# Policy-driven City Energy Systems Planning

-Modelling Long-term Strategies

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025

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# Abstract

To limit global warming to well below 2°C, deep and rapid reductions of greenhouse gas emissions are indispensable. Cities account for around 75% of total global energy consumption and contribute to 70% of total emissions. Cities play critical roles towards achieving decarbonisation targets and contributing to national climate actions. This thesis investigates the impact of city energy plans and associated short-term targets, and their alignment with national and regional climate objectives, while addressing key sectoral interactions within the energy systems' development pathways.

An integrated approach is employed, encompassing inter-connected demand-side and supply-side dynamics. The long-term decarbonisation targets and policy measures are incorporated using a cost optimisation model. The TIMES model generator is used to develop the TIMES_Northern European city model, which is characterised by high heating and transportation demands. Gothenburg is chosen as the representative case, to evaluate the impacts of its energy plan and its alignment with Swedish and European climate objectives. With the implementation of policy-based scenarios, long-term sectoral developments of the heating and transportation sectors are evaluated. To facilitate the representation of technological parameters based on demographic characteristics, the city has been spatially divided into five sub-regions.

The implementation of the city energy plan results in a 33% reduction in cumulative carbon dioxide emissions compared to the reference case. The city energy plan leads to deep and rapid emission reductions, although, due to its short-term nature, it results in higher annual emissions in Year 2050 compared to the national and regional objectives. The results for heating supply options emphasise the declining cost-effectiveness of district heating as new apartments shift from district heating to heat pumps over time. New single-family housing chooses heat pumps as their primary heating option. 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. Gradual investments in low-voltage distribution grid infrastructure are essential for enabling the electrification of residential heating and passenger vehicles, with capacity needs surpassing 100% of the existing grid capacity in high-density sub-regions.

This study presents the impacts of local energy plans and their alignment with long-term national and regional climate targets. Aligning short-term plans with long-term decarbonisation targets is crucial to achieving significant and rapid emissions reductions that are sustainable in the long-term. 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; City energy plans; Sectoral integration; Spatial characterisation; Cost-optimisation; TIMES*

# 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, and E. O. Ahlgren, “Analysis of City Energy Systems Modeling Case Studies: A Systematic Review,”. (Submitted for publication at International Journal of Sustainable Energy Planning and Management)

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

**III.** K. Gupta, K. Karlsson, and E. O. Ahlgren, “City energy transitions: Modelling policy alignments with sectoral integration at sub-city levels,” (Manuscript under internal review)

# Author contributions

Kushagra Gupta is the principal author of Papers **I–III** and performed the literature review, modelling, analysis and draft writing for all three papers. Kenneth Karlsson contributed with methodology development, editing and discussions to Paper **II** and **III**. Erik Ahlgren contributed with methodology development, editing and discussions to all the papers, along with funding acquisition for the project.

# Acknowledgements

I would like to express my sincere gratitude to my supervisors: Erik Ahlgren for his guidance and support throughout my research journey and sharing his vast experience in the field to enhance my learning experience and helping me achieve my goals; and Kenneth Karlsson for his constant support with the modelling work and regular discussions to improve the quality of my work.

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On a personal note, I am grateful to my family for their constant support throughout the journey. And, special thanks to my wife Deepanjali for always believing in me and being there for me through the ups and downs and being an amazing travel partner.

*Kushagra Gupta*
Gothenburg, December 2024

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# List of abbreviations

| | |
|---|---|
| CEP | City energy plan |
| CHP | Combined heat and power plant |
| $CO_2$ | Carbon dioxide |
| ESM | Energy system model |
| EU | European Union |
| EU-ESR | European Union-Effort Sharing Regulation |
| GHG | Greenhouse gas |
| HOB | Heat only boilers |
| LCT | Low-carbon technologies |
| NECP | Integrated national energy and climate plan |
| PKM | Passenger kilometre |
| PV | Photovoltaic |
| REF | Reference |
| TIMES | The Integrated MARKEL EFOM System |
| TIMES_NE | TIMES Northern European |

# 1 Introduction

The Paris Agreement, adopted in 2015 under the United Nations Framework Convention of Climate Change, aims to limit the global temperature increase to well below 2°C and to pursue efforts to limit the increase to below 1.5°C compared to pre-industrial levels [1]. Human activities linked to greenhouse gas (GHG) emissions have been the main driver of global warming, with the temperature rise already reaching 1.1°C in the past decade [2]. To meet the targets outlined in the Paris Agreement and limit global warming to well below 2°C, with efforts to restrict it to 1.5°C, rapid and significant reductions of GHG emissions are essential, as the remaining carbon budget to limit the temperature rise may soon be exhausted, making it increasingly difficult to avoid the most-severe impacts of climate change.

Following the Paris Agreement, the European Climate Law (2021) sets a legally binding target for the European Union (EU) to reach net-zero GHG emissions by the year 2050 [3]. Deep and rapid emissions reductions are indispensable for achieving climate neutrality within the next three decades.

Energy accounts for three-quarters of the total GHG emissions globally, which means that extensive energy system transitions are required to achieve climate neutrality [4]. Cities account for around 75% of global energy consumption and close to 70% of the total GHG emissions. Cities, where more than 50% of the worldwide population resides and which is expected to increase to 70%, have been identified as crucial for achieving deep reductions of GHG emissions and advancing climate-resilient developments [5]. Cities have substantial roles to play in the fight against climate change, as they are key to achieving the Paris Agreement targets.

Cities are an essential part of the overall national climate action plan and have the capability to transform national actions into actions on the ground. Globally, many cities have adopted policies and plans to decarbonise their energy systems. Indeed, many city energy plans currently focus on short-term goals and tend to prioritize independent, sector-specific initiatives rather than aligning with comprehensive, long-term national decarbonisation strategies.

## 1.1 Aims and Research Scope

This thesis aims to investigate the impact of cities and their climate policies in the decarbonisation of the energy system, focusing on the inter-sectoral and intra-sectoral interactions in the long-term development pathways. Furthermore, the thesis aims to investigate how local-level energy plans align with national and regional climate objectives to transform city energy systems in the long-term perspective. These overall aims are addressed by answering the following research questions:

I. How do the city energy plans, and short-term policy targets impact the future cost-optimal city energy systems?
II. How do the city-level energy plans align with national and regional climate objectives in the long-term perspective?
III. What are the critical sectoral interactions identified in the city´s energy systems transition pathways?

To address these research questions, this study incorporates a long-term integrated energy systems optimisation modelling approach, including the inter-related demand- and supply-side dynamics of the city energy system. The integrated energy systems model evaluates the impacts of local and national-level energy and climate plans and identifies interactions within and between sectors through scenario assessments and uncertainty analyses.

## 1.2 Outline of the thesis

This thesis comprises of the three appended papers and a summary essay. Section 2 provides a brief background regarding the city's energy systems and energy systems modelling to guide energy planning at the local level. Section 3 describes the modelling work that is incorporated into this work. Section 4 presents the key findings 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.

**Paper I,** presents a literature review that investigates the representation of city energy systems' complexities, and the research objective themes behind the modelling of city energy systems.

**Papers II** and **III** adopt an integrated energy systems modelling approach, including inter-related demand- and supply-side energy systems for multiple sectors. Energy systems optimisation 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.

**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.

Guiding the long-term, policy-driven energy system's developments, both papers highlight inter-sectoral interactions through the allocation of resources among the competing sectors.

# 2 Background and related research

The transition of energy systems is critical in the efforts to limit global warming to well below 2°C, in line with international climate goals. Several key trends drive this process: an increase in the share of renewable energy; expansion of electrification across sectors; improved energy efficiency; and alternative transportation methods. In addition, consumer participation is growing as new regulatory frameworks emerge, placing greater emphasis on sustainability and carbon reduction measures [6].

Cities play a central role in climate mitigation efforts due to their substantial contributions to energy use and GHG emissions. Consequently, urban energy systems have become a focal point for policymakers who are developing strategies to decarbonise local energy use. 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. In this context, the decision-making process entails considering a broad range of factors, including investments, operational decisions, environmental and social concerns, and institutional frameworks. The complexity of these systems necessitates advanced tools and methodologies for city-level energy planning [7].

In response to the challenges, cities worldwide are adopting energy system models (ESMs) to guide their decision-making processes [7]. These models support the planning of energy transitions by simulating different scenarios, evaluating trade-offs, and identifying the most-effective pathways for reducing emissions while ensuring economic and social feasibilities [8,9]. Through these models, cities have become better equipped to navigate the complexities of their energy systems and to implement strategies that align with global climate goals. Studies representing different aspects of city energy systems in ESMs are presented in the following section.

## 2.1 Modelling to support energy planning in cities

Energy models have been extensively used to support 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.

Techno-economic studies based on optimisation and simulation techniques are identified as being essential for representing complex decision-support systems for strategic energy planning. 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. The results from literature review conducted in **Paper I** shows the usage frequency of modelling tools among the analysed 32 city-level energy modeling case studies in **Figure 1**. A detailed review of city energy modelling case studies is available in **Paper I**.

*Figure 1: Modelling tool with usage frequency represented by the font size (Source:* ***Paper I****).*

The built environment and transportation are the main contributors to energy usage and GHG emissions in cities. Modelling studies focused on city energy planning have attempted to represent the different aspects of the buildings and transportation sectors. Decarbonisation of the heating supply solution in combination with demand-side measures is the key transition pathway for the buildings sector. Transport sector decarbonisation is driven by fuel and technology switches, along with a shift towards shared mobility and active transportation modes.

Different heating supply solutions have been investigated for municipal energy planning, to identify cost-efficient mixes of centralised and decentralised solutions [10-12]. Heating system decarbonisation has also been investigated with improved spatial resolution, to support heat planning at the urban level [13, 14]. To incorporate heat supply and heat savings into the planning process, the optimal mix of supply and savings have been investigated in several studies [15-18]. In addition, studies focused on the buildings sector have introduced a methodology for improved representation of the building demand [8,19]. Among the transportation sector modelling studies, cost-optimal transport sector decarbonisation and its impact on local air quality have been presented [20]. The role of electric vehicle (EV) promotion policies on EVs and their environmental benefits have been investigated in two cities in China [21-22].

### 2.1.1 Sectoral integration in city energy modelling

Sectoral integration in energy systems is defined as the linking of different energy carriers with various energy end-uses. Sectoral integration allows for the optimisation of the overall energy system by including multi-sectoral interactions [23]. 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 [24–27]. 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 an integrated city energy systems model [28,29].

## 2.2 Allocation of limiting 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 Policy Council, these two measures would contribute more than 50% of the required GHG mitigation in Sweden, as shown in **Figure 2**. A report by the Energy Transition Commission has highlighted the increasing use of bioresources, citing the risk of over-utilisation beyond the availability of sustainably sourced resources [30]. When it comes to electrification, electricity has been the fastest-growing form of final energy over the last few 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 [31,32].

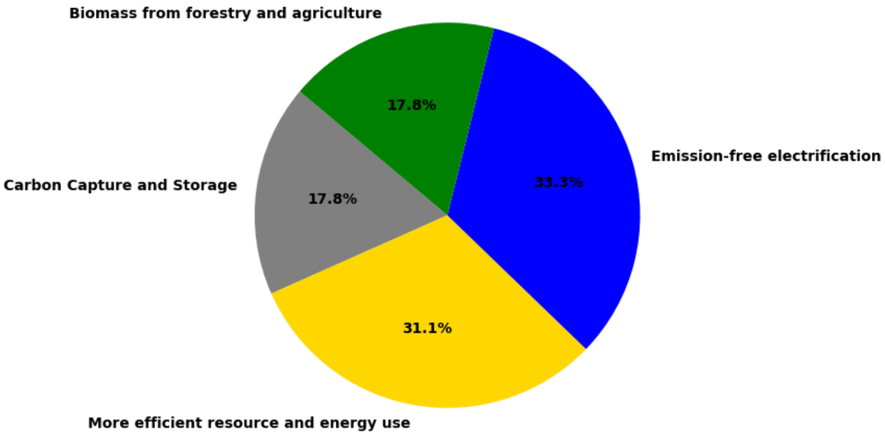


*Figure 2: Four key areas for achieving the climate targets in Sweden according to the Swedish Policy Council (Data utilised from the report of the Swedish Climate Policy Council 2022 [33])*

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 [34]. Another set of studies constrained the availability of biomass, to analyse its roles in the electricity and heating systems [26,35]. 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 [36,37]. The integration of heat pumps and photovoltaic systems has been analysed for typical rural and urban grids in Belgium [38]. The costs for grid reinforcements linked to the deployment of LCTs have been evaluated for different spatial set-ups with exogenously provided penetration levels [39–41].

## 2.3 Research gaps

A brief overview of the existing literature on energy system modeling at the city level is presented in this chapter and **Paper I**. Most of these studies have focused on the development of independent sectors, with limited emphasis on an integrated approach that considers interactions within and between sectors while addressing supply and demand dynamics. Furthermore, few studies have included the allocation of resources in long-term energy systems planning or have accounted for competition among the interacting sectors. Similarly, there is a lack of studies that include spatial characterisation of the city to include the technological parameters, and a representation of individual investment decisions based on demographics in their long-term city energy systems modelling. Although some studies have investigated the various aspects of energy policy, there is a lack of comprehensive research exploring the impact of a city’s energy plans or how these local plans align with national and regional climate objectives.

# 3 Methodology and case study

This section briefly introduces the case that was selected for the model application and the applied methodological framework.

## 3.1 Modelled case

As outlined in the previous section, buildings and transportation sectors are the main contributors to the total final energy consumption and their transition is essential to achieving the long-term climate objectives. To represent the inter-sectoral interactions and to account for the allocation of electricity and bio-based resources in the heating and transportation sectors, a northern European city characterised by high heating and transportation demands is selected.

The city of Gothenburg is selected as a representative case. Gothenburg has a well-established heating system with options to use an extensive district heating network or individual heating solutions. Simultaneously, the heating system of Gothenburg is in the planning stage, with major plants reaching retirement age and uncertainties surrounding the continued use of biomass and waste heat from refineries and waste incineration. With ambitious climate targets and the influence of local authorities on the local energy systems' work, Gothenburg has been identified as a suitable case to apply the TIMES_NE (TIMES Northern European) city model.

According to the Municipal Energy Planning Act (1977:439), all municipalities in Sweden must have an energy plan that encompasses the supply, distribution, and use of energy in the municipality. Göteborgs Stads energiplan (city energy plan of Gothenburg) was adopted under the Municipal Energy Planning Act to promote the implementation of measures that would lead to the city of Gothenburg reaching its environmental goals [42]. The environmental and climate program for the period of 2021–2030 is the starting point for the energy plan. The purpose of the energy plan is to promote the implementation of measures in the energy sector to reach the environmental goals for the climate set out in the Environment and Climate Program. With policies and plans in place, Gothenburg is a suitable case to investigate the impact of policy interventions at different governance levels.

## 3.2 Policy objectives

This thesis incorporates key national policies and aims to investigate the impacts of policy interventions in shaping the city energy system in the long-term perspective. This section provides brief information on the national policies and policy interventions that serve as the foundation for scenario formulation.

### 3.2.1 National policy and measures

- **Energy and Carbon Dioxide ($CO_2$) taxes**: Based on the Swedish energy taxation system, energy and $CO_2$ taxes are applied to the energy commodities. Biofuels are exempt from both the energy tax and $CO_2$ tax.
- **Reduction obligation**: To reduce fossil fuel emissions in the transport sector, a reduction mandate with respect to gasoline and diesel has been introduced, requiring fuel suppliers to increase progressively the proportions of biofuels in conventional transportation fuels.

- **Building regulations**: Following the building regulations, all new buildings and alterations to existing buildings need to follow strict guidelines regarding the buildings' specific energy requirements [43].

### 3.2.2 City Energy Plan (2022–2030)

Göteborgs Stads energiplan, stated in this thesis as the City Energy Plan (CEP) was adopted in line with the Municipal Energy Planning Act, including plans for energy supply, distribution, and use [42]. The energy plan aims to promote measures to reach the environmental goals set within the Gothenburg Environmental and Climate program. The primary environmental goals highlighted within the energy plan include:

a) Reduction of energy use in buildings.
b) Production of energy from renewable sources.
c) Reduction of the climate impact of the transportation sector.

### 3.2.3 Integrated National Energy and Climate Plan, Sweden

Sweden adopted its National Energy and Climate Plan (NECP) in Year 2019 in line with the EU Governance Regulations of the Energy Union and Climate Action [44]. The NECP extends the set of policies and plans, aimed at achieving net-zero emissions by Year 2045, with reductions of no more than 15% derived from additional measures. In addition, NECP sets intermediate targets and Year 2030 targets for the transportation sector.

### 3.2.4 European Union – Effort Sharing Regulations

The European Union (EU) has adopted a climate policy framework, which aims to reach net-zero emissions by Year 2050 within the union borders [45]. As part of the EU Legislation framework, Member States have committed to increase their emission reductions within the EU Effort Sharing Regulations (EU-ESR). The EU-ESR defines interim targets for Sweden covering emissions not included in the EU Emissions Trading System with targets for Years 2030 and 2040.

## 3.3 Energy systems modelling

This work develops and applies a cost-optimisation modelling framework in **Paper II** and **Paper III** to investigate the impacts of above-mentioned energy and climate policies and to understand the different aspects of city energy systems.

The TIMES (The Integrated MARKEL EFOM System) model generator has been selected to develop the framework applied in this study. It offers flexibility in terms of representing different supply- and demand-side sectoral developments, combined with flexibility in time and space. The TIMES model is implemented using mixed-integer linear programming and is based on perfect foresight. Perfect foresight is defined as a hypothetical scenario in which the model is provided with complete and accurate information about the future. Mixed integer linear programming allows for a better representation of economies of scale by applying discrete investment levels into new production capacities. The objective function of the model is to minimise the total system costs over the modelling time horizon.

The key modelling characteristics incorporated into the modelling framework developed in this study are presented in **Figure 3**. **Figure 3** is adopted from **Paper I** and modified to incorporate the modelling characteristics of the methodology adopted in this thesis.

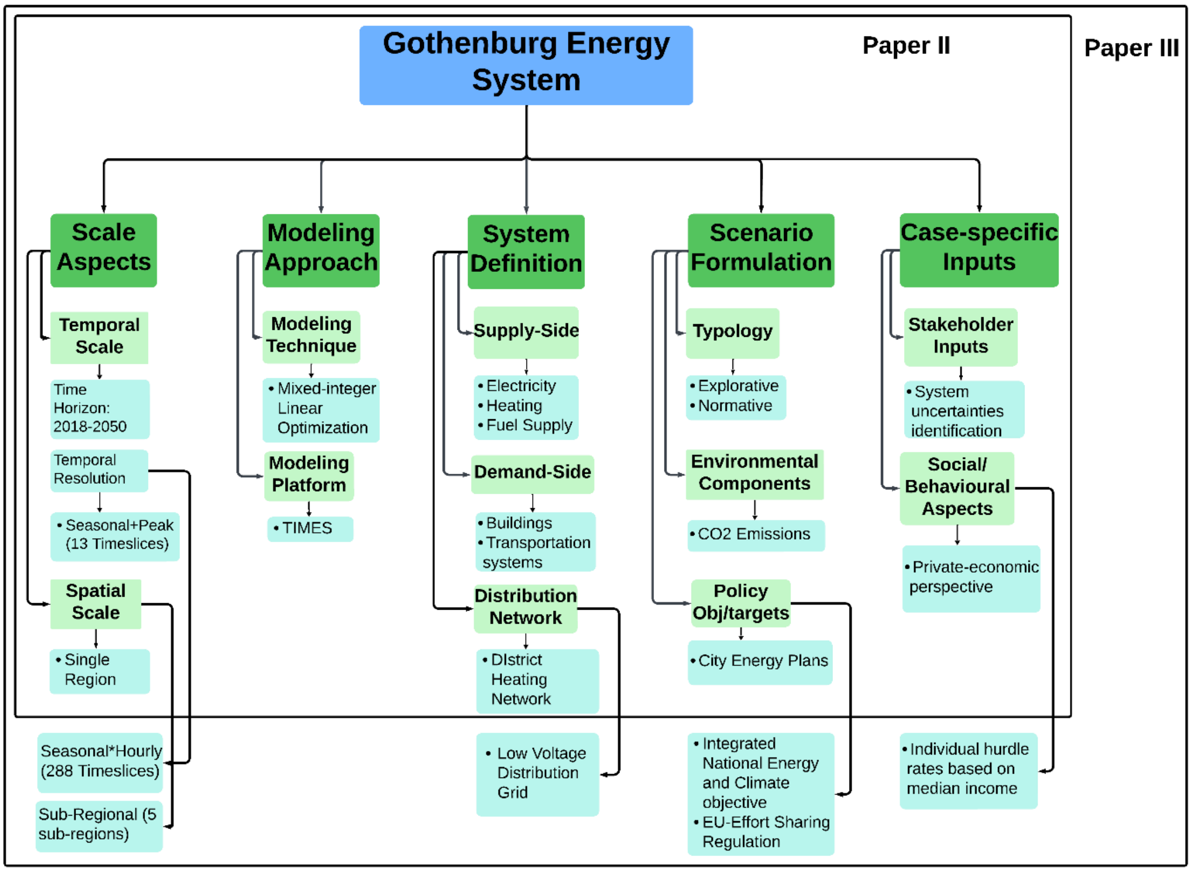
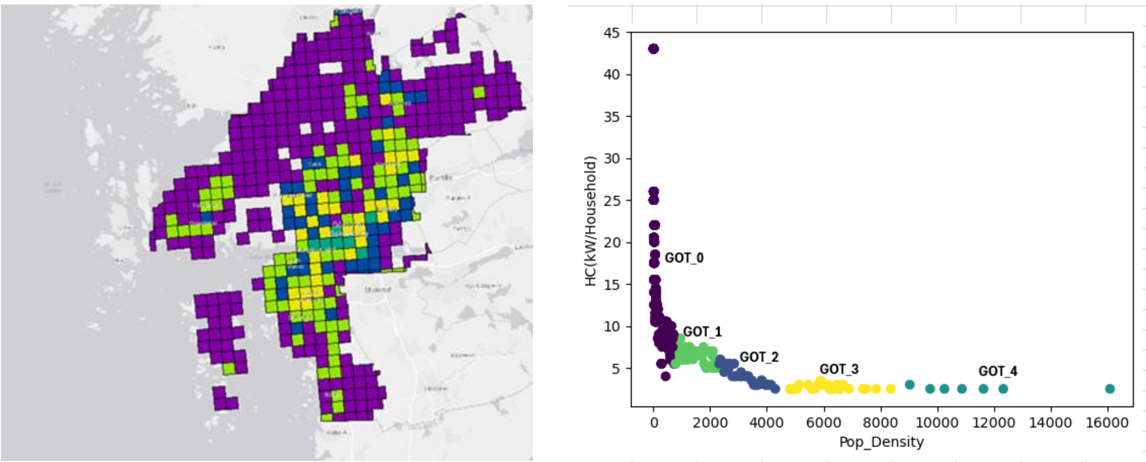


*Figure 3: Key modelling characteristics for the applied modelling framework with developments between Paper II and Paper III.*

### 3.3.1 Scale aspects

In both papers, the model's temporal horizon is long-term, with base year of 2018 and a modelling horizon extending up to Year 2050, divided into periods of different duration. In **Paper II,** the temporal resolution of the model set-up is seasonal, to represent the seasonal variations of the heating system. **Paper III** includes both seasonal and hourly variations, such that each year is divided into 12*24 time-slices, to represent the seasonal and hourly variations of the heating and electricity systems. Seasonal variations in the heating load are calculated based on hourly demand data for the case study, being aggregated at the monthly level, along with a 3-day representative period that replicates the peak load. For **Paper III,** the hourly data have been aggregated into representative hours for each month.

Spatial resolution is a significant development between **Paper II** and **Paper III**. In **Paper II**, the city is modelled as a single region, whereas in **Paper III**, the city's spatial boundary is further divided into five sub-regions based on their demographics (**Figure 4**). The main driver behind the regional segmentation of the city is to facilitate representation of the varying technical parameters among the different demographic groups. Technical parameters with a regional representation include low voltage distribution grid capacities, district heating network connection costs, individual hurdle rates, and the user profiles for charging of electric vehicles. Hurdle rate is a technology specific discount rate, when defined for independent consumers is stated as the individual hurdle rate. Technology-specific hurdle rates are applied in the model to represent the consumer's willingness to invest in new technologies. At the sub-regional level, hurdle rates for residential customers are applied based on the spatial distribution of household income in Gothenburg [46]. User profile for charging is defined as the share of different commercial and home-based charging infrastructure to fulfil electric vehicles charging demands.



a) b)

*Figure 4: Spatial distribution of the city based on clustering of synthetic square kilometers grids into five sub-regions (a) with colour-based representation on the map, and (b) k-means clustering based on the hosting capacity (HC) and population density. The dataset on synthetic square kilometers grids is acquired from [47]. GOT_0-4 is the nomenclature used to specify the sub-regions of Gothenburg.*

### 3.3.2 System definition

The energy system represented in this study incorporates the energy supply infrastructure, distribution system, and end-user service demands. The energy system representation in the TIMES_NE city model is presented in **Figure 5**.

The energy supply infrastructure includes the primary resources, centralised heat and power production facilities, and individual heating solutions. From the perspective of urban systems, primary resources are modelled as imports to the city energy system from a centralised system. Heat and power production includes the existing infrastructures of local production facilities, which include combined heat and power plants (CHPs), heat-only boilers, centralised heat pumps, and decentralised electricity production facilities. Future investment options include biomass, biogas, natural gas-based CHP units, heat-only boilers, and heat pumps. Individual heating supply options include heat pumps, boilers, and direct electrical heating.

The distribution system includes a district heat network, an electricity distribution network, and a fuel supply infrastructure for transportation fuels. In **Papers II** and **III**, the existing district heat network capacity is estimated based on the base year's demand, and future connections require additional investments in the network. For the case of electricity distribution, **Paper II** assumes that the existing capacity of the distribution grid will be sufficient to meet the future electrification demands. In **Paper III**, the existing capacity of the distribution grid for the residential load is estimated based on the base-year demand, and investments in reinforcements and new infrastructure are required after a threshold of electrification is reached. For the transportation sector, a limitation on the existing distribution infrastructure is only applied to gas filling stations and the charging infrastructure.

End-use service demands include the demands for buildings and road transportation. Buildings include residential and commercial structures, and transportation services include road-based passenger and freight transportation. Residential buildings are further disaggregated into multi-family housing (MFH) and single-family housing (SFH).

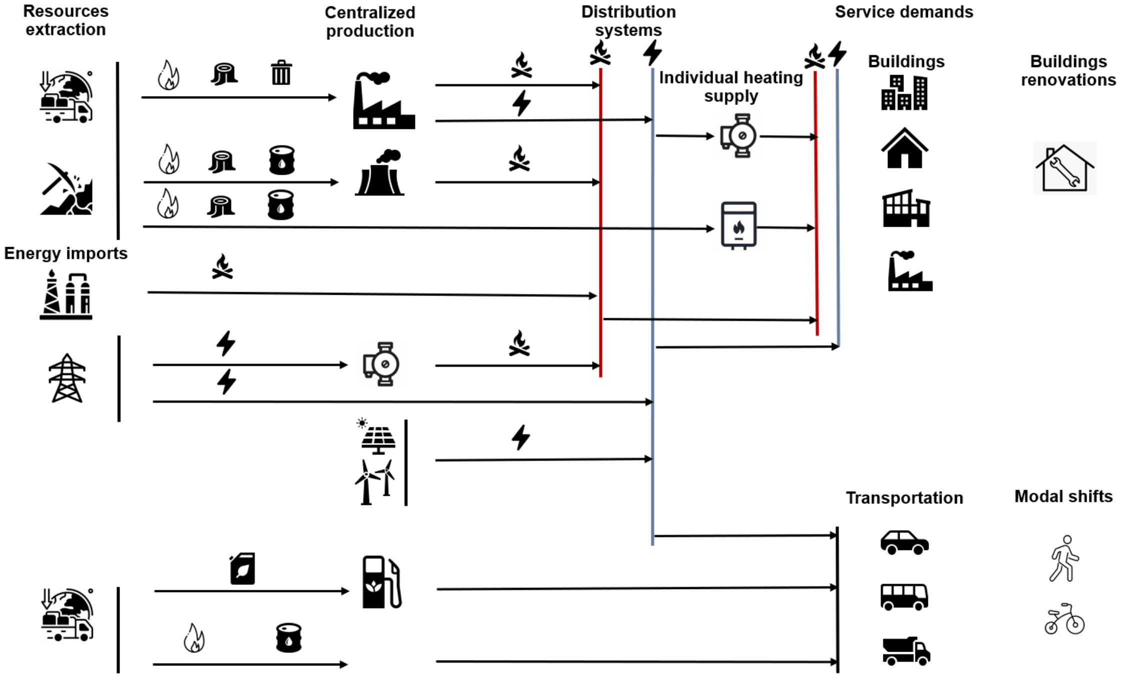


*Figure 5: Reference energy system defining the representation of the Gothenburg energy system in the TIMES_NE city model (Source:* ***Paper III****).*

### 3.3.3 Scenario formulation and uncertainty analysis

Scenario formulations have been used in energy systems optimisation models to evaluate possible future developments and different expected futures. When exploring possible, probable or preferable futures, scenario typologies are described as predictive, explorative, and normative [48]. In this context, different scenarios are formulated to explore the potential impacts of policy interventions specified in 3.2. By incorporating policy measures to describe the possible impacts of strategic decisions, in combination with preferable futures associated with the application of climate objectives, this study combines explorative and normative scenario designs. The following scenarios are considered:

- Reference (REF) scenario
    - National policy measures
    - Technological developments
- City Energy Plan (CEP) scenario
    - Extension of the REF scenario
    - Includes the measures and climate objectives identified in the Göteborgs Stads energiplan (2022–2030)

- Integrated National Energy and Climate Plan (NECP) scenario
    - Extension of CEP
    - Updated emissions reduction targets in line with the national climate objectives
- EU-Effort Sharing Regulations (EU-ESR) scenario
    - Extension of CEP
    - Updated emission reduction targets in line with Sweden's commitment to the EU-ESR.

Due to the study's long-term horizon (with projections into the distant future), different assumptions are made concerning future prices and system developments. Thus, an uncertainty analysis is incorporated into the scenario formulation process. Uncertainties associated with the design of future systems are identified as system uncertainties, and uncertainties associated with assumptions regarding future prices are identified as price sensitivities.

- System uncertainties
    - Future demand projections
    - Waste heat availability
- Price sensitivities
    - Bio-resource prices
    - Electricity prices

The scenario tree incorporated in this thesis, including uncertainties, is presented in **Figure 6**.

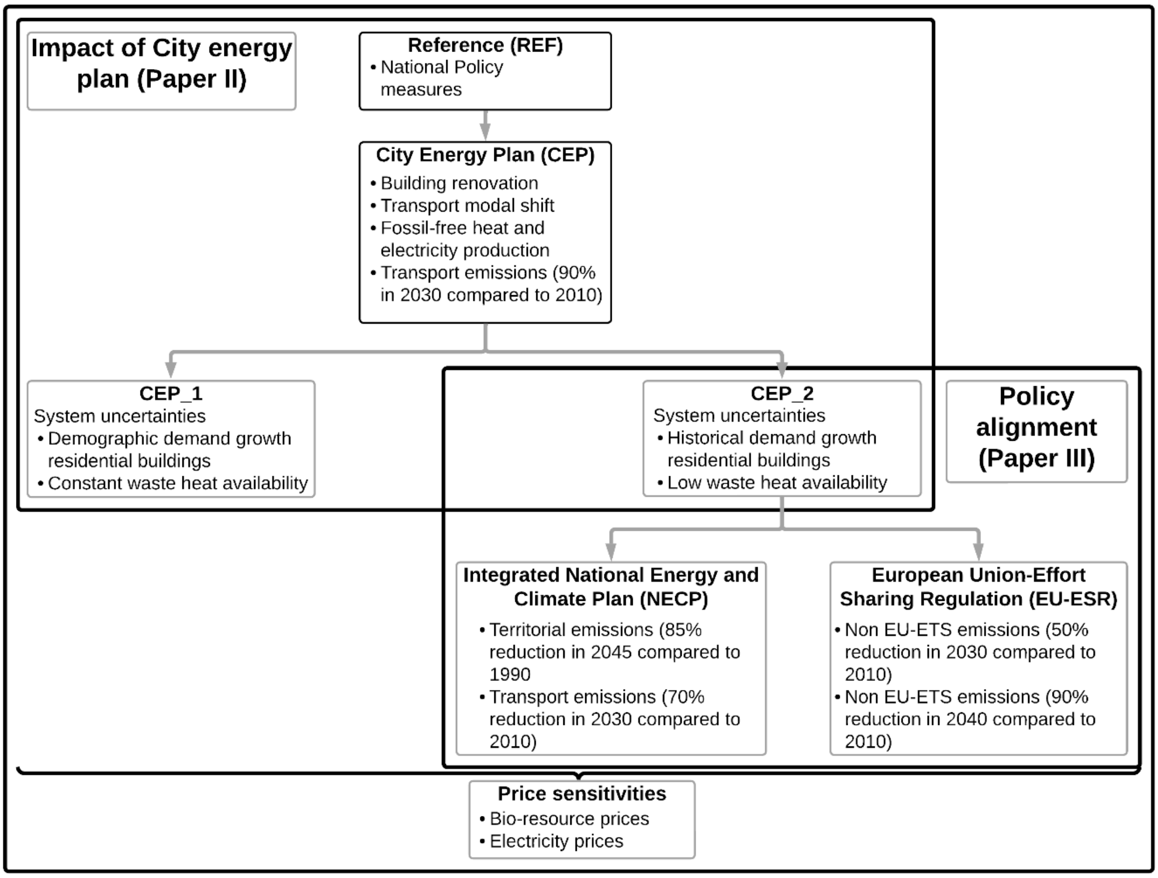


*Figure 6: Scenario tree combining policy scenarios with uncertainties, as incorporated into the modelling case studies.*

*Emissions scope*

- Fossil $CO_2$ emissions include emissions associated with all the combustion of fuel. In this aspect biofuels and electricity are $CO_2$ neutral.
- Territorial $CO_2$ emissions include emissions associated with the burning of the fuel and emissions associated with the production and distribution of the fuel. In case of territorial emissions, biofuels and electricity also have $CO_2$ emissions.

### 3.3.4 Customers' cost perspectives

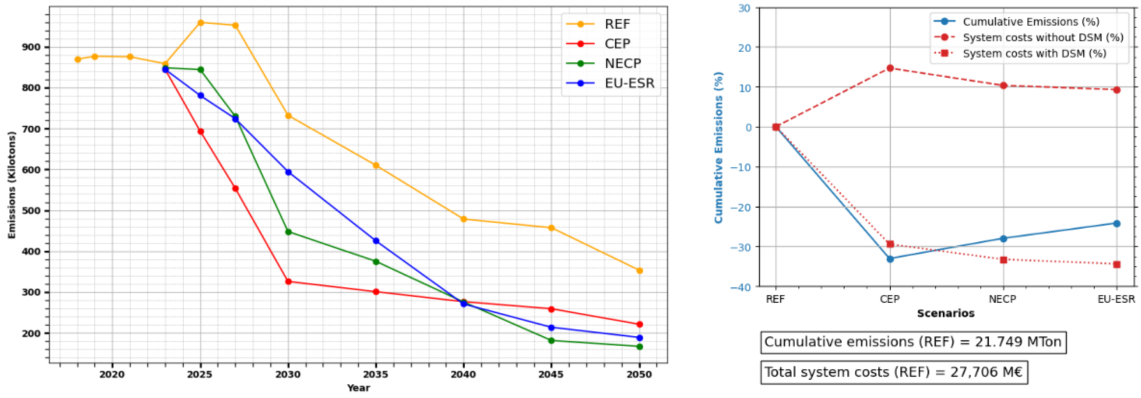
City energy systems are driven by the investment decisions made by individuals. In **Paper II**, the prices and taxes associated with the use of energy resources are differentiated for different residential and commercial users of energy services, to account for customer's perspectives on investment and operational decisions. In **Paper III**, individual discount rates are applied to model investment decisions, reflecting the investor's expected rate of return and the individual's willingness to invest in new technologies. Customer discount rates are highly dependent on the household income-level. The assumptions on hurdle rates are made at the sub-regional levels for residential customers based on the mapped income distribution for the city [46].

# 4 Results and discussion

**Paper I** is a literature review, and its findings are briefly presented in the background section of this study. This section presents selected results from **Papers II** and **III,** along with the analyses and discussions. The results are further categorised into two sub-sections. Section **4.1** presents the results regarding the impact of the investigated policies and climate objectives in the city energy system. Section **4.2** presents the results related to allocating resources to account for sectoral interactions in the city energy systems' transition pathways.

## 4.1 The impact of city energy plan and their alignment with National and European climate objectives

**Paper II** investigates the impacts of city energy plan on the city energy system, and **Paper III** offers further insights into their alignment with the national and regional climate objectives. The results for the territorial emission trajectories highlight the impacts of the investigated policy measures and climate objectives, as shown in **Figure 7.** In the REF scenario, in which national policy instruments are implemented, a substantial portion of the emissions persists within the city's energy system. Notably, emissions peak in Year 2025 due to the revised directive on fossil fuel reduction obligations in Year 2024. This directive revised the obligations pertaining to biofuel shares in diesel from 30% down to 6%, leading to a sudden rise in emissions. Going forward, the emissions trajectory starts to decline due to applied policy measures. A significant gap is evident between the emissions trajectories of 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. This gap corresponds to up to 33% lower cumulative emissions in the CEP scenario compared to the REF scenario, accounting for 6.2 $MtCO_2$ (**Figure 7b, primary y-axis**).



*a)* *b)*

*Figure 7: (a) Emissions trajectories and (b) cumulative emission budgets and total system costs compared to REF scenario, highlighting the impacts of the city energy plan and their alignment with national and regional climate objectives. DSM, demand side measures (Source: **Paper III**).*

Comparing the alignment of the CEP scenario with the NECP and EU-ESR scenarios, distinct trajectories are evident, that converge to similar levels of annual emissions by Year 2050. With stringent Year 2030 targets, deep reductions in emissions are observed in the CEP scenario compared to the national and EU climate targets. Due to the short-term nature of CEP, the emissions trajectory starts to lag after Year 2040. By year 2045, when Sweden aims to achieve a minimum 85% reduction in annual territorial emissions, annual emissions within the city's energy system under the CEP scenario will be 42% higher than the levels required by the NECP.

At the cumulative level, deep and rapid reductions under the CEP scenario contribute to reduced utilisation of emissions budgets over the modelling time horizon, as compared with the NECP and EU-ESR scenarios. The CEP scenario results in 1.1 $MtCO_2$ lower cumulative emissions compared to the NECP scenario. Different levels of emissions reduction obligations account for different costs to the system. **Figure 7b (secondary y-axis)** compares the changing total system costs for the policy scenarios with the REF scenario. Since the demand side measures (DSMs) are exogenously implemented without any additional costs to the system, total systems costs are presented with and without the inclusion of DSMs. Cost-optimal transition measures to reduce the levels of emissions under the CEP scenario led to a 3% increase in system costs. Within the NECP and EU-ESR scenarios, the cost increases are 2% and 1.86% respectively. The CEP's target to reduce rapidly its transport-related emissions leads to higher system costs compared to the other policy scenarios. Another important result shown here is the cost savings associated with DSMs. The desired system changes in the CEP scenario can be achieved with 5.9% lower costs than in the REF scenario. This highlights the role that DSMs can play in supporting the city energy systems' transition to a decarbonised future energy system.

To acquire a better understanding of the evolving system dynamics under policy-driven scenarios, long-term development pathways for the heating and transportation sectors are examined.

### 4.1.1 Heating system

**Paper II** presents the district heating production mixes for the centralised heating system comparing the REF and CEP scenarios, together with the applied system uncertainties, as shown in **Figure 8**. With the applied energy and carbon taxes, fossil fuels become uneconomical, except for gas CHP use in Year 2025 under the REF scenario. Under the CEP scenario, a ban on the use of fossil fuels is applied from Year 2025 to ensure their elimination under any future uncertainties. The fossil fuel ban forces additional investments in biomass CHP, compared to a small biogas CHP addition under the REF scenario. Another major difference observed between the REF and CEP scenarios is associated with a reduced demand for district heat with renovations of multi-family housing. Furthermore, the CEP scenario is extended to include uncertainties associated with Gothenburg's heating system. The future district heating system is dominated by heat pumps in combination with biomass CHP and biogas CHP meeting the additional peak-load demands. With the uncertainty related to the reduced availability of waste heat, additional investments are seen in heat pumps and biomass CHP. It is also interesting to note that with the application of the NECP scenario in **Paper III**, further reductions of territorial emissions lead to an even lower level of utilisation of waste incineration plants towards Year 2045, to ensure that the desired emissions levels are reached. The changing dynamics of the district heating production mix are further investigated with price sensitivities highlighting the importance of assumptions on future bioresource and electricity prices. The results are presented in **Paper II**.

Furthermore, the heating supply solution mixes for the residential buildings are investigated. The results from **Paper III** regarding the heating supply solution mixes for residential buildings at the sub-regional levels are presented in **Figure 9**. Since the heating system is already free of fossil fuel-related emissions, the results for the NECP and EU-ESR scenarios are not presented in this thesis. Another important point to highlight before further analysing the results, is that the CEP scenario in **Paper III** corresponds to CEP_2 in **Paper II,** as presented in the scenario tree (**Figure 6**).

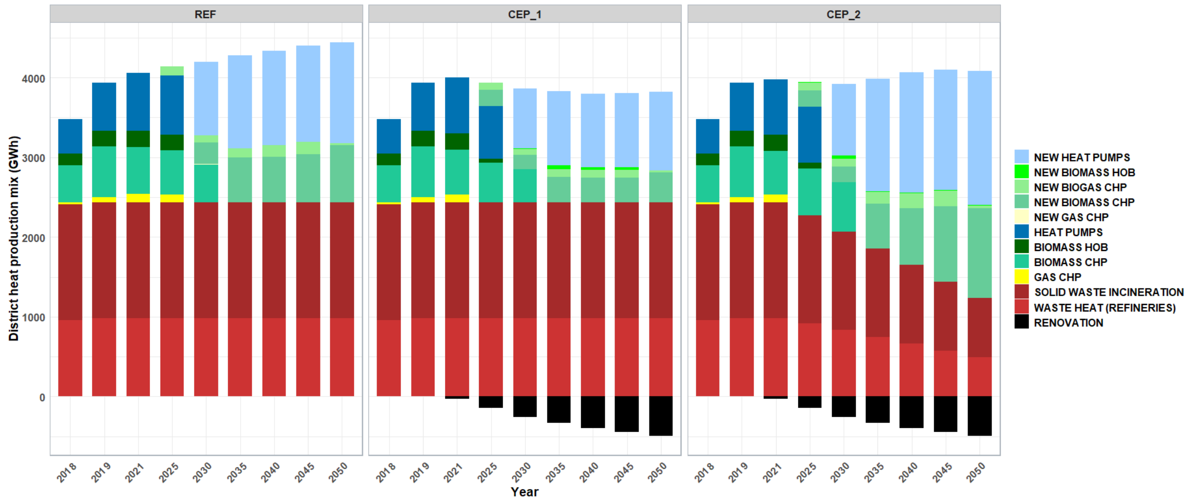
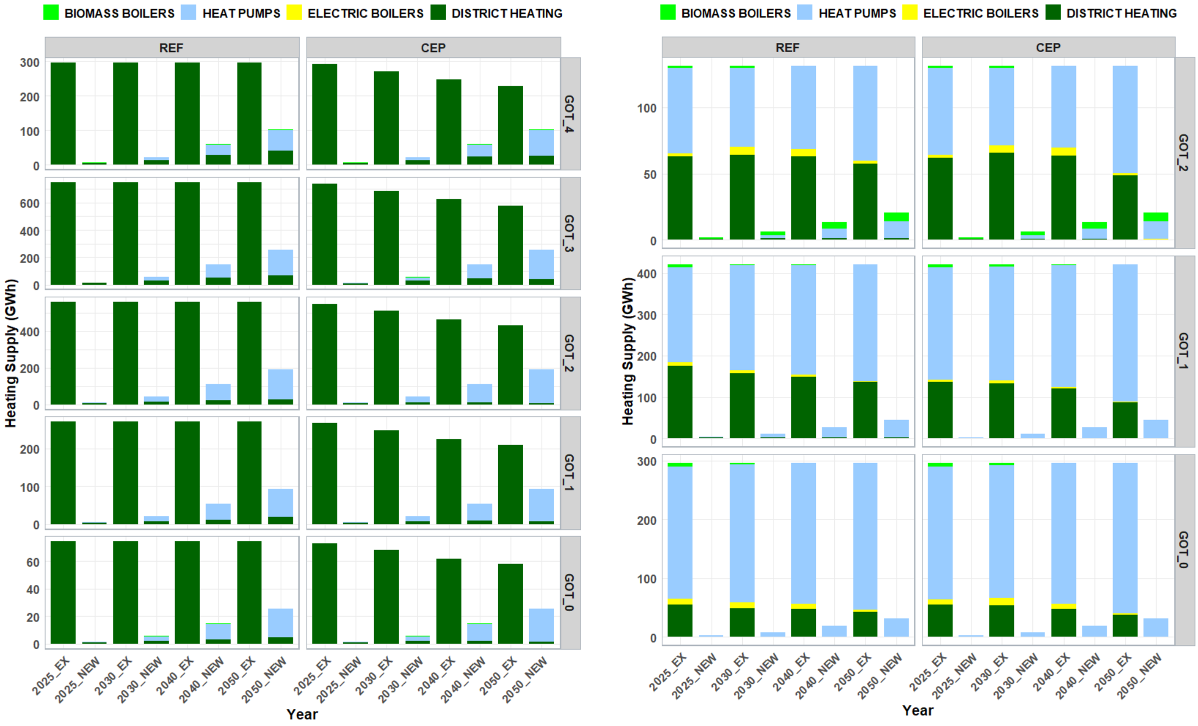


*Figure 8: District heating production mixes for the REF and CEP scenarios combined with system uncertainties (Source:* ***Paper II****, with updated visualisation)*

The results for existing and new multi-family and single-family housing are presented for the REF and CEP scenarios for the GOT_0-4 sub-regions in Error! Reference source not found. In the case of multi-family housing, existing housing is assumed to be always connected to the district heating network, and the main changes correspond to changing demands due to renovations. The changing demand for district heating in existing multi-family housing in turn leads to higher shares of new multi-family housing connections to the district heating network in the CEP scenario, as compared with the REF scenario. For single-family housing, with the existing heating supply mix including district heating and individual heating options, the possibility to switch between supply solutions is allowed. When comparing the future heating supply solution mixes, the main differences are observed at the sub-regional levels.

The choice of new district heating connections is driven by the district heating network connection cost and the future district heating production mix. District heating network connections costs are influenced by heat demand densities, which in turn are dictated by population densities and housing types at the sub-regional levels. Individual heating supply investments at sub-regional levels are influenced by hurdle rates and distribution grid capacities. In the case of new multi-family housing, the changing dynamics of future heating is seen from two different perspectives. Higher shares of multi-family housing connections to district heating network are observed in the beginning and more heat pumps start to penetrate as we move towards Year 2050. The main reason for this dynamic is the changing district heating production mix: as the availability of waste heat starts to decline, bio-resources become expensive and existing production facilities reach their retirement stage. When comparing the supply solutions at the sub-regional levels, higher shares of district heating connections are observed in the sub-regions with dense areas, due to reduced connection costs, although overall, the heating in new buildings is dominated by heat pumps for all regions as we move towards Year 2050. For single-family houses, following the same rationale, existing buildings with district heating connections show some shift towards heat pumps by Year 2050. New housing units are fully supplied by heat pumps, except for GOT_2, which has 1/3rd penetration of biomass boilers in Year 2050, driven by higher hurdle rates and high investment costs for heat pumps.

As we investigate the future heating system, district heating starts to become less economical with the reduced availability of waste heat and increasing bio-resource prices. Furthermore, it has been assumed that the existing district heating distribution network will not require any future reinforcements. Should there be a need for future investments in existing distribution networks, district heating would become even less competitive economically. However, measures such as thermal heat storage, reduced grid temperatures, and new sources of waste heat could improve the effectiveness of district heating systems as also shown in another study [49].



a) b)

*Figure 9: Heating supply solution mixes for multi-family housing (a) and single-family housing (b) at sub-regional levels (GOT0-4 sub-regions) for the REF and CEP scenarios (Source:* ***Paper III****). Year_EX corresponds to the existing building stock, and Year_NEW corresponds to the new building stock.*

### 4.1.2 Transportation sector

The long-term development pathways for the transportation sector are analysed by investigating the fuel supply mix and transportation activity categorised by vehicle type. In **Paper II,** the changing fuel compositions for the transportation sector of Gothenburg are presented, and **Paper III** investigates the changing vehicle fleet compositions resulting from applied policy interventions.

The transportation sector is recognized as a challenging area for achieving emission reductions, and this applies to the city of Gothenburg. **Figure 10** presents the fuel compositions for the existing and future transportation sector of Gothenburg. The existing vehicle fleet in Gothenburg is composed of conventional vehicles with a small share of electric vehicles and biomethane-run vehicles. Similar trends persist into the future, with electrification starting to become cost-competitive later around Year 2040. Within the CEP scenario, a 90% reduction in fossil emissions is required by 2030. Short-term decarbonisation is achieved through the penetration of biofuels in the freight and urban buses, combined with electrification of the passenger car fleet. In the latter half of the modelling time horizon, electric vehicles start to become economically competitive, resulting in 90% electrification by Year 2050 and the remaining fossil use will exist in heavy freight transport.

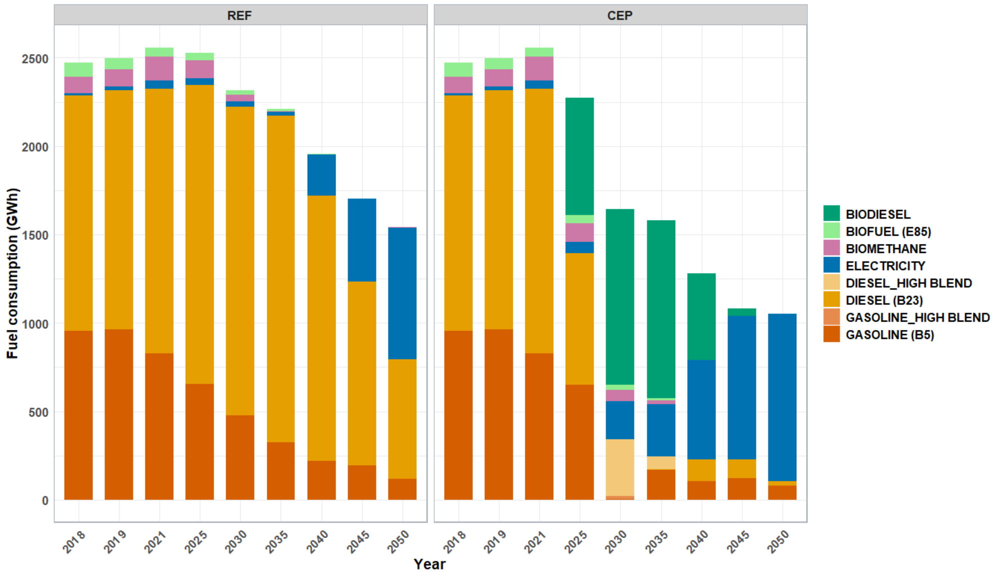


*Figure 10: Fuel consumption for the transportation sector under the REF and CEP scenarios (Source: **Paper II**, with updated visualisation).*

Before presenting the results, it is important to highlight that biofuel blending shares in fossil fuels have been changed between **Paper II** and **Paper III** to reflect the changing regulatory framework for reduction obligations in Year 2024. The changing vehicle fleet shares that occur with the applied policy measures and climate targets show the development of the different road transportation modes in **Paper III**. **Figure 11** shows the transportation activities for passenger car fleet with different policy scenarios at the sub-regional levels. The existing passenger car fleet is dominated by gasoline and diesel-powered cars. In the REF scenario, electric vehicle shares start to increase by Year 2030 in the GOT_0-1 sub-regions. For the remainder of the sub-regions, electric vehicle deployment starts in Year 2035 with all sub-regions reaching full electrification by Year 2040. Sub-regional differences in deployments are associated with income distribution (hurdle rates), distribution grid capacities, and user profiles in relation to charging. The GOT_0-1 represents the parts of Gothenburg that are characterised by low population density, higher proportions of single-family houses with a high median income. Single-family housing units have greater opportunities to use in-house charging, which is not the case for regions that mainly comprise apartment buildings in high density zones. Moreover, electrified heating in single-family housing means higher existing distribution grid capacity zones in GOT_0-1 compared with the other sub-regions.

When comparing policy interventions, different rates of electrification are observed for the more challenging GOT_2-4 sub-regions. The CEP scenario has the most-stringent Year 2030 target for transportation emissions, followed by the NECP and EU-ESR scenarios. This is reflected in the different rates of electric vehicle deployment in the GOT_2-4 sub-regions. These sub-regions also have some biofuel-based vehicles to reach the short-term objectives of the CEP scenario. Moreover, it is important to highlight that the changing service demands between the REF and policy scenarios are due to the applied modal shift.

Similarly, the results for the long-term deployment of urban buses and road freight transportation are presented in **Paper III,** comparing the REF and policy scenarios.

*Figure 11: Passenger car transportation activity shares by vehicle fleet in million passenger kilometers (PKM), under the REF and policy scenarios, presented at the sub-regional levels (Source: **Paper III**).*

## 4.2 Resource allocation

The results presented in **Paper II** as well as literature on future decarbonisation pathways, highlight the increasing importance of electrification and bio-resource use for the decarbonisation of the future energy system. To explore in greater depth the allocation of electricity resources, constraints on existing low voltage distribution grid capacity for residential use, and future capacity investments are analysed at the sub-regional levels (**Paper III**).

**Figure 12** shows the existing capacity and future distribution grid capacity investments for the CEP scenario with changing electricity and bio-resource prices at the sub-regional levels. 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. Existing capacities in the GOT_0-1 sub-regions are estimated to be higher due to the already electrified heating systems in single-family housing. The total distribution grid capacity more than doubles by Year 2050 for GOT_3-4 sub-regions and increases by 80% for GOT_2 sub-region. The phased development of grid capacities underscores the need to integrate these capacities into long-term planning. To keep up with the speed of electrification, parallel investments are essential; any shortfall in infrastructure development could impede the electrification progress in the heating and transportation sectors.

Furthermore, the changing dynamics from Year 2030 to Year 2050 in relation to the electricity use for residential heating and passenger transportation is presented in **Figure 13**. Future investments in grid capacity are driven by increased penetration of heat pumps in new multi-family housing and in passenger cars, as also seen in the results for the sectoral developments in **Figure 9a** and **Figure 11**, respectively. Larger investments are required in the GOT_2-3 sub-regions, which also contribute to the slower pace of electrification of passenger cars in these sub-regions, along with the other demographic parameters.

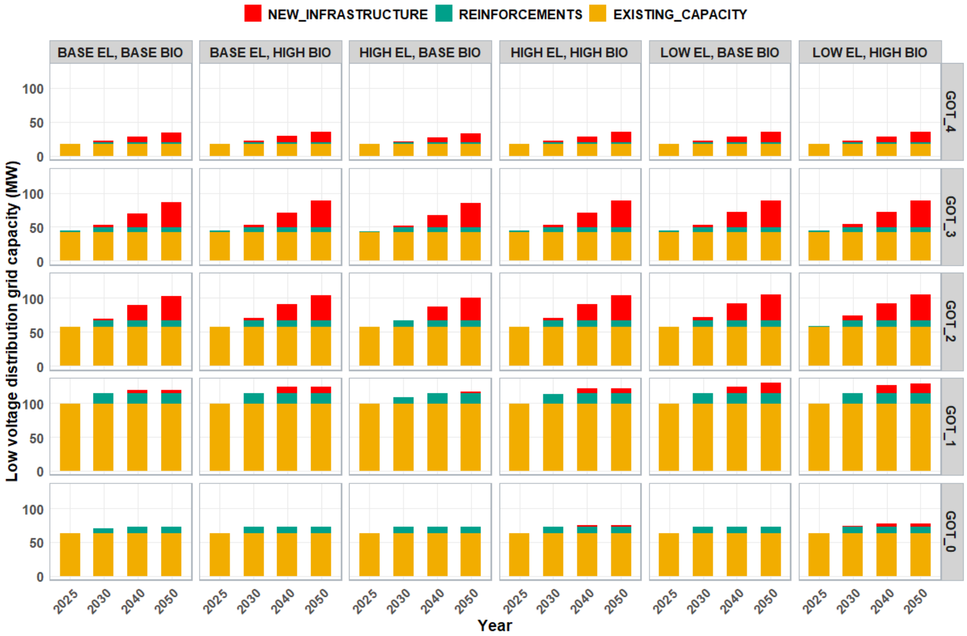


*Figure 12: Existing and new grid capacities for the low voltage distribution grid at sub-regional levels with price sensitivities (EL: Electricity price, BIO: Bio-resource prices) under the CEP scenario (Source: **Paper III**).*

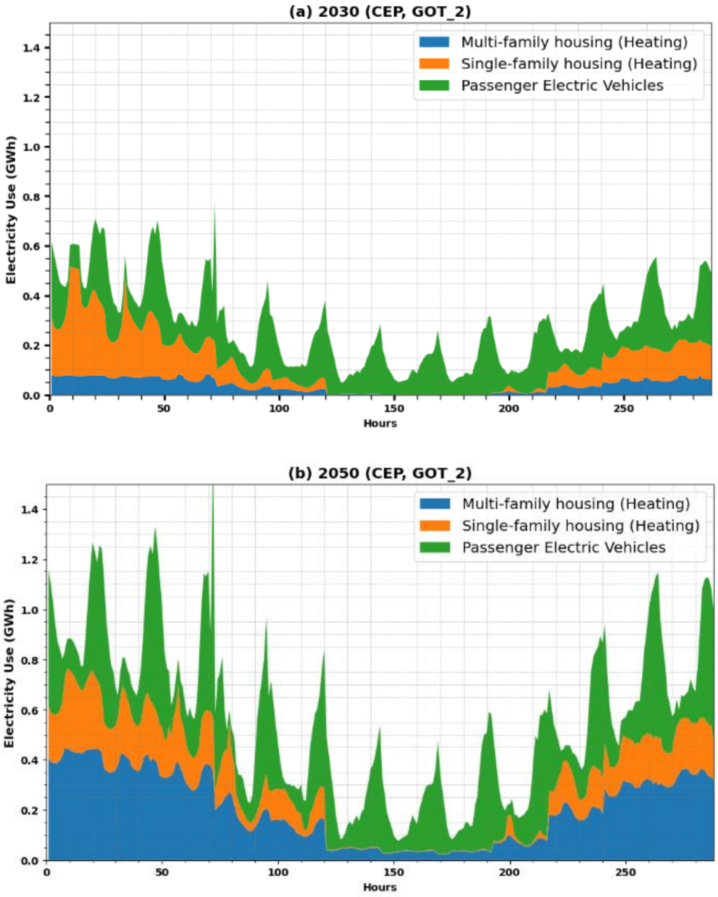


*Figure 13: Electricity use levels for domestic heating and passenger cars for the Year 2030 (a) and Year 2050 (b) for the GOT_2 sub-region, under the CEP scenario. (Source: **Paper III**)*

Since the district heating system starts to become economically less competitive, and the electrification of passenger cars is inevitable given the desired emission reduction targets, no significant changes in the investments are observed between the different price sensitivities. High bio-resource prices are driving the need for grid investments slightly higher than base bio-resource prices. The changes are less significant when comparing the different electricity prices. Similarly, the results for the allocation of bio-resources among the competing sectors are analysed with the applied price sensitivities, and the outcomes are presented in **Paper III**.

# 5 Reflections on the adopted methodology

This thesis applies an integrated modelling approach that includes inter-related demand-side and supply-side energy systems, to investigate cost-optimal, long-term development pathways for the city energy system. This approach facilitates investigations of the intra- and inter-sectoral interactions and accounts for allocations of resources among competing sectors in line with policy measures and climate objectives.

Long-term planning has been identified as a key factor for supporting decision-making processes, guiding the when and how of energy systems' developments [49]. 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. The temporal resolution in **Paper II** accounts for seasonal variations (monthly and peak demand days), while that in **Paper III** accounts for seasonal and hourly variations (12*24). 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 optimisation 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. However, investment decisions are also influenced by market dynamics and behavioural characteristics. Lack of representation of the market dynamics and behavioural aspects is a weakness of the applied approach. As an aspect that evolves from **Paper II** to **Paper III**, technology-specific hurdle rates are used to represent customers' willingness to pay. For residential customers, these hurdle rates are derived from the spatial distribution of the median household income.

Heating system developments include supply alternatives such as district heating and individual household-level heating solutions. The results highlight an increasing share of individual heating solutions as district heating systems start to become economically unfeasible over the time horizon. Within the scope of this study, measures such as thermal energy storage, new sources of waste heat, and reduced district heating grid temperatures are not included. 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 [48].

The driving patterns of different transport modes are presented as annual averages, without accounting for the variations that occur at higher temporal resolutions. Furthermore, the same assumptions persist over the time horizon. This limits the representation of actual driving conditions, which could influence choices related to cost-optimal vehicle fleet composition. 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 main driving 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 inter-sectoral interactions, accounting for the allocation of grid infrastructure. Future investments in grid capacity are prompted by higher peaks due to the penetration levels of heat pumps and electric vehicles. In this aspect, the same load profiles are assumed for future heating and electric vehicle charging based on historical data and do not incorporate demand-side measures aimed at load shifting. This assumption is identified as a weakness of the model. Furthermore, the impact of increased electrification is represented through aggregated infrastructure capacity rather than voltage/load violations. This simplification allows representation of a low-voltage grid infrastructure in the long-term planning and complements previous studies [38-40] 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 associated with fuel usage and fuel supply and distribution. The tail-pipe emissions from the transportation sector or the local emissions associated with the burning of biomass are not included. Furthermore, a technological shift in the energy system leads to a shift in 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 relation to the scope of emissions could lead to undermining or over-estimations of the climate impacts of policy interventions and associated targets.

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 [50]. 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 generalisable 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 decarbonisation 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 Thesis contributions and main findings

The main contribution of this thesis is the application of an integrated approach incorporating inter-related demand-side and supply-side energy systems, to investigate cost-optimal, long-term development pathways for a city energy system. This integrated approach allows investigations of intra- and inter-sectoral interactions. Sectoral interactions are further detailed by accounting for resource allocation across sectors in their development pathways. Furthermore, **Paper III** incorporates the city's spatial distribution to capture variations in technological parameters influenced by demographic characteristics. Key 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 for residential customers, based on spatial mapping of average household income. This study also incorporates long-term planning of low-voltage distribution grid capacity to support the electrification of residential heating and passenger transportation. Key modelling characteristics and their development between **Paper II** and **Paper III** are presented using an analytical framework adopted from **Paper I**.

The integrated approach is used to investigate the impacts of 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 decarbonisation targets, alignment of short-term city energy plan 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. In this context, the methodology allows analyses of system developments from three different perspectives. First, using a long-term perspective, it is possible to evaluate potential developments over time. Second, inclusion of spatial characterisation of the city in **Paper III** allows for developments driven by demographic characteristics and associated technological parameters. Third, the application of policy scenarios facilitates analyses of different future cost-optimal system designs aimed at achieving specified future climate goals.

The main findings from the applied model runs, to address the stated research questions are discussed below.

The impact of city energy plan and their alignment with national and regional climate objectives are presented by accounting for GHG emissions trajectories and long-term development pathways for the heating and transportation sectors. The results obtained for the city’s energy system emissions highlight the important roles of emissions trajectory and long-term targets. The existing gap between the REF and CEP scenarios emissions trajectories, underscores the need for strict measures to successfully achieve the CEP targets. Comparing the alignment of policy scenarios, annual emissions under the CEP are 42% higher in Year 2050 compared with the national climate objective. However, due to its steep emissions reduction trajectory, cumulative emissions under the CEP scenario are 7% lower than under the NECP scenario. This highlights the importance of aligning, short-term local-level plans with long-term decarbonisation objectives to ensure rapid decarbonisation sustained over time. Achieving deep and rapid reductions in emissions results in higher system costs; however, combining system developments with demand-side measures can help lower the abatement costs to reach the targeted emissions levels.

The heating system of Gothenburg accounts for a small share of fossil emissions and CEP's fossil fuel ban ensures its complete elimination. Changing dynamics of the city's heating system are more sensitive to uncertainties and fuel prices. District heating system with future low availability of waste heat are used to analyse the changing dynamics of the heating supply solution mix for residential buildings. Overall, the future of district heat connections is significantly influenced by rising bio-resource prices and the availability of low-cost waste heat, along with the decommissioning of existing heat production facilities. New housing shift towards heat pumps as district heating production becomes uneconomical. At the sub-regional levels, varying network costs of district heating system are driven by the heat demand density and housing type, thereby influencing the choice of heating supply options. The main findings highlight a shift in the solution mix from district heat to individual heat pumps over the time-horizon.

Policy interventions are imminent to achieve the 90% reduction targets under the CEP scenario for the transportation sector. Without short-term decarbonisation targets, a large share of the emissions lies in the transportation sector, as opposed to the heating sector. Meeting the Year 2030 targets requires a significant shift in fuel composition, entailing a substantial increase in biofuel use in the transportation sector. The importance of this shift has increased to changes in regulations relating to reduction obligations, making the decarbonisation objectives more challenging to achieve. The results for passenger car fleet composition indicate that electrification of car fleet is economical but requires a more rapid shift than in the REF scenario to meet the Year 2030 targets. Analysing the fleet mix at the sub-regional levels, the results highlight the importance of the spatial characterisation of the technological parameters. The GOT_2-3 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 regions to achieve 100% electrification of passenger car fleet.

The results on the distribution grid capacities and changing dynamics of residential electricity demand sheds light on the sectoral interactions in their development pathways. To keep up with the pace of accelerated electrification of residential heating and passenger cars, it is important to account for infrastructure development within the long-term planning horizon. While current grid capacity estimates are largely influenced by residential electricity loads and electrified heating in single family houses, future grid capacity investments will be shaped by the shift towards using heat pumps for heating apartment buildings and rapid deployment of passenger electric vehicles. Information on a sub-regional level, shows the bottlenecks in the low-voltage grid infrastructure and the focus areas for future investment plans are the high-density sub-regions with large share of multi-family housing.

# 7 Future work

Energy systems modelling entails continuous development, and each step in the process contributes to bringing the model representation closer to the real-life system. The results and discussion arising from this thesis, combined with the literature review in **Paper I** on key modelling characteristics representative of city energy systems, provide us with various prospects for development in the field of energy systems modelling. The following avenues for future work, to further expand the field of modelling to support city energy planning, are identified in this thesis:

*Co-benefits:* In urban areas, the transition to a decarbonised energy system will confer multiple co-benefits in addition to reduced GHG emissions. Decarbonisation of the transportation sector could significantly improve air quality through reduction of exhaust emissions, with associated health benefits. However, expanded electrification risks increasing the levels of non-exhaust emissions given that the average vehicle curb weight of electric vehicles is increasing, as shown in **Figure 14.** This makes it interesting to include local air pollution as an environmental component and as an avenue for future work. Additional co-benefits that warrant investigation include the efficiencies of urban areas, with increased productivity, energy efficiency, and reduced social inequality.

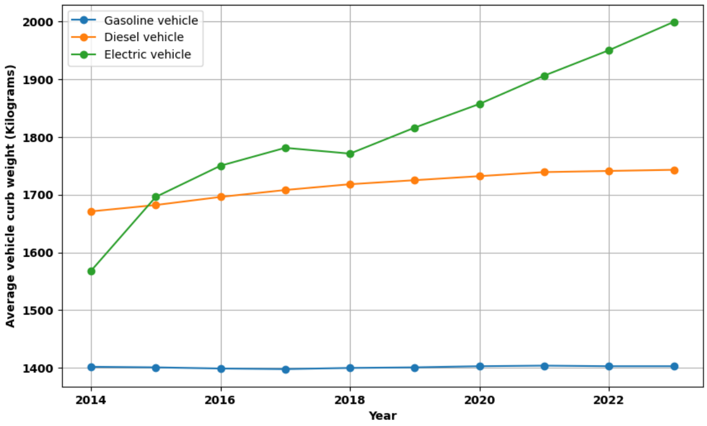


*Figure 14: Average curb weight by fuel type for passenger cars in use in Sweden for the period of 2014–2023 [51].*

*Improved system definition:* Traditionally, cities have relied on electricity supplied by the national grid to meet their energy needs. However, as electricity production becomes more decentralised through renewable energy sources, cities are acquiring a significant potential to generate their electricity locally. In the existing system, decentralised electricity production is under-represented, and there is room for a more-comprehensive integration of local wind and solar power generation. In addition, the adoption of PV systems may impact the capacity requirements of the distribution grid.

*Model versatility:* The modelling framework is designed to be applied to cities with colder climates with high heating needs, representing a northern European city. With this unique geographical scope, the general applicability of the results is limited. However, with some structural modifications, the framework could be applied to cities that have different energy system dynamics. Using this framework to investigate the long-term impacts of energy plans for cities with different demands and supply compositions would be interesting. A potential case study that is being investigated involves applying the designed modelling framework to a city in India with dynamics that differ from those of the Gothenburg energy system. Such a study would provide valuable insights into the versatility of this modelling framework for varied applications.

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