights into regional diffusion of electric vehicles [88]. Technology-specific hurdle rates have been used to represent investment behavior of households based on different policy environments for energy efficiency retrofits in Denmark [87]. For households, cost of capital depends on the individual's economic situation, hurdle rate differentiation based on income levels can be used to represent socioeconomic differences across residential consumers [89]. However, the use of hurdle rates to represent socioeconomic heterogeneity across households, particularly in urban contexts remains limited.

3 Methodology

This chapter outlines the methodological approach developed to support long-term planning of integrated city energy systems. The thesis adopts a progressive method development framework to capture the multiple dimensions of urban energy system planning, incorporating both intra- and cross-sectoral interactions across supply and demand sides over a long-term modelling horizon. To support informed decision-making in cities, a comprehensive approach is presented that integrates high spatial resolution data on energy supply, demand, and socioeconomic characteristics with policy-oriented energy system modelling. This integrated framework enables the assessment of sectoral dynamics and interactions, while also investigating the distribution of climate action co-benefits and potential unintended negative consequences.

Supply-side systems include heating, electricity, and transportation fuels. Demand sectors include buildings and road transportation. This integrated energy system identifies the interactions within and between sectors and accounts for the allocation of resources in the city energy system's transition pathways. The spatial representation of socioeconomic and demographic characteristics enables a detailed assessment of sectoral developments and associated co-benefit distributions at sub-city levels, thereby advancing the literature on long-term energy systems planning in cities.

Incorporating long-term decarbonization targets and policy measures using a mixed-integer linear cost optimization model, model outcomes are generated for the future development of city energy systems. Policy-driven scenarios are further extended by applying system uncertainties, price sensitivities, and hurdle rate sensitivity to income levels. With income-dependent hurdle rates, representing socioeconomic disparities, model outcomes are evaluated using key indicators to assess how co-benefits are distributed across the city with the application of policy measures and decarbonization targets.

3.1 Model and modelling

The TIMES (The Integrated MARKAL-EFOM System) model generator, an optimization model, was chosen to analyze the impact of energy and climate policies on the future cost-optimal city energy system due to its flexibility in terms of representing different urban (supply and demand) sectors and temporal (short and long-term) representation [23].

To support long-term planning at the local levels, the model provides insights into the investment and operation decisions to fulfill end-user service demands under the defined user constraints. Apart from the techno-economic analysis, the TIMES model generator offers the opportunity to represent the environmental emissions and materials associated with the energy system. The authors selected the TIMES model generator due to its ability to analyze the impact of energy-environmental policy on the overall energy system from a long-term planning perspective.

The model developed in this study, referred to as the TIMES_NE city model, is representative of a northern-European city with high heating and transportation demands. The modelling framework is formulated as a mixed-integer linear cost-optimization problem under an assumption of perfect foresight. Mixed integer linear programming allows for a better representation of economies of scale by applying discrete investment levels into new

production capacities. Perfect foresight is defined as a hypothetical scenario in which the model is provided with complete and accurate information about the future.

The objective function of the optimization problem minimizes total system costs over the modelling time horizon (Eq. 1). The social discount rate ($d_{r,y}$), applied to discount future costs and benefits to the base year is calculated using (Eq. 2) to derive the socially optimal solution, based on the OECD report [90].

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r,y) \qquad (\mathbf{1})$$

- NPV, net present value, is the total cost that is minimized.
- $ANNCOST(r,y)$ is the annual cost in region r in year y, including capital investment and fixed operation and maintenance costs, running costs, taxes, etc.
- $d_{r,y}$ is the discount rate.
- $REFYR$ is the discounting reference year.
- $YEARS$ are the years for which any costs are present.
- R is the set of regions investigated.

$$d_{r,y} = \delta + \mu g \qquad (\mathbf{2})$$

- δ is the rate of pure time preference
- μ is elasticity of marginal utility
- g is the average expected growth rate

The model is configured with a long-term planning horizon divided into multiple time periods. The base year for the model runs is 2018 (Paper II and III), and 2023 (Paper IV). The modelling time-horizon extends from 2018 to 2045, using shorter time intervals in the early years up to 2030, followed by five-year periods.

Key methodological contribution of this thesis involves detailed system assessment accounting for intra- and cross-sectoral interactions, different spatial and temporal scale applications, consumer perspectives and socio-economic representations in techno-economic assessments. The following sub-sections elaborate on the important aspects of city energy systems planning incorporated into the TIMES_NE city model.

3.1.1 System definition

The TIMES_NE city model is designed to supply heating, electricity, and transportation fuel to fulfil end-use service demands for the buildings and road transportation sectors. The energy supply infrastructure includes primary resources, centralized and decentralized heat and power production facilities. The distribution system includes local electricity distribution grid, district heating (DH) network for DH distribution, and fuel supply infrastructure for the distribution of transportation fuels and charging infrastructure for EV charging.

End-use service demands are included for the buildings and transportation sectors. Buildings include residential housing disaggregated into multi-family housing (MFH) and single-family housing (SFH), along with commercial and industrial buildings. The service demand for the transportation sector include road-based passenger and freight transportation demands.

Passenger transportation includes cars and urban buses; freight transportation includes heavy freight and light commercial vehicles. Figure 2 presents the graphical representation of the city energy system's representation in the model.

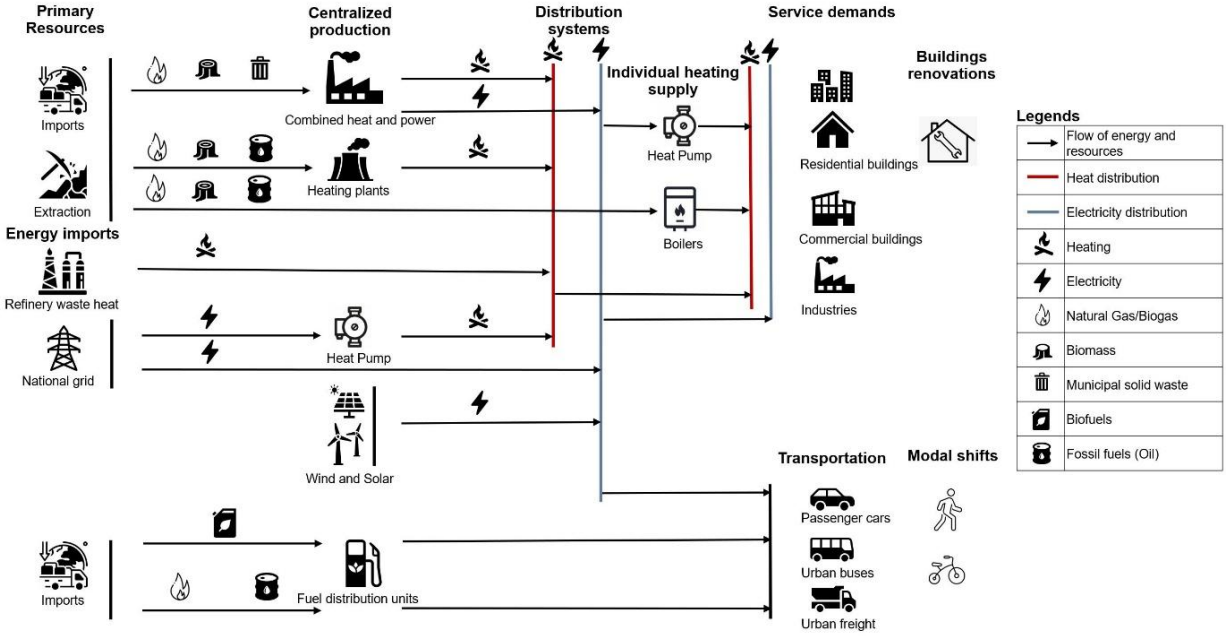


Figure 2: Reference city energy system representation in the TIMES_NE city model.

3.1.2 Scale aspects

The temporal resolution of the model is seasonal combined with peak demands to account for seasonal and annual variations in the heating and electricity system (Paper II). To incorporate seasonal and daily variations, each year is subdivided into 12*24 time slices. The monthly time slices represent seasonal variations, and the 24 time slices represent daily variations. Hourly data has been aggregated into a 12*24 dataset by averaging data for each representative hour for each month (Paper III, IV). Technical parameters that are modelled with the stated temporal resolution include heat pumps (HP) coefficient of performance, solar PV capacity factors, and electricity spot prices. All heating and electricity loads, as well as load profiles for EV charging, are also modelled with 12*24-time slicing. In case of EV charging, different load profiles are assumed based on the charging type, adopted from Ref. [91].

Spatially, city boundary within the control of municipal authorities is identified as a region (Paper II). In Paper III and IV, the city is spatially divided into multiple sub-regions, based on similarities in socioeconomic and demographic characteristics. The adopted method for spatially dividing the city into sub-regions is detailed in Section 3.

Spatial characterization of the city is applied to facilitate the representation of service demands and technological parameters associated with the residential customers based on demographic characteristics. At the sub-regional levels, the following parameters are represented, to represent socioeconomic and demographic characteristics:

1. Service demands for residential buildings and passenger cars.
2. Local distribution grid capacities, to distribute electricity for residential consumers.

3. DH network costs, for connections of new SFH and MFH to the network.
4. EV Charging infrastructure for passenger cars
5. Technology-specific hurdle rates, to represent income levels of residential consumers in different sub-regions.

3.1.3 Consumers' cost and investment perspectives

To account for consumers' perspectives in the investment and operations decisions, the prices and taxes associated with the use of energy resources are differentiated for different residential and commercial users of energy services. In Paper III and IV, technology-specific hurdle rates are applied to model investment decisions, reflecting the expected rate of returns for commercial investments, and willingness to invest in new technologies for residential consumers. Due to the dependence of hurdle rates on the household incomes, hurdle rates are used to represent socioeconomic differences across sub-regions. Hurdle rates dependence on income levels is estimated using Equation 3, reflecting inverse corelation of income levels and expected hurdle rates.

$$H_i = H_m * \left(\frac{I_m}{I_i}\right)^{\{\alpha\}} \qquad (\mathbf{3})$$

- H_i is the income dependent hurdle rate.
- H_m is the median hurdle rate, corresponding to city's median income.
- I_m is the city's median annual income.
- I_i is the sub-city level annual income.
- α is the income dependence on hurdle rate.

The magnitude of the relationship between socioeconomics and hurdle rates is not well defined and is shaped by heterogeneous preferences, behavioral responses, and external barriers [87]. Hence, a sensitivity analysis is conducted with variations in H_m and α, as shown in Section 3.3.3.

3.2 Modelled case, and associated assumptions

The methodological approach was applied to the city of Gothenburg, to support long-term energy systems planning. Gothenburg is a Northern-European city, located on the west coast of Sweden as shown in Figure 3. It is the second largest city in Sweden, with more than 600,000 inhabitants in 2024 [92]. Gothenburg has a well-established and diverse heating system with options to use an extensive DH network or individual heating solutions. Heating and electricity systems of Gothenburg are highly decarbonized, and use of conventional fossil fuels in the transportation sector remains the primary source of GHG emissions in the city.

Figure 3: Location of Gothenburg, from the European context.

Gothenburg has decided to limit its climate impacts and have adopted the Environment and Climate Programme 2021–2030 to transition into a sustainable city by 2030 [93]. The authorities have updated their energy plan in line with the energy and climate programme, and adopted the Gothenburg City Energy Plan, 2022–2030 [94].

Gothenburg's heating system is currently in a planning phase, with major production plants approaching retirement and uncertainties surrounding the continued availability of biomass and waste heat from refineries and waste incineration. Simultaneously, the city must reduce its climate impact from the transportation sector. The city authorities are thus tasked with cost-efficient future planning of the heating, electricity and transportation sectors. Accordingly, this thesis selects Gothenburg as a suitable case study to apply the developed methodological approach for long-term planning of integrated city energy systems.

3.2.1 Policy instruments and future assumptions

Key policy instruments considered for the long-term development of the city energy system include efficiency standards and building regulations for new buildings, CO_2 and energy taxes for energy commodities, and reduction obligations for gasoline and diesel use in the transportation sectors. The national policy instruments included in the analysis are presented in Table 1.

Key future assumptions encompass energy commodity price trajectories, projected service demand for buildings and transportation, the availability of technologies to meet future demands, and associated developments in their techno-economic parameters.

Table 1: Key national policy instruments included in the long-term development of the city energy system.

Serial Number	Policy Instruments	Policy Implementation	References
1.	Buildings regulations	• 75 kWh/m² (Multi-Family Housing) • 95 kWh/m² (Single-Family Housing)	[95]
2.	Carbon Dioxide Taxes	• CO_2 tax on fossil emissions (134 €/tonne, 2025)	[96]
3.	Energy Taxes	Energy tax on energy commodities, as per Swedish taxation system.	[96]
4.	Reduction obligations	• 7.6% Gasoline, 30.6% Diesel (2023) • 6% Gasoline & Diesel (2024) • 10% Gasoline & Diesel (2025)	[97]

3.2.2 Spatial characterization

In Paper III, to spatially divide the city into multiple regions, open-source data at the square kilometer level in Sweden was utilized, and the dataset associated with the administrative boundary of Gothenburg was filtered [98]. The city of Gothenburg is spatially divided into 492 grid cells, each covering an area of 1 square kilometer. Using the dataset on population density and distribution grid hosting capacity, K-means clustering grouped the grids into 5 clusters.

To account for socioeconomic and demographic characterization of the city, RegSO ("Regionala statistikområden": Regional statistical areas) level data is used in Paper IV. RegSO divides Sweden into 3,363 areas, with municipalities divisions varying from 2 to 147 statistical areas [99]. The city of Gothenburg is divided into 147 RegSO. Using population by RegSO, and urbanized area (Tätorter), population density by RegSO was calculated. Using population density and average annual income, the 147 areas are clustered into 5 sub-regions using the K-Means clustering algorithm, grouping the areas with similarities in population density and annual incomes.

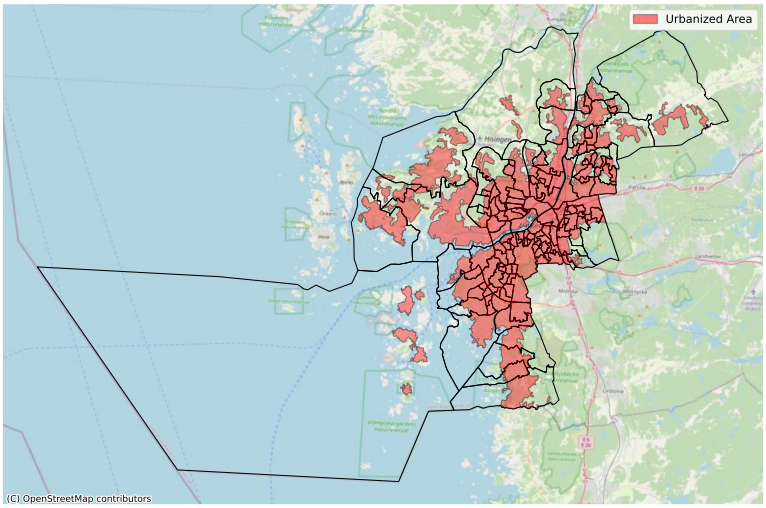


Figure 4: Gothenburg division into 147 RegSOs, with the red shades showing the inhabited area in each RegSO

In this thesis, RegSO based socioeconomic and demographic characteristics are used to sspatially divide the city into sub-regions. Gothenburg distribution into 147 RegSO and

associated urbanized areas is presented in Figure 4. The output of K-Means clustering is shown in Figure 5, and its graphical representation is shown in Figure 6. The sub-regions of Gothenburg are denoted as GOT0–GOT4, while system descriptions related to centralized infrastructure are referred to as GOTC.

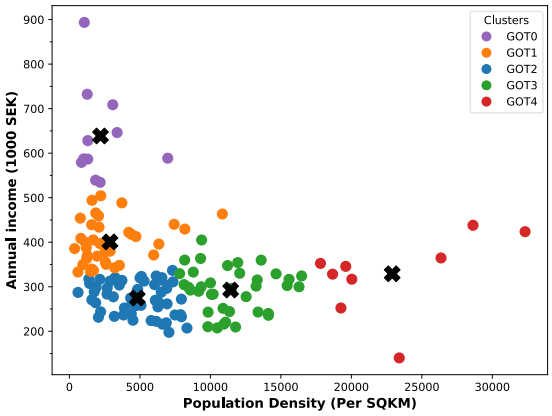


Figure 5: K-Means Clustering of the 147 RegSO, with centroids used to represent population density and average income associated with each of the sub-regions.

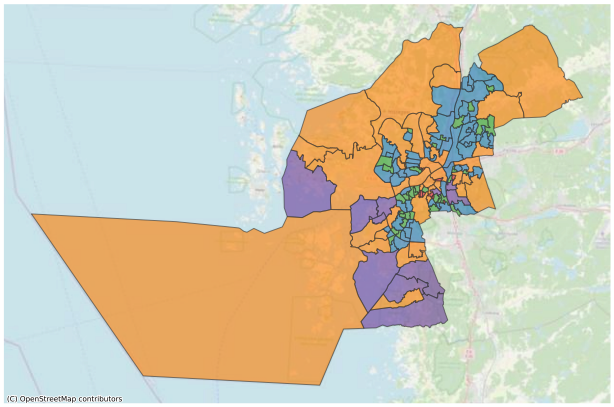


Figure 6: Graphical illustration of grouping the 147 RegSO into 5 sub-regions with same color coding as shown in Figure 5.

3.3 Policy Scenarios, and Sensitivity assessments

To support long-term urban energy system planning, model runs are conducted under multiple policy scenarios to explore system developments across a range of future conditions. Furthermore, sensitivity analyses based on different fuel price assumptions are conducted to evaluate their impact on the allocation of competing resources. Finally, the model outcomes are examined using key indicators to analyze the distribution of co-benefits from urban climate actions under different income-dependent hurdle rate assumptions. The indicators used to analyze the distribution of co-benefits include, urban resource efficiency, local air pollution concentrations, and energy affordability. Detailed descriptions on the indicators for co-benefits assessment are presented in Paper IV.

The scenario assessment and associated sensitivity analysis conducted in this thesis to answer the research questions, are presented in Figure 8, and discussed below:

3.3.1 Policy-based scenarios

In addition to a reference case, two policy interventions are investigated to explore future cost-optimal system developments, at the city and sub-city levels.

Reference (REF): The reference scenario extends the base year model over the modeling time horizon. It includes technological developments and options to invest in new technologies, as well as all national policy instruments stated in Table 1.

City Energy Plan (CEP): The CEP scenario extends the reference case, and energy policy and plans stated under the City Energy Plan 2022-2030 are applied in this scenario [94].

Integrated National Energy and Climate Plan (NECP): Sweden has adopted the Integrated National Energy and Climate Plan per the governance regulators of the Energy Union and

Climate Action [4]. Emission targets are upgraded under the NECP scenario in comparison to the CEP scenario.

3.3.2 Price sensitivities

To investigate the allocation of electrification and bio-resources among the sectors, price sensitivities based on future fuel price assumptions are applied. Sensitivities related to future bio-resource prices (Table 2) and electricity (Table 3) are integrated into the scenario assessment process.

Table 2: Assumptions associated with future bio-resources prices (€/MWh) compared to the base year prices.

Bioresource price	**Future projections (2030)**	**Future projections (2045)**
Baseline	25% increase compared to 2018	50% increase compared to 2018
High Prices	50% increase compared to 2018	100% increase compared to 2018

Table 3: Assumptions associated with future electricity spot prices (€/MWh) compared to base year prices.

Electricity price	**Price (€/MWh, 2030-2045)**	**Future projection**
Base year	51 (2023 Spot Price)	
Baseline	60	
High Prices	67	1.33 times the base year price by 2030

3.3.3 Hurdle rates and Income sensitivity

Model runs are conducted with distinct levels of median technology-specific hurdle rate and α values associated with hurdle rates dependence on income levels, and modelled hurdle rates calculated based on Equation 3. Median hurdle rates in the base hurdle rates are assumed to be 12%, with a direct inverse proportionality of income and hurdle rates represented with $\alpha = 1$. A policy environment with a high level of policy and economic uncertainties is represented by high hurdle rates, using higher level of median hurdle rate, and $\alpha > 1$. A lower level of median hurdle rate is used to represent more favorable conditions for individual's investment making with $\alpha < 1$, as low hurdle rate case. The different parameters associated with hurdle rates assumptions for different cases are presented in Table 4. Figure 7 shows the median hurdle rates and hurdle-rates associated with different sub-regions.

Table 4: Median technology-specific hurdle rates and income sensitivity for the three cases of hurdle rates.

	High-hurdle rates	Base-hurdle rates	Low-hurdle rates
Median values	15%	12%	9%
Income elasticity (α)	1.25	1	0.75

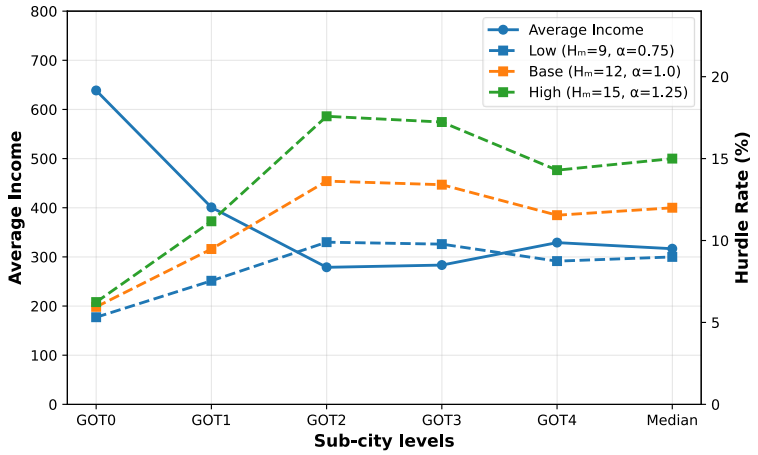


Figure 7: Median hurdle rates and their dependence on the average income for the different sub-regions in Gothenburg under the three hurdle rate assumptions.

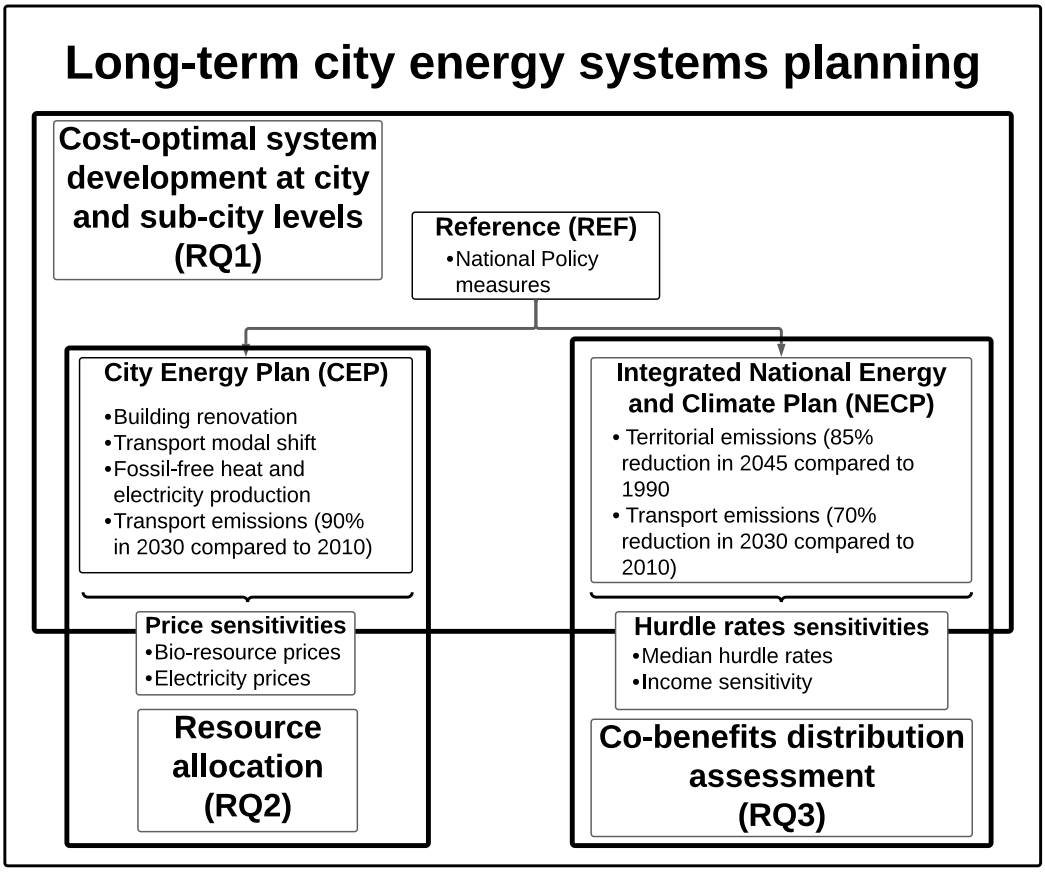


Figure 8: Scenario tree combining policy based scenarios, along with the application of price sensitivities, and hurdle rates to answer the three research questions.

4 Main Results and Discussion

This section presents the main results to support energy system planning strategies, focusing on sectoral developments, and associated economic and environmental co-benefits at the city and sub-city levels. The results are structured to support city energy planning from the perspective of competing objectives of the energy trilemma. Focusing on energy security and resource utilization, Section 4.1 presents the buildings and transportation sector developments with the implementation of energy systems policies and plans and inter-sectoral interactions through allocation of resources. With emphasis on environmental sustainability, and energy equity perspective, Section 4.2 evaluates the impact of policy action on emissions, local air pollution and energy affordability at high spatial resolution. The presentation of main results is followed by the discussion of the key findings in Section 4.3.

The results presented in this thesis are derived from Papers II, III, and IV. The model runs used to generate these results are based on the most recent model developments described in Paper IV. Consequently, the results presented in the thesis may differ from those reported in the appended papers.

4.1 Sectoral developments, city and sub-city levels

The impact of energy plans and policy targets on future cost-optimal design of city energy systems is investigated through buildings and transportation sector developments over the modeling time horizon. In Paper II, impacts of city energy plan on the city level sectoral developments are analyzed, and Paper III further investigates the policy alignment by investigating sectoral developments under national climate targets. Paper III also presents the results at the sub-regional levels. The interaction between the buildings and transporation sectors is presented through electrification and bioresource utilization among sectors under the different price assumptions.

4.1.1 Buildings sector

Sectoral developments for the buildings include district heating production mix and heating supply solution mix for the residential buildings. The base heating load in the district heating system of Gothenburg is based on waste incineration and waste heat from refineries. Biomass and gas fired CHP, biomass boilers, and heat pumps produce the remaining district heat. Also, due to the uncertainty with future availability of refinery waste heat, and waste incineration (Paper II), gradual decrease in the waste heat is assumed. As the existing capacities start to retire, new investments begin to appear in 2027. In the REF scenario, small investments in gas CHP are observed along with investments in centralized heat pumps and biomass CHP. Similar results are observed in the CEP scenario, apart from Gas CHP due to the CEP target of fossil free heating by 2025. Notably, under the NECP scenario in Paper III, investments in biomass-based CHP are substantially lower than in the CEP scenario, resulting in approximately 15% lower district heating production by 2045, ensuring desired emission targets of 2045 are reached. Distric heat production mixes for the centralized heating system comparing the REF, CEP, and NECP scenarios, are shown in Figure 9. It is important to note that in these model runs, building renovations have a cost opposed to exogenous implementation in Paper II and III. A detailed assessment of DH production under different uncertainties and price assumptions under the CEP scenario is presented in Paper II.

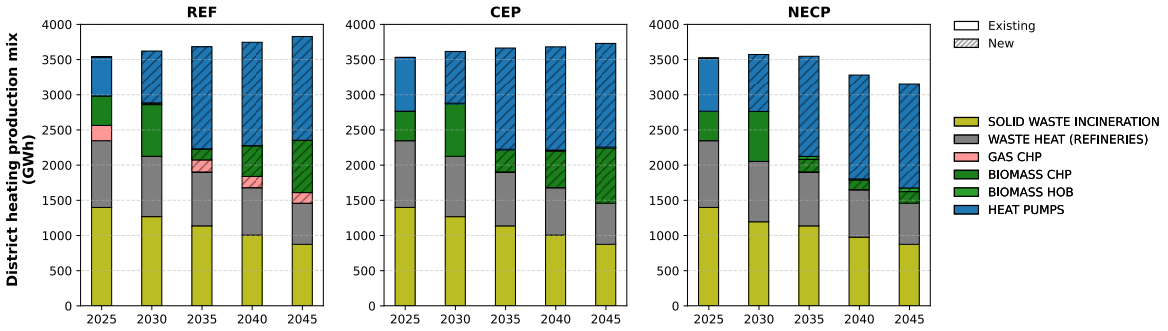


Figure 9: District heating production mix under the REF, CEP, and NECP Scenarios including production based on existing plants and new installations of DH production facilities. Results are based on the analysis in Paper II and include assumptions on low waste h heat availability based on uncertainty presented. DH production under the NECP scenario is based on the Scenarios included in Paper III.

In addition to the DH production mix, the composition of heating supply solutions for both new and existing residential buildings is analyzed in Papers II and III. Paper IV further integrates the results on heating supply solutions with electricity consumption, rooftop PV generation, and battery storage to assess resource efficiency in residential buildings. With the implementation of sub-regional characterization in Paper III, and IV, heating solution mix for residential builings are analysed at sub-city levels. Existing mix of DH and individual solutions is based on the assumption that all existing multi-family housing are connected to the district heating network, and 70% of existing single-family housing are heated using individual heat pumps. The main changes across apartments correspond to changing demands due to renovations. For single-family housing, with the existing heating supply mix including district heat and individual heating options, a possibility to switch between supply solutions is allowed.

In sub-regions with higher shares of multi-family housing (GOT2-4), a larger share of buildings are connected to the DH network in the initial period. Over time, however, heat pumps increasingly penetrate the heating supply mix toward 2045 in both the REF and CEP scenarios. In other sub-regions dominated by single-family housing, heat pumps emerge as the cost-optimal heating solution for new buildings. In the NECP scenario, higher penetration of heat pumps is observed even in the multi-family housing dominated sub-regions. The main reason for this changing dynamic over time is the changing DH production mix, as the availability of waste heat starts to decline, bio-resources become expensive and existing production facilities reach their retirement stage. In the NECP scenario, constraints on territorial emissions limit biomass use, which further incentivizes new households to transition toward heat pump based heating solutions. The heating supply solution mix for residential buildings at the sub-regional leves across policy scenarios is shown in Figure 10. The results comparing the dynamics of heating solutions for the multi-family housing and single-family housing are shown in Paper III.

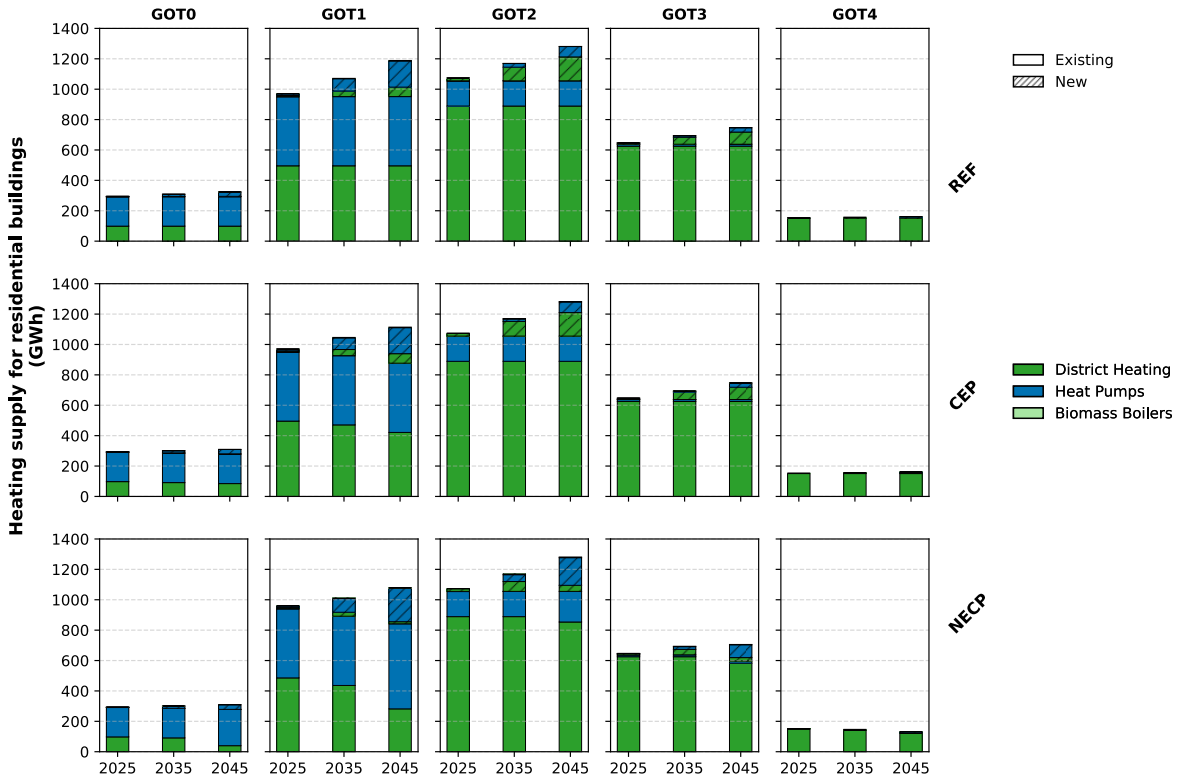


Figure 10: Heating supply solution mixes for existing and new residential buildings (MFH, and SFH) at sub-regional levels for the REF, CEP and NECP scenarios. Results are based on the analysis from Paper II and III.

4.1.2 Transportation sector

The long-term development pathways for the transportation system are analyzed by investigating the fuel supply mix and transportation activity for passenger transportation and urban freight. City-level fuel consumption for the transportation system of Gothenburg across REF and CEP scenario are investigated in Paper II. Paper III presents the investigation on the changing vehicle fleet compositions resulting from applied policy interventions, with a special focus on passenger car fleet compositions at the sub-regional levels.

In Paper IV, data processing based on socioeconomic and demographic characteristics enables differentiation of vehicle fleet composition and travel activity at the sub-regional level; consequently, passenger car fuel consumption results are presented on a per-capita basis. The existing passenger car fleet is dominated by gasoline and diesel-powered cars, with 9.5% penetration of EVs. In the REF scenario, all new vehicles starting in 2030 are EVs in GOT0 sub-region. For the remainder of the sub-regions, EV deployment starts in 2035 with 100% electrified passenger car fleet by 2045. In the CEP scenario, increased use of biofuels combined with faster electrification is required to reduce transportation sector emissions by 90% by 2030 compared to 2010. Within national climate objectives, similar trends are observed across regions, however with slower pace of decarbonization. Figure 11**(a)** presents the fuel consumption for passenger car fleet on a per-capita basis.

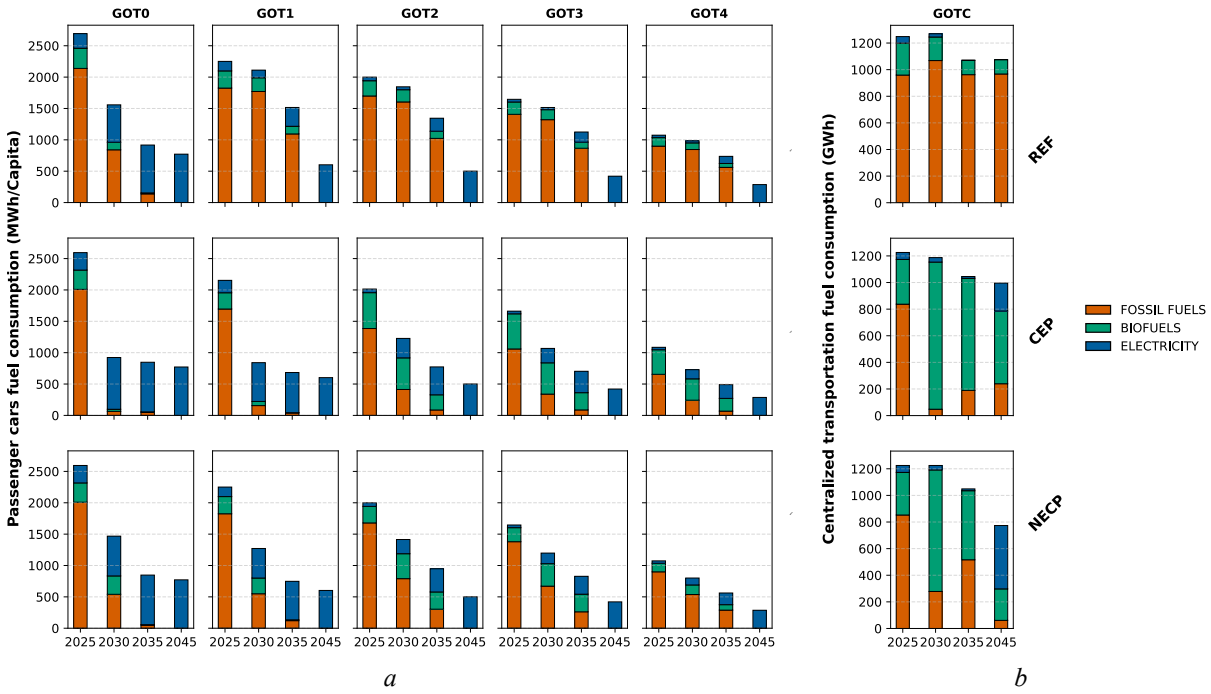


Figure 11: Fuel consumption for the transportation sector under the REF, CEP, and NECP Scenarios. Figure 11(a) shows fuel consumption per capita for the passenger cars at the sub-regional levels represented by GOT0-4, fuel consumption is derived from transportati transportation activity for cars from Paper III, and results are presented on a per-capita basis to represent the impact of sub-regional data processing on service demands at the sub-regional levels (Paper IV). Figure 11(b) shows fuel consumption at the centralized level, represented by GOTC, and the results are derived from results on transportation activity for passenger buses, heavy freight, and light commercial vehicles from Paper III.

Existing freight and buses include diesel vehicles, with small shares of biomethane and electric fleet. With high cost-premiums for electric buses and trucks, diesel vehicles continue to be the cost optimal choice. In the policy scenarios, short term goals can be achieved through increased use of biofuels. Over time biofuels, are complemented with different shares of fleet electrification. Figure 11(b) presents aggregate fuel consumption for centralized transporation system, under the REF and policy scenarios. Developments for the passenger buses, and urban freight is presented in Paper III, however some differences in model outcomes are observed due to developments in fuel prices, and reduction obligations for fossil fuels. With high operational expenses, centralized transport modes are more sensitive fuel prices.

4.1.3 Allocation of competing resources

To examine the allocation of electricity resources, constraints on existing low-voltage (LV) grid capacity are applied and future grid capacity investments evaluated at the sub-regional level with different assumptions on electricity and bioresource prices. Additionally, bioresource allocation across heating and transportation sectors is assessed through the application of price sensitivities. As a systemic development between Paper III and Paper IV, rooftop solar PV and battery storage are included in the technology options, and hence overall capacities for electrification infrastructure are investigated in this thesis.

Existing grid capacities are estimated based on base-year electricity demand and grid capacity can be expanded by 15% through reinforcements. Further increases in capacity can be achieved through investments in new infrastructure. The largest investments in grid capacity are observed in the GOT1 sub-region, followed by GOT2. The application of price sensitivities

does not result in significant changes, underscoring the economic robustness of electrifying residential heating and electric vehicles. While grid investment levels remain largely unaffected by electricity price variations, higher electricity prices lead to increased investments in solar PV systems and energy storage. As these technologies compete with grid-supplied electricity, their cost-effectiveness is strongly influenced by electricity prices. Figure 12 shows the existing capacity and new capacity investments in the electrification infrastructure for the CEP scenario under different assumptions of electricity and bioresource prices at the sub-regional levels. It is important to note that the inclusion of solar PV systems and battery storage reduces the need for new infrastructure investments compared to the analysis presented in Paper III.

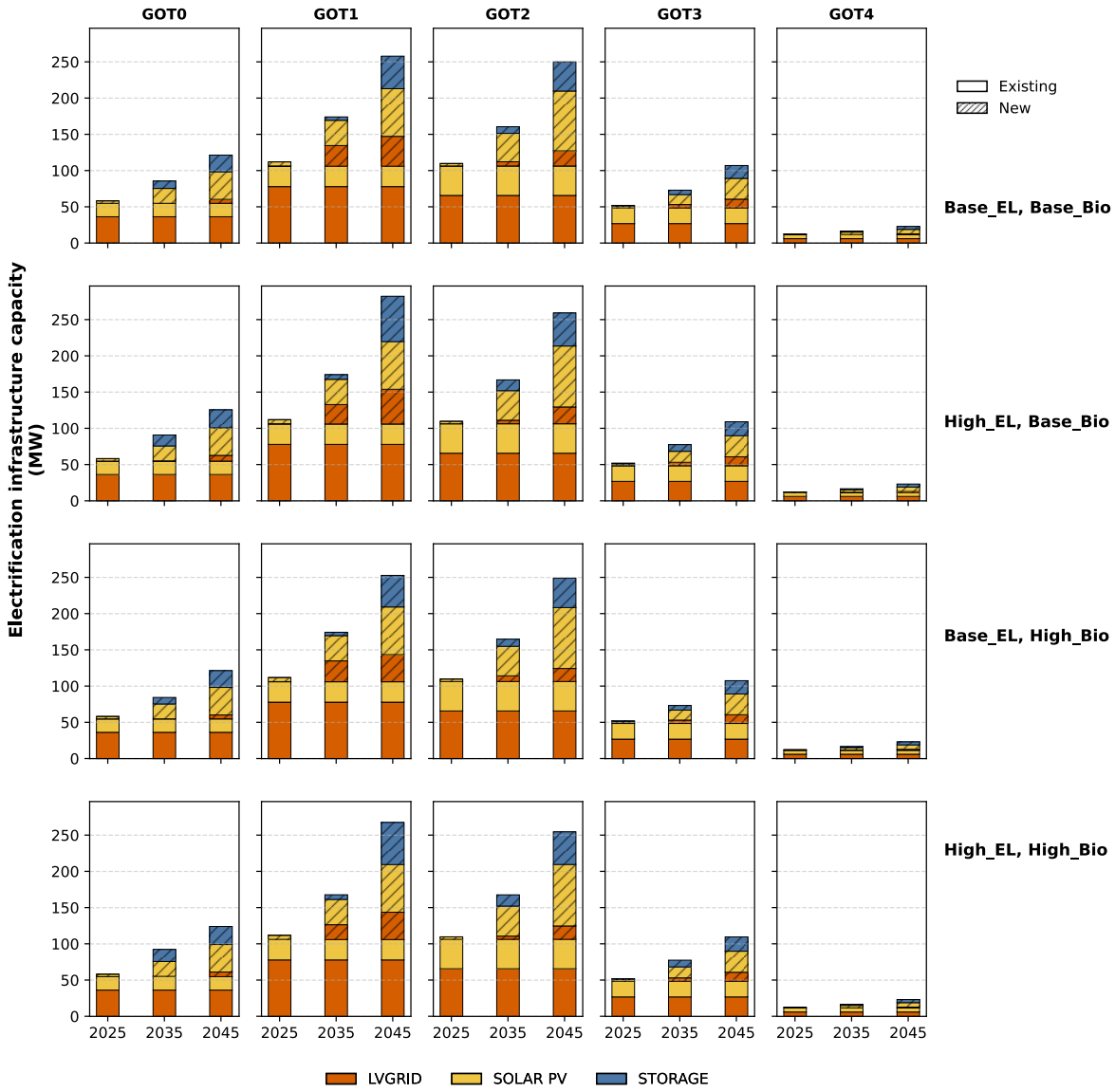


Figure 12: Existing and new infrastructure for electrification including LV grid capacities from Paper III, and capacities for rooftop PV and battery storage introduced in Paper IV. Infrastrucuture capacity are presented at sub-regional levels under different assumptions for electricity prices.

Bioresource use in the transportation sector is more sensitive to the electricity and biofuel pricing. Due to high operational expenses of freight and buses, larger shares of biofuels are observed under the base prices of biofuels, compared to high price assumptions. Bioresource use in the heating sector follows similar trend across price assumptions, with the exceptions of

very high utilization in the case of high prices for electricity and bioresources. Biofuels play a transitory fuel in the electrification journey of transportation sector. The results on bioresource use among the heating and transportation sector, for the CEP scenario under different assumptions of electricity and bioresource prices are presented in Figure 13.

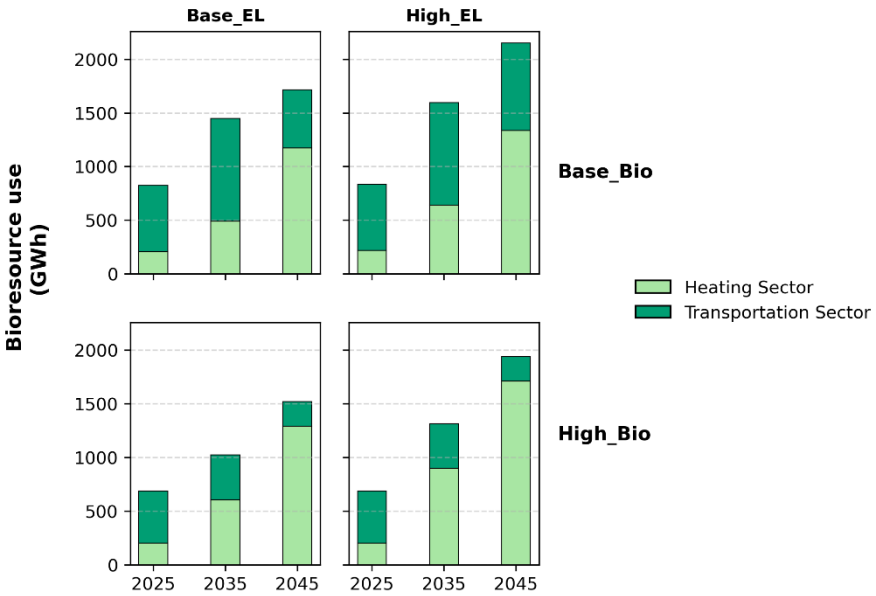


Figure 13: Bioresource utilization under the CEP Scenario with different price assumptions for bio-resources and electricity based on the analysis presented in Paper III.

4.2 Emissions reduction, and associated co-benefits delivery and distribution

To investigate the impact of applied policy measures on energy systems emissions, annual territorial emissions under the REF scenario are compared with the CEP and NECP scenario. The emissions contributions are further investigated across sub-regions, as well as centralized transportation and heat production. In the REF scenario, which reflects the implementation of existing national policy instruments, a significant share of emissions remains within the city's energy system. Over time, however, the emissions begin to decline, across sub-regions as the share of EVs start increasing. A significant gap exists between the emissions under the REF and CEP scenarios, emphasizing the impact of the CEP on the city's energy system and the necessity for additional measures to achieve the targets outlined in the CEP scenario.

With stringent 2030 targets, deep reductions in emissions are observed in the CEP scenario compared to the national climate targets. Due to the short-term focus of the CEP scenario, approximately 35% of base-year emissions remain in 2045, largely driven by the continued use of fossil fuels in heavy freight transport and bus fleets. By 2045, when Sweden aims to achieve a minimum 85% reduction in total territorial emissions, annual emissions within the city's energy system under the CEP scenario will be 35% higher than the levels required by the NECP. The results for the territorial emission trajectories highlight the impacts of the investigated policy measures and climate objectives, are shown in Figure 14**.** The results on cumulative emissions and associated system costs for different policy scenarios are presented in Paper III.

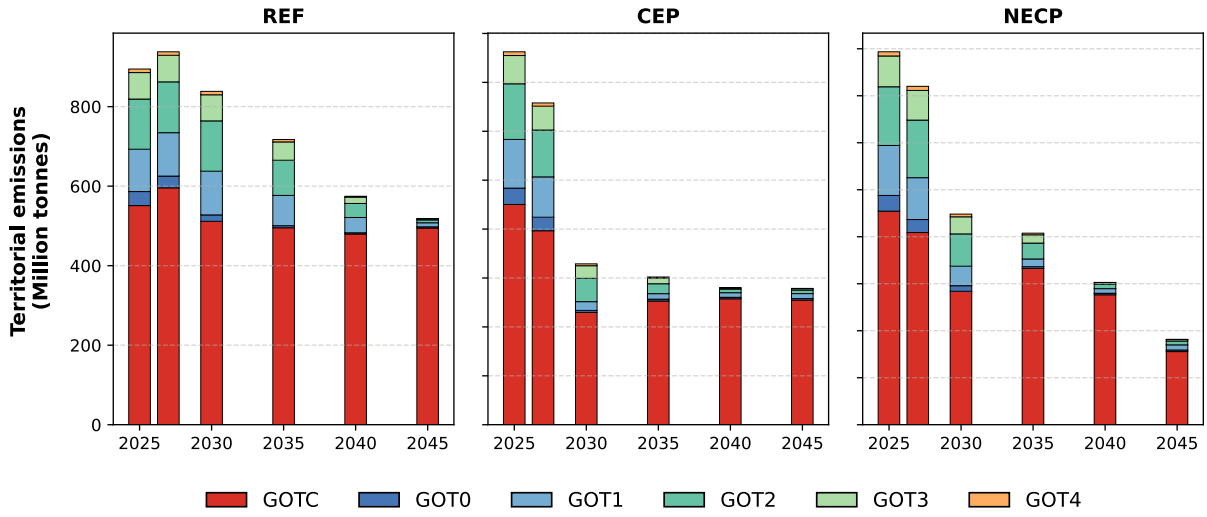


Figure 14: Annual territorial emissions under the REF, CEP, and NECP Scenarios, further distributed based on the contribution from centralized emissions (GOTC), as well as emissions from the sub-regions (GOT0-4).

4.2.1 Co-benefits distribution associated with the emission reduction

This study investigates the co-benefits arising from the implementation of urban energy system transition measures beyond binding emission reduction targets aimed at achieving national climate objectives. The sub-city level results highlight how socioeconomic and demographic differences across sub-regions impact the equitable distribution of these co-benefits. In Paper IV, impact of energy transition measures on urban resource efficiency, local air pollution, and energy affordability are investigated. The results on urban resource efficiency are integrated into the investigation of sectoral developments (Section 4.1), and the results on local air pollution and energy affordability are presented below.

Local air pollution

In the base hurdle rate assumptions, exhaust emissions per-capita follow a steep downward trend only in the sub-regions exhibiting the fastest rates of fleet electrification. Emissions decline to negligible levels in the GOT0 and GOT1 sub-regions by 2035, as a result of complete electrification of passenger cars. In GOT2-4 sub-regions, slower pace of electrification leads to delays in improvements in local air quality. The eventual electrification across sub-regions leads to near-zero exhaust emissions from passenger cars by 2045. It is important to note that reductions in carbon monoxide emissions in the intermediate years are primarily driven by a shift from gasoline to high-biofuel-blend diesel fuels, as required to meet climate objectives.

Sensitivity analyses on hurdle rates highlight the influence of income-related investment barriers on the distribution of co-benefits. As the EVs are expected to reach price parity with conventional vehicles, EV investments are less sensitive to investment barriers, beyond 2035. Main difference is observed in the case of low hurdle rates, with faster EV penetration in the sub-region with lowest income levels (GOT2). Changes in the per capita exhaust emissions with base, high and low hurdle rate assumptions across sub-regions are presented in Figure 15.

Over time, particulate matter (PM) emissions are expected to persist in the city, as urban climate actions alone are unlikely to deliver benefits associated with reduction of PM concentrations, unless mitigation strategies also incorporate reduced vehicle activity and promote adoption of active transportation modes. The majority of PM emissions originate from non-exhaust sources

and are primarily driven vehicle activity rather than changes in the fleet composition. Vehicle activity associated with GOT0 is the largest contributor to PM emissions followed by GOT1-4. While fleet electrification contributes to reduced PM emissions due to regenerative braking, higher vehicle curb weights of EVs compared to conventional vehicles may lead to increase in road and tire wear. Per-capita PM emission contributions from passenger car activity across sub-regions is presented in Figure 16 for the three hurdle rate assumptions.

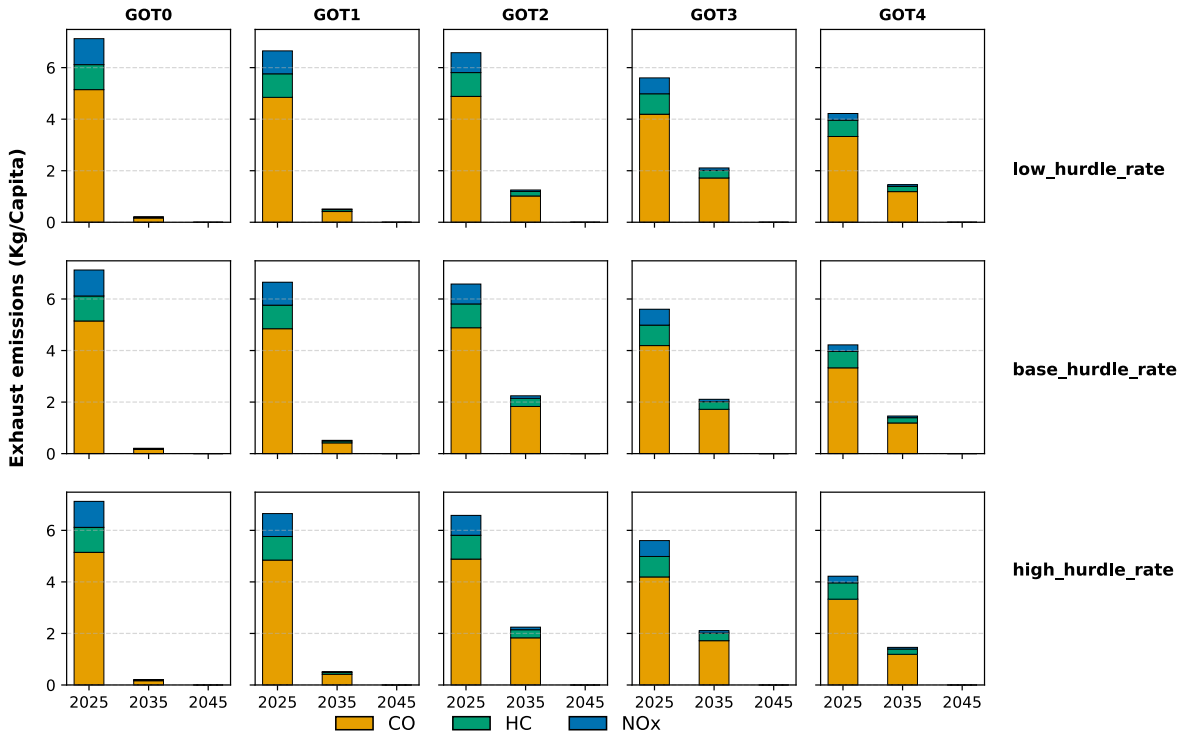


Figure 15: Exhaust emissions associated with passenger cars activity for different sub-regions under the base case, high and low hurdle rate sensitivity on per capita basis. Exhaust emissions include Carbon Monoxide (CO), Hydrocarbons (HC), and Nitrogen oxides (NO_x). The results are based on the analysis presented in Paper IV, and sensitivity analysis conducted under the NECP scenario.

Energy affordability

Energy systems transformation pathways, aimed at achieving the 2045 climate neutrality targets, are expected to impact the affordability of the city energy system. Impacted by investment decisions and operational expenses, changes in the affordability are sensitive to the hurdle rate assumptions in the long term. Additionally, hurdle-rate assumptions influence the decisions of lower-income households more than those of higher-income households, reflecting the assumed inverse relationship between financial resource availability and hurdle rates.

In all cases, increased energy costs are observed in the intermediate year 2035. On progressing towards 2045, median income allocation increases by 6% and 8% respectively for the base and high hurdle rates, while it decreases by 2.2% in the case of low hurdle rates. Furthermore, outliers exceeding an income allocation of approximately 4–4.5% are observed in the dataset, indicating an increased financial burden for certain RegSOs. At the city level, the share of the population experiencing an energy burden exceeding 3% increases from 4.1% in 2025 to 15% by 2045 under high hurdle rate assumptions. In contrast, under low hurdle rate assumptions, the proportion of the population allocating more than 3% of income to energy remains stable at around 4%. The annualized cost of energy services as a share of annual income for 2025,

and the impact of transitioning energy system on energy affordability and its distribution over the different statistical areas is shown in Figure 17 for all hurdle rate assumptions.

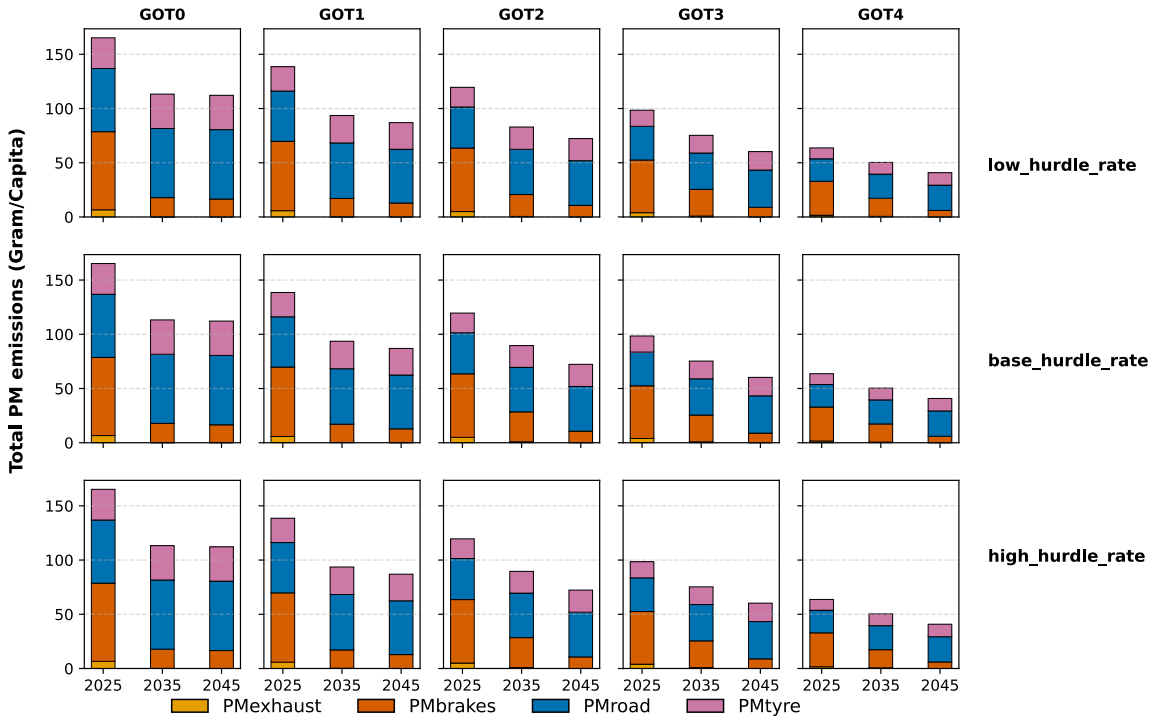


Figure 16: Particulate matter (average) emissions from exhaust as well as non-exhaust emission sources associated with passenger car activity for different sub-regions under the base case, high and low hurdle rate sensitivity on per capita basis. The results are based on the analysis presented in Paper IV, and sensitivity analysis conducted under the NECP scenario.

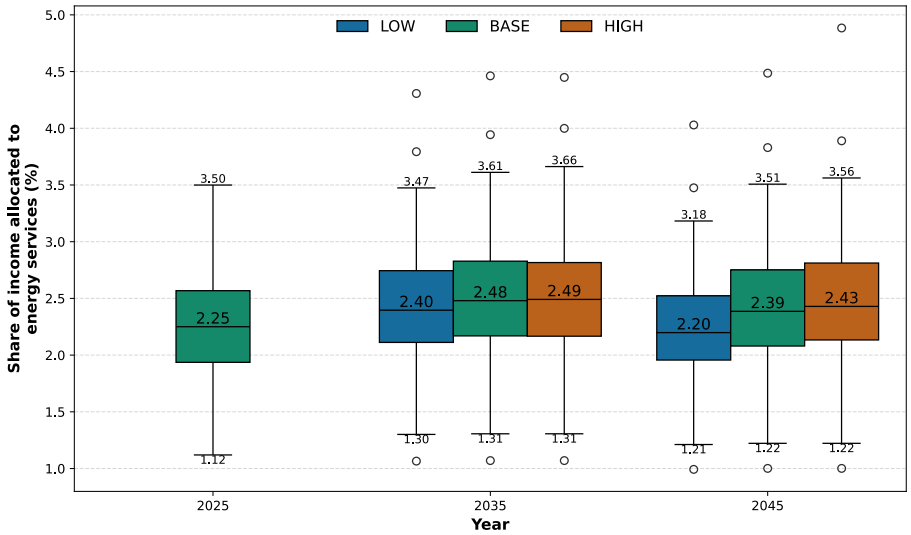
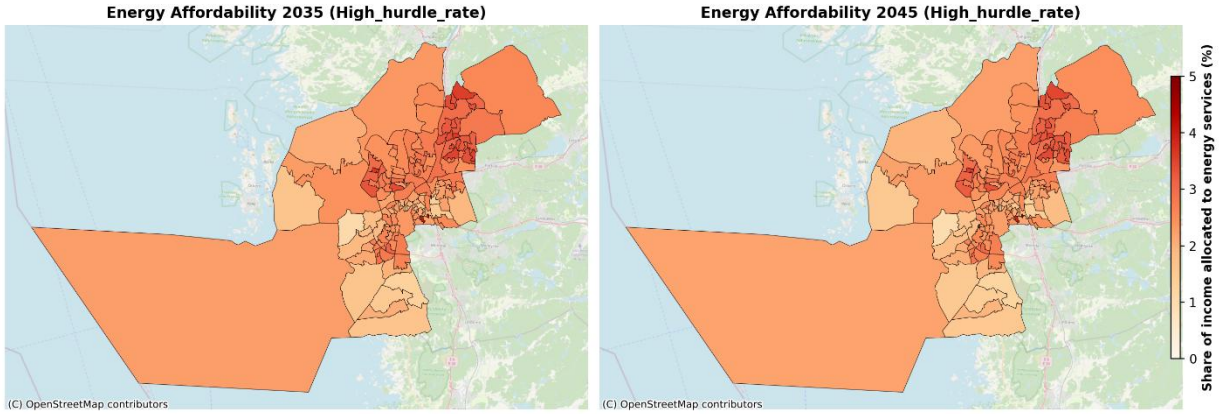
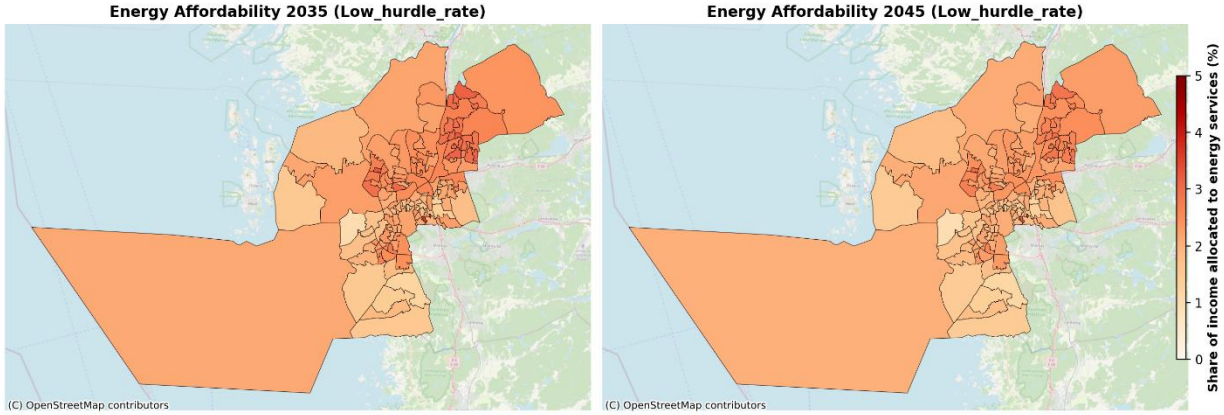


*Figure 17: Share of income utilized to fulfil the energy service demands in 2025, along with income allocation for the low, base, and high hurdle rates in 2035 and 2045. The box represents the interquartile range (25th–75th percentile), with the central line indicating the median. Whiskers extend to the minimum and maximum values (1.5*Inter-quantile range), including outliers. The results are based on the analysis presented in Paper IV.*

Spatial distribution of share of income allocated to energy services for the high and low hurdle rates for the intermediate year 2035 and 2045 are shown in Figure 18(a) and Figure 18(b) respectively.



a



b

Figure 18: Spatial distribution of the share of income allocated to energy services across RegSO in Gothenburg, under the high hurdle rate assumption (a) and low hurdle rate assumption (b) for the Year 2035 and Year 2045.

4.3 Discussion of the results

This work focuses on the impact of energy policies and climate targets on the future cost-optimal system developments. With ambitious short-term targets, energy systems designs within the city energy plan follow a path of deep and rapid decarbonization compared to the reference case. As the reference case includes current policy measures, differences across scenarios emphasize a need for additional policy incentives to achieve the environmental goals of the city energy plan. Comparing energy systems designs under the city energy plan and national energy and climate plans, independent policy-based scenario applications could result in different cost-optimal systems developments. This also demonstrates how governance structures, capacities and choices shape the transitions trajectory differently. By coordinating the city plans with national objectives, the deep reductions achieved through short-term targets could be maintained through a sustained long-term reduction trajectory.

Bioresources and electrification drive developments in the heating and transportation sectors. District heating production in the city is largely decarbonized, with only small remaining shares of gas-based combined heat and power plants, which are expected to be gradually replaced by biomass-based solutions. Across policies, a main difference is observed in the shares of biomass use, as the territorial emissions targets under national objectives constrain the use of biomass. In all cases, future district heating production in the city is estimated to be highly

resource efficient, based on centralized heat pumps, and waste heat recovery, further emphasized by previous studies investigation of operation of the future district heating system in the city [100,101].

Decarbonization of the transportation system is a more challenging task for the city, and heavy freight and buses are the hardest to decarbonize and require large penetration of biofuels to achieve the immediate 2030 decarbonization goals. Reduction in the obligations to reduce climate impact of fossil fuels, further exacerbates the challenges to transportation sector decarbonization [97]. On the other hand, decarbonization of the passenger car fleet is found to be cost-optimal, with a fully electrified fleet achieved even in the reference scenario. However, the pace of electrification is projected to be slower than required to meet climate targets, due to unfavourable conditions for certain consumer groups.

Consumer heterogeneity, based on spatial disparities in socioeconomic and demographic characterisitcs, is a key determinant factor for the adoption of decarbonization strategies. Housing composition, population density, and income levels are used to characterize sub-regional differences within the city. Technology-specific hurdle rates for residential consumers are applied to represent investment behavior shaped by socioeconomic conditions and policy environment across the city. Previous studies have adopted similar approaches to represent consumer behavior at the national scale [87,88]. The importance of accounting for consumer heterogeneity is further demonstrated by the findings presented in Papers III and IV.

Heating supply solutions for new buildings are impacted by housing type, demand densities, and district heating production infrastructure. Individual heating supply investments at sub-regional levels are further influenced by hurdle rates and capacities for low voltage distribution infrastructure. As future heating systems are evaluated, district heating becomes progressively less economically attractive due to reduced availability of waste heat and increasing bio-resource prices. In the beginning, sub-regions with high shares of apartment buildings connect to district heating network, however as the existing infrastructure starts reachings its retirement, individual heat pumps become a more cost-effective alternative.

At the sub-city levels, challenges with the electric vehicle adoption are observed in high density sub-regions with apartment buildings characterized by lower income levels. In the early years, hurdle rates strongly influence investment decisions for electric vehicles due to their high upfront costs. Combined with high investment barriers, charging profiles in such areas comprising large shares of commercial charging increase the operating cost for electric vehicles compared to in-house charging as also emphasized in the study comparing levelized cost of charging [102]. High upfront costs delay electric vehicle uptake in lower-income areas, leading to a greater reliance on biofuels to meet mobility needs and constraining access to the operational benefits of electrification.

Favorable conditions among high-income single-family households have facilitated early adoption of electric vehicles; however, market growth is expected to slow once these households have largely electrified their vehicle fleets. Failing to account for sub-regional socioeconomic and demographic heterogeneity may therefore result in misleading projections of future electric vehicle market shares based on historical trends, as also reflected in recent evidence of slower-than-expected electrification [97]. This underscores the importance of distinguishing between early adopters and future electric vehicle consumers when assessing transition pathways.

The results on grid capacity investments and bio-resource use highlight their important role in the decarbonization of the city's energy system. Electrification infrastructure includes low-voltage grids, rooftop photovoltaic systems, and battery storage. The introduction of distributed electricity generation and load-shifting capabilities reduces the need for grid infrastructure investments compared to the findings presented in Paper III. In the model setup, grid infrastructures are represented in a simplified manner through aggregate capacity constraints, without explicitly capturing voltage or load-limit violations. This simplification enables the inclusion of distribution grid considerations in long-term energy planning, as limitations in grid infrastructure could slow the pace of electrification in urban energy transitions [12]. Furthermore, biofuels play a significant role in the short-term transport sector decarbonization. With changing prices, the main impact is seen on biofuel use for the commercial transportation. With high operational costs, heavy freight and urban buses are more sensitive to the changing fuel prices. Over time, bio-resources play a role of a transitional fuel complementing the electrification of the transportation sector, and as a primary fuel fulfilling the district heating demand in the heating sector. However, the district heating production mix under the national climate objectives limits the use of biomass, and reaching territorial emission targets while using biomass as a primary district heating fuel would require additional measures such as bioenergy with carbon capture and storage [103].

Energy systems transformations aimed at reducing the climate impact are expected to deliver environmental and societal benefits. Improvements in local air quality are directly linked to the electrification of passenger vehicles, with declining exhaust emission concentrations following the trend of electrification across sub-regions. However, with 60% of city's population concentrated in the two sub-regions with slow electrification rates, their contribution to local air pollution has a larger impact on the city's air quality improvements over time. Barriers to investments in electric cars, will delay the impacts of fleet decarbonization on air quality improvements. Furthermore, particulate matter emissions from non-exhaust sources are expected to persist even with a fully decarbonized vehicle fleet. Many studies have highlighted the persistent challenge of non-exhaust emissions, particularly in urban areas where particulate matter emissions impose substantial health and economic burdens [104,105]. It is important to note that, within the scope of this study, sub-regional variations in air pollutant concentrations are attributed to the location of vehicle ownership rather than actual vehicle activity. This approach limits the assessment of health and economic impacts associated with changes in air quality, which are primarily impacted by the spatial distribution of local emissions. Depending on whether it's an area of dense or sparse nature, population exposure per unit of pollutant emissions varies significantly [106].

In addition to local air pollution, impacts of climate action on energy affordability are investigated. Energy affordability, defined as the share of annual household income spent on energy expenditures is widely recognized as a key indicator of energy equity, and improvements in energy affordability resulting from energy system transformations are identified as an important socioeconomic co-benefit [17]. Under high hurdle rate assumptions, a larger proportion of the population is expected to face increased income burdens to meet their energy needs, whereas these burdens remain comparatively lower under low hurdle rate assumptions. These findings underscore the long-term operational benefits of decarbonization measures once barriers to upfront investments are addressed. For example, when constraints on electric vehicle investments persist, strategies to meet climate targets increasingly rely on

biofuels to reduce emissions, leading to higher operational costs. In contrast, policy environments characterized by lower investment hurdles facilitate a more equitable distribution of benefits, including improved energy affordability, by reducing barriers associated with upfront investment premiums.

Sweden has ambitious climate objectives, with municipalities committed to rapid decarbonization [4]. At the same time, Sweden exhibits one of the fastest-growing levels of inequality in Europe, largely driven by housing-related reforms over recent decades [107]. Addressing socio-spatial disparities is therefore essential to ensure equitable access to alternative solutions and to prevent high upfront costs from excluding certain communities from long-term operational and system-wide benefits. As previously highlighted, transformation of urban energy and mobility systems can reinforce existing socio-spatial inequalities in access to decarbonization measures and their associated benefits [85]. In this context, incorporating socio-spatial disparities into research and policy decisions should be a priority, enabling more equitable and effective long-term urban energy systems design. Failure to ensure inclusive access to resource-efficient measures and system developments risks leaving segments of the urban population vulnerable to external shocks, including prolonged market disruptions such as those arising from current geopolitical conflicts in West Asia.

5 Strategies for long-term city energy systems planning

This thesis applies an integrated modelling framework that captures the interdependencies between demand-side and supply-side energy systems, to investigate cost-optimal, long-term development pathways for the city energy system. A central focus is the representation of consumer heterogeneity through socioeconomic and demographic characterization at high spatial resolution. This framework enables the analysis of intra- and cross-sectoral interactions while accounting for resource allocation among competing sectors in accordance with policy objectives. Integrating socioeconomic and demographic characterization into consumer representation enhances the analysis of technology adoption dynamics while also accounting for equity considerations and the fair distribution of benefits of urban climate action.

Long-term planning has been identified as a key factor for supporting decision-making processes, guiding the when and how of energy systems' developments [16]. In this context, the present study assumes perfect foresight, eliminating future uncertainties and operating under the assumption that anticipated future outcomes will materialise as expected. Long-term modelling, encompassing several years, also limits the temporal resolution of the modelled system, thus flexibility in the choice of time-slicing is included in the framework. The temporal resolution in Paper II accounts for seasonal variations (monthly and peak demand days) for the heating sector and annual variations in the transporation sector. In Paper III and IV, with the need for detailed daily variations in the electricity sector, temporal resolution accouts for seasonal variations of the heating sector and hourly variations of the electricity sector through 228 (12*24) time-slices. While the applied method accurately captures the variations associated with the heating and electricity systems, aggregating loads to a lower temporal resolution serves to under-estimate the peak load and, thus, under-estimates the need for reserve capacity.

City energy systems, unlike national or regional systems, are often shaped by the investment decisions made by individual stakeholders. For consumers, these investment decisions are mainly driven by the cost-effectiveness of the technologies available to them. Furthermore, local authorities are tasked with ensuring the efficient use of taxpayer funds in their investment and operational decisions to meet end-user service needs. Therefore, an optimization technique is applied to compute the energy system design characteristics, aiming to identify the optimal system configuration that minimises the total system costs. Decisions regarding future investments are based exclusively on the cost-effectiveness of the technologies. In Paper II, the consumer cost perspective represents variations in the cost of energy services, including differences in electricity prices and grid charges, across housing archetypes and consumer categories such as residential and commercial users. As an aspect that evolves from Paper II to Paper III&IV, technology-specific hurdle rates are used to represent customers' investment decision making. For residential customers, these hurdle rates are derived from the spatial distribution of the median household income. In this manner, behavioural aspects of investment decision-making influenced by socioeconomic conditions are accounted for. However, service demand developments impacted by behavioral shifts are not included in the analysis. Service demand changes associated with behavioral changes, lower per-capita living space requirements and avoid-shift strategies in the transportation sector can significantly contribute to delivering resilient climate-neutral urban systems [108,109].

An additional dimension of consumer heterogeneity that warrants further investigation is the inclusion of residential tenancy types. Accounting for tenancy arrangements would affect hurdle rate assumptions for investment decisions related to rooftop PV and building renovations, and it may reveal that the benefits of such transition measures do not fully transfer to the end consumers.

Heating system developments include supply alternatives such as district heating and individual household-level heating solutions. The results indicate a growing reliance on individual heating solutions as district heating systems become increasingly economically unfeasible as the existing intrastructure reaches its retirement. This effect is particularly evident under territorial emissions constraints imposed by the national climate plan, where the use of biomass and waste incineration is restricted due to emission targets and the expansion of centralized heat pumps is constrained by the availability of excess heat. Within the scope of this study, supply-side measures such as options for thermal energy storage, new sources of excess heat, and bioenergy with carbon capture and storage, as well as demand-side measures such as reduced district heating grid temperatures and changes in indoor environmental requirements are not included in the analysis. The representation of future developments in the district heating systems could improve their cost-effectiveness, as also highlighted by the authors in their analysis of the challenges and opportunities for district heating [110].

Driving patterns for different transport modes are represented as annual averages, without capturing variations at finer temporal resolutions. In addition, these assumptions are held constant over the entire time horizon. This simplification limits the representation of real-world driving conditions and may affect decisions regarding the cost-optimal composition of the vehicle fleet. It is important to highlight that the model set-up has been designed to be able to represent changing driving patterns on a higher timescale. However, several developments limit analyses of the key factors that are impacting the model outcomes. The present study focuses on investigating the effects of investment and operational costs, infrastructure for charging and distribution grids, resource allocation, and hurdle rates on the changing transportation system.

Low-voltage distribution grid capacity investments are an important outcome of the model runs that highlight the cross-sectoral interactions, accounting for the utilization of low voltage grid infrastructure. Future investments in grid capacity are prompted by higher peaks due to the increasing electrification of residential heating and transportation sectors. In Paper IV, systemic developments are examined through the inclusion of batteries and rooftop PV systems, which have the potential to influence optimal grid infrastructure investments and enable load shifting. Furthermore, the impact of increased electrification is represented through aggregated infrastructure capacity without considering voltage/load violations. This simplification allows representation of a low-voltage grid infrastructure in the long-term planning and complements previous studies [63–65] that have detailed the impacts on the grid of pre-defined shares of technology deployments.

The emissions scope of this thesis is limited to CO_2 emissions arising from fuel use as well as fuel supply and distribution, consistent with national and city-level climate targets. Exhaust and non-exhaust emissions from the passenger car usage are included in Paper IV, as an indicator to evaluate further benefits of transport sector decarbonization. Strategies such as electrification, renewable energy deployment, and building renovation aimed at reducing the

climate impact of urban energy systems shift emissions away from fuel combustion toward material-based embodied emissions. Although the accounting for emissions is considered adequate for assessing the impacts of local policies and their alignment with national and regional climate goals, limitations in the emissions scope may result in inaccurate estimates of the climate impacts of policy interventions and their associated targets. The findings on non-exhaust emissions already underscore the importance of measures beyond purely technological transitions and highlight the need for reduced vehicle activity to achieve the intended environmental benefits. Integrating behavioral changes that lower end-use service demand, together with the inclusion of emissions beyond fuel consumption based emissions to material-based emissions, is expected to further emphasize the necessity of limiting consumption to remain within planetary boundaries.

As every city has a unique urban context, the selection of the case influences the future development of the energy system. The demand dynamics, existing infrastructure, availability of resources, demographic characteristics, and policies implemented at the city and national levels influence the findings of the model runs. In the global context, Sweden is a high-income country, which means that the risks associated with investments in technological developments are lower in Swedish cities [111]. Gothenburg has a well-established district heating network and good availability of low-cost waste heat, which drives the existing heating system. This makes it crucial to understand the existing set-up in terms of available resources and infrastructure, to identify the long-term development pathways. While the results highlighted in this thesis are influenced by the unique characteristics of the Gothenburg energy system, many aspects of the modelling results are generalizable to comparable city energy systems.

While the generalisability of the results is limited to specific cases, the adopted methodological framework can be applied to different urban contexts to address research questions related to their decarbonization journeys. The application of this framework to other cities with different urban contexts will allow the framework development to be more versatile, such that it can be applied to support the decision-making processes in different cities.

6 Main findings and thesis contributions

This section is organized into two subsections. Section 6.1 presents the key findings addressing the three research questions, followed by a discussion of the methodological contributions of this work in Section 6.2.

6.1 Main findings

The overarching research objective of this work is to develop and apply a comprehensive methodological approach to support long-term energy systems planning in cities. With the application of the developed method to the energy system of Gothenburg, three research questions are investigated to evaluate strategies for long-term energy systems planning.

The research questions formulated in Section 1.1 guide this study, and the findings addressing these questions collectively enable the fulfillment of the thesis's overall research objective.

I. How do short-term energy plans and policy targets influence the future cost-optimal design of city energy systems at city and sub-city levels, and to what extent do local-level energy plans align with national climate objectives in the long term?
II. In their optimal pathways, how are the limited resources allocated among the competing sectors?
III. What are the co-benefits of urban climate action, and how do spatial differences in socioeconomic and demographic characteristics influence the equitable distribution of their co-benefits?

To answer RQI, a set of policy-based scenarios were applied to the developed energy systems model, and model outcomes investigated to evaluate future cost-optimal system developments at the city and sub-city levels. The heating system of Gothenburg accounts for a small share of fossil emissions and fossil fuel ban under the city's energy plan ensures that the remaining fossil-fuel use will be fully eliminated. Under the National Energy and Climate Plan scenario, district heating production is reduced in the future as territorial emission constraints restrict the use of biomass for heating. A future district heating system with limited waste heat availability is used to assess changes in residential heating supply. Rising bioresource prices, reduced low-cost waste heat, and the phase-out of existing infrastructure make district heating less competitive, shifting new residential developments toward heat pump solutions. The main findings highlight a shift in the solution mix from district heat to individual heat pumps over the time-horizon.

Policy interventions beyond the current national policy measures are imminent to achieve the 90% reduction targets under the city energy plan scenario for the transportation sector. Meeting the 2030 targets requires a significant shift in fuel composition, entailing a substantial increase in biofuel use in the transportation sector, while national climate objectives ensure sustained emission reduction beyond short-term targets. Analysing the fleet mix at the sub-regional levels, the results highlight the importance of the spatial characterization of the technological parameters. The GOT2-3 sub-regions, which are characterised by a lower median household income, a user charging profile based on commercial charging, and lower existing low-voltage grid capacity, are the slowest to electrify their car fleet. The results for passenger car fleet composition indicate that electrification of the car fleet is economical but requires a more rapid shift than in the reference scenario to meet the 2030 targets.

In response to RQII, model outcomes under the city energy plan scenario are tested with price sensitivities based on future fuel price assumptions for bioresources and electricity. The results on the distribution grid capacities sheds light on the sectoral interactions in their development pathways. Future grid capacity investments will be shaped by the shift towards using heat pumps in apartment buildings and rapid deployment of passenger electric vehicles. Introduction of distributed generation and battery storages, reduce the need for grid infrastructure, however its impact on voltage violations and associated reinforcemetns need to be investigated. Information on a sub-regional level shows bottlenecks in the low-voltage grid infrastructure and high-density sub-regions with large share of multi-family housing should be prioritized in future grid investment planning. Biomass is used as a primary fuel in the heating sector fulfilling district heating demands, while biofuels in the transportation sector are used as transitional fuels complementing the electrification journey. The changing utilization rates of bio-resources over time highlights their varying role in the heating and transportation sectors.

To investigate the delivery and distribution of co-benefits of urban climate action (RQIII), model outcomes from the National Energy and Climate Plan scenario are used to assess co-benefit indicators under different assumptions of income-dependent hurdle rates. Changes in exhaust emissions per capita follow a steep downward trend only in the sub-regions exhibiting the fastest rates of fleet electrification, however in GOT2-4 sub-regions, slower pace of electrification leads to delays in improvements in local air quality. Particulate matter emissions from non-exhaust sources are expected to persist in the city, as urban climate actions alone are unlikely to deliver benefits associated with reduction of particulate matter emission concentrations, unless mitigation strategies also incorporate reduced vehicle activity and promote adoption of active transportation modes.

Under high hurdle rate assumptions, achieving climate targets is projected to increase the share of the population allocating more than 3% of their income to energy services from 4% to 15%. However, under policy environments that reduce barriers to upfront investments, this share remains considerably lower. These findings highlight the long-term operational benefits of decarbonization measures, provided that barriers associated with initial investment premiums are adequately addressed in decision-making processes.

6.2 Thesis contributions

The introduction and literature review presented in this thesis highlight the critical role of city energy systems in global climate action and the importance of supporting their long-term planning due to their inherently dynamic nature. City energy systems are not just technical, they are also shaped by policy frameworks and centered around people. By understanding these technical, policy, and social dynamics over time, pathways toward climate-neutral, resilient, and socially just cities can be effectively designed.

The main contribution of this thesis is the development of a comprehensive integrated methodological framework to support long-term strategic planning for city energy systems.

This integrated modelling approach, which links interrelated demand-side and supply-side energy systems to explore cost-optimal, long-term development pathways for an urban energy system, enables the analysis of both intra- and cross-sectoral interactions. Sectoral interactions are further detailed by accounting for resource allocation across sectors in their development

pathways. The integrated approach is used to investigate the impacts of the city energy plan and short-term policy targets on the long-term energy systems development. Highlighting the important role of city energy systems in contributing towards overall national decarbonization targets, alignment of short-term city energy plans with long-term national and regional climate objectives is investigated. The usefulness of this integrated modelling approach lies in allowing for investigations of changing dynamics of city energy systems over the modelled time horizon.

This work places a particular emphasis on the inclusion of city's socioeconomic and demographic characteristics at high spatial resolution to represent customer heterogeneity. Such characteristics are incorporated into the integrated energy systems model, to evaluate the impact of differences on the adoption of decarbonization measures, as well as to assess the extent to which differences in these characteristics affect the equitable distribution of urban climate action co-benefits. Based on socio-spatial disparities, key techno-economic parameters at the sub-regional level are defined for residential heating options, electricity and district heating distribution grids, passenger car charging infrastructure, and technology-specific hurdle rates are used to account for socioeconomic differences across the city.

In this context, the methodology allows analyses of system developments from three different perspectives. Firstly, the application of policy scenarios facilitates analyses of different future cost-optimal system designs aimed at achieving specified future climate goals. Secondly, using a long-term perspective, it is possible to evaluate potential developments over time. Inclusion of spatial characterization of the city allows for developments driven by demographic characteristics and associated technological parameters. Customer heterogeniuty based on socioeconomic and demographic differences facilitates policy decisions that support decarbonization efforts aligned with the principles of social equity and justice, ensuring that the transition benefits all segments of society. This requires inclusive energy policies that address both environmental and social dimensions, rather than focusing solely on technical or economic outcomes.

7 Limitations and proposed future work

The main findings of this work are based on a cost-optimization modelling framework that assumes perfect foresight and bases future investment decisions on the cost-effectivenss of available technology options. In practice, however, investment decisions are also shaped by market design, regulatory structures, and behavioural factors which are not fully captured in the model. As a result, modelled transition pathways may differ from real-world investment trajectories. More broadly, the results are sensitive to the underlying assumptions used to simplify and represent complex real-world energy systems within a mathematical optimization framework. While such simplifications are necessary to represent complex system designs, and to understand model outcomes, acknowledging these simplifications is crucial as they constitute key limitations and should be carefully considered when interpreting the results and their policy relevance.

Energy systems modelling entails continuous development, and successive developments aim to improve the representation of real-world energy systems through necessary simplifications and assumptions. Within the scope of this thesis, the modeling framework primarily focuses on existing and emerging core technologies while omitting several measures that could influence future system performance. Supply-side options such as thermal energy storage, additional sources of waste heat, and bioenergy with carbon capture and storage (BECCS) are not included, as well as demand-side measures such as reduced district heating grid temperatures and changes in indoor environmental requirements are not included in the analysis. These exclusions limit the ability to fully capture potential improvements in the system flexibility, particularly in the evolutions of future district heating systems. Future research could extend the current modeling framework by incorporating additional supply-side and demand-side measures into integrated energy systems modeling to better reflect prospective developments in urban energy systems. Including options such as thermal energy storage, expanded waste heat utilization, and BECCS could enhance the assessment of long-term decarbonization pathways and improve the cost-effectiveness of district heating systems.

Infrastructure for the low-voltage distribution grid is crucial to support the electrification of heating and transportation sectors, and inclusion of grid infrastructure is idenfied a a crucial step in long-term energy systems planning at the local level. In this work, as a simplification of grid representation, limits on grid capacity are applied and investment in distribution grid to facilitate the electrification are represented through additional capacity investments. With the introduction of distributed electricity generation, findings show a reduced need for investments in the distribution grid. However, a more detailed representation of grid such as voltage violations arising from increasing peak loads, would likely reveal additional requirements for grid reinforcements. This includes addressing voltage violations induced by photovoltaic installations, beyond the load-related constraints currently captured through aggregate grid capacity limits.

The modeling approach applied in this thesis planning primarily focuses on technology adoption as the energy transition measures to achieve the desired energy and environmental objectives. While this approach enables a detailed assessment of cost-optimal technological pathways, it does not explicitly account for behavioral dimensions of service demands. Key behavioral strategies such as avoid–shift measures, changes in per-capita floor space, and reductions in end-use service demands are therefore not represented. Although consumer

behavior is partially captured through investment decision-making assumptions (e.g., hurdle rates), broader behavioral responses that influence consumption patterns over time remain outside the scope of this work. The results on non-exhaust emissions further indicate that technological measures alone may not be sufficient to achieve desirable environmental outcomes. Future work is needed to complement technology-focused modeling approaches with explicit representations of behavioral changes. Advancing approaches to quantify behavioral responses such as reduced service demands, shared mobility, changes in living space requirements would allow for more comprehensive assessments of urban decarbonization pathways.

The main research objective of this work was to support strategies for long-term urban energy systems planning and the developed methodological framework was applied to the energy system of Gothenburg. As also highlighted in Section 0, due to the strong representation of the unique urban context in the application process, there exists limitations on the generalizability of the main findings. Applications of the developed methodological framework to investigate long-term developments for different urban energy systems is identified as a prospect for future work. The methodological application can be conducted in two stages. In the first stage, the approach can be tested across Swedish municipalities, which share similar demand- and supply-side energy system dynamics and for which the necessary datasets used in this study are available. In the next step, with some structural modifications the framework could be applied to different urban contexts. Such studies would provide valuable insights into the versatility of this modelling framework for varied applications. Currently, work is ongoing to improve the accessibility of the model, and automation of processes is under progress to facilitate the spatial assessment for different Swedish municipalities with similar data availability.

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