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City energy planning: Modeling long-term strategies under system uncertainties

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ABSTRACT

Cities are facing the dilemma of fulfilling energy service demands for their rapidly growing population while also working towards climate mitigation efforts. City energy planning is essential to deal with this dilemma. Thus, this study explores the role of city energy plans on future cost-efficient energy systems. A technology-rich cost-optimization model was developed using TIMES with intra-sectoral and inter-sectoral interactions and applied to the Gothenburg energy system. The model outcomes are investigated with the application of policy-driven scenarios and further tested under system uncertainties and price sensitivities identified using a participatory approach. Heating sector developments include DH production based on biomass CHP and heat pumps combined with improved building energy efficiency. Cost-efficient transport sector developments show a rapid deployment of biofuel vehicles, followed by increasing electrification later in the time horizon. With the applied uncertainties, different cost-optimal district heat production mixes and heating supply solutions are observed, providing alternative planning strategies. The model results also signify competition of biomass and electricity among sectors in their development pathways. The modeling outcomes enable decision-makers to assess various energy systems transition strategies from a long-term perspective.

1. Introduction

To limit global warming to 2 °C or 1.5 °C by the end of this century, rapid reductions of the energy sectors' greenhouse gas (GHG) emissions are required [1]. Cities, being the economic centers with an 80 % contribution to global GDP, are major energy consumers and significant contributors to carbon dioxide (CO_2) emissions. With over 2/3rd of the total final energy consumption (TFEC), cities generate around 70 % of the global CO_2 emissions. Cities are thus required to play a critical role in contributing to global climate mitigation efforts [2]. Working closely with companies, utilities, organizations, and residents to drive local developments, cities and municipalities are identified as essential stakeholders in national climate mitigation efforts [3].

The world is undergoing rapid urbanization, with 66 % of the global population expected to live in urban areas by 2050. More than 74 % of Europe's population lives in urban areas, and this share is expected to increase to 80 % by 2050 [4]. Continuous growth and rapid urbanization put local authorities (cities) in a big dilemma. While cities need to fulfill the energy requirements of a growing population, they must also implement policies to meet climate targets and mitigate GHG emissions. Due to the identified role of cities in climate mitigation and the complexities underneath, municipal energy planning has gained increased attention over the last decade [5]. City energy systems are identified as complex socio-technical systems affected by multi-scale, multi-sectoral, technological, economic, and structural aspects.

The built environment and transportation are the main contributors to city energy usage and emissions. The buildings sector accounts for 30 % of the 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]. Recognizing the importance and complexity of the sectors, studies focused on city energy systems have often applied modeling techniques to analyze the impact of implementing measures to mitigate the climate impact of the buildings and transport sectors.

Carbon-neutral heating supply solutions and building renovations

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Abbreviations

Greenhouse gas (GHG)
Carbon Dioxide (CO2)
Total final energy consumption (TFEC)
Combined heat and power plant (CHP)
Heat Pump (HP)
District heat (DH)
Electric vehicle (EV)
Municipal solid waste (MSW)
Passenger kilometers (PKM)
Tonne kilometers (TKM)
Multi-Family Housing (MFH)
Single Family Housing (SFH)

have been identified as key contributors to the decarbonization of the building sector. Considering the importance of heating systems in temperate urban contexts, studies have investigated different aspects of heating. To compare different heating supply solutions focused on identifying the role of combined heat and power plants (CHPs) and heat pumps (HPs), a modeling tool was developed for municipal energy planning activities [9]. System-wide cost-efficient heat supply solutions were determined using a local TIMES model for low-energy buildings [10]. The results showed large heat networks as the most cost-effective heating solution in most cases with short distances to existing district heat (DH) networks and linear heat densities. Another study modeled the decarbonization of heating systems under different scales of spatial resolution to investigate optimal heating supply mixes under different resolution scales [11]. The impact of electricity price fluctuations with high temporal resolution on the operation of the DH systems was analyzed to investigate the correlation between electricity price and CHP operations [12].

Studies have also focused on representing the building stock and its potential for energy savings. A methodology for building-specific stock modeling to investigate locally optimal renovation strategies was proposed [13]. A dynamic bottom-up modeling framework, ECCABS, was developed, and residential building stock was modeled based on the actual conditions of existing buildings. From the energy savings perspective, the balance between heat savings and heat supplies was investigated for different countries [14]. Supporting the municipality's strategic energy plan, an optimal mix of renewable-based heating supply and savings at the urban scale was presented [15]. Further adding to the literature, the importance of balance between heat savings and heat supply was highlighted [16,17]. Another example of integrating urban building demand with energy system simulation to support municipal energy planning strategies was presented in Ref. [7].

Key measures identified in city transportation include fuel and technology switching and a shift towards public transportation and active modes. In urban areas, the representation of the energy-use of the public transit system and the shift in transport modalities has become increasingly essential. Among the transport sector modeling analysis, a bottom-up modeling study investigated the cost and local air pollutant impacts of New York City's carbon reduction policies [18]. For the city of Beijing, a bottom-up technology-rich transport model was presented to evaluate the environmental co-benefits of quota limit and electric vehicle (EV) promotion policies [19]. Another study focused on EV penetration policies assessed the impact of EVs using an integrated land-use transport model [20]. Focusing on the demand side, a national modeling study presented a novel method incorporating behavioral change to integrate modal shifts endogenously [21].

Most modeling studies analyzing city energy systems have focused on independent sectors. However, a deeper analysis of sectoral integration is needed since different sector analyses recognize decarbonization pathways following similar strategies, such as biofuel use, electrification, and cost-efficient decarbonization. Sectoral integration is defined as linking various energy carriers and the various end-uses. Sectoral integration allows for optimization of the overall energy system [22]. While some studies have touched on multi-sectoral aspects, including multiple demands, supply-side measures and their combined effects, they have not delved into resource allocation/resource competition and their impact on the overall energy system. Technology-rich integrated assessment models were developed to investigate optimal solutions for achieving low-carbon local energy systems [23,24,25]). The results presented energy consumption and emissions for the overall energy system accounting for sectoral integration. Another integrated assessment study combined an energy economy model with a GIS urban model to analyze the impact of policies on energy use and emissions for the overall energy system [26].

From a policy perspective, energy plans and CO_2 reduction targets at a municipal level play a significant role in national climate mitigation efforts. However, existing urban energy plans are primarily short-term plans and often include independent sectoral initiatives instead of long-term national mitigation plans [16]. 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. When analyzing policy-driven scenarios, studies have often applied normative long-term GHG emission reduction targets to identify optimal solutions to achieve the decarbonization goals [23,25,27,28]. Strategic municipal plans were included in the scenario description of a Danish municipality to compare with alternating scenarios [24]. Focused 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 [29].

As presented above, despite the crucial role of city energy plans in long-term energy systems transition planning, there is a lack of representation of these plans in the scenario assessment for integrated city energy system models. Further, in the rather limited number of studies focusing on integrated assessment of city energy systems, there is a lack of studies evaluating allocation of limiting resources among competing sectors and their impact on the overall city energy system.

Thus, this paper aims to develop and apply (to a selected case) an integrated city energy systems model to investigate intra and inter-sectoral interactions with the implementation of city energy plans from a long-term energy systems development perspective to answer the following key research questions.

- How do the city's energy plans and associated short-term targets impact the long-term future cost-efficient city energy system?
- What important sectoral interactions are identified in the city's energy systems transition pathways?

The rest of the paper is structured as follows: Section 2 presents the methodology adopted for developing the modeling framework. Section 3 introduces the chosen case and the data associated with the case study. Section 4 presents the results related to the analyses of the identified scenarios. Sections 5 and 6 present a brief discussion and conclusion for the analyzed case study.

2. Methodology

The research questions guiding the study approach focus on exploring the role of city energy plans on future cost-optimal energy systems. The framework used in this study is designed to evaluate the role of energy policies and measures on the city energy system development in the long-term horizon. The interim goals are translated into applied measures and investigated using policy-driven scenario analysis to understand the role of short-term city energy plans. This section presents an overview of the methodological framework adopted in this study.

2.1. Study approach

An integrated approach, including interrelated demand and supply-side energy systems, is adopted to investigate long-term development pathways for a city energy system. 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.

This framework incorporates key transition measures for the future urban energy system. Based on a review of city strategies [5], a set of future energy system development pathways are identified.

- Building energy efficiency.
- Clean energy production.
- Alternative heat supply options.
- Alternative fuel choices and vehicle technology switch.
- Modal shifts in the transport sector.

The developed framework is then applied to a case municipality. Model outcomes are generated by applying policy-driven energy scenarios for the future development of city energy systems. Policy-driven scenarios are further extended by applying system uncertainties and price sensitivities. In long-term modeling, with projections into the distant future, uncertainties around future assumptions are inevitable [30]. Due to this study's long-term modeling horizon, it is important to include uncertainty analysis to account for possible disruptions in the future. Uncertainties can be associated with the design of the future system and with uncertainty associated with projections on model parameters. In this analysis, the uncertainties around the future energy system are identified as case-specific system uncertainties. Parametric uncertainties are represented in this study as price sensitivities.

This study followed a participatory approach, including local stakeholders, to identify case-specific system uncertainties. Municipality stakeholders were involved in this process to identify the uncertainties faced in the energy systems planning process. In the first step, the stakeholders were familiarized with the model setup and the model's flexibility to incorporate system uncertainties. In the next step, discussions were conducted with the stakeholders to extend the policy-driven scenarios to incorporate the system uncertainties. To evaluate the relevant price sensitivities, modeling results are analyzed to understand the role of different energy carriers in long-term energy systems development.

With the application of policy-driven energy scenarios, the following model outcomes are calculated and analyzed to answer the research questions.

- DH production mix and heating supply solutions for the modeled time horizon.
- Choices for the future transport system development represented through fuel shares.
- Sector-wise utilization of electricity and bio-based resources.

An illustration of modeling workflow summarizing the study approach is presented in Fig. 1.

2.2. Model development

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.

TIMES was developed by the IEA-ETSAP Technology Collaboration Programme (International Energy Agency-the Energy Technology Systems Analysis Program). TIMES is an economic model generator, providing technology-rich energy dynamics over a multi-period time horizon [31]. TIMES is a powerful tool for analyzing energy systems and evaluating cost-optimal pathways to achieve the desired decarbonization targets. 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.

TIMES is implemented using mixed-integer linear programming and is based on perfect foresight. The key inputs to the model include end-use energy service demands and technical and economic parameters for the existing and future energy supply infrastructure. The model developed in this study, referred to as the TIMES_NE city model, represents a Northern European city with high heating demands. The model setup incorporates a long-term modeling horizon divided into periods. 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. Spatially, city boundary within the control of municipal authorities is identified as a region. The model includes exogenous energy service demands and the import/extraction of primary resources to feed into energy conversion technologies. Transmission and distribution systems are modeled to provide energy to fulfill end-users service demands. This modeling structure is built upon the already-developed model setup [29]. Fig. 2 presents the schematic of the TIMES_NE city model.

A three-step process was adopted to validate the TIMES_NE city model. In the first step, model runs for the base year are validated with the historical data. Secondly, the model's response to parameter changes is analyzed. Key parameters used for model validation include fuel costs, technology availability factors, and efficiencies. While the uncertainty analysis is applied to deal with uncertainties in future assumptions, it contributes to the second step of the model validation process. Third, model outcomes were discussed with local stakeholders to complete the validation process.

2.2.1. Energy supply infrastructure

The energy supply infrastructure includes primary resources, centralized heat and power production facilities, a distribution network for electricity, and DH distribution and fuel supply infrastructure for the transport sector. Due to its urban nature, most primary resources are imported into the system. At the city level, the electricity demands are mainly fulfilled by electricity transmission from the national grid and local electricity production units. Local production includes electricity from CHP units and decentralized production using solar and wind

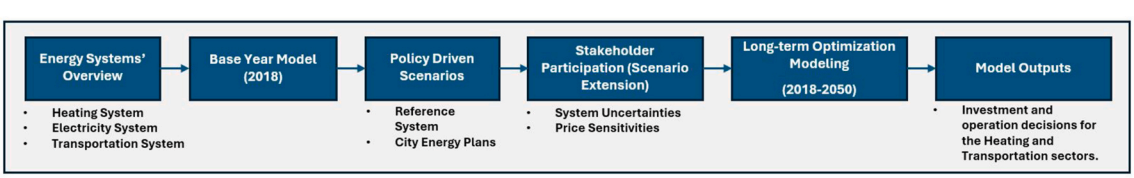

Fig. 1. Modeling workflow illustrating the study approach of this study.

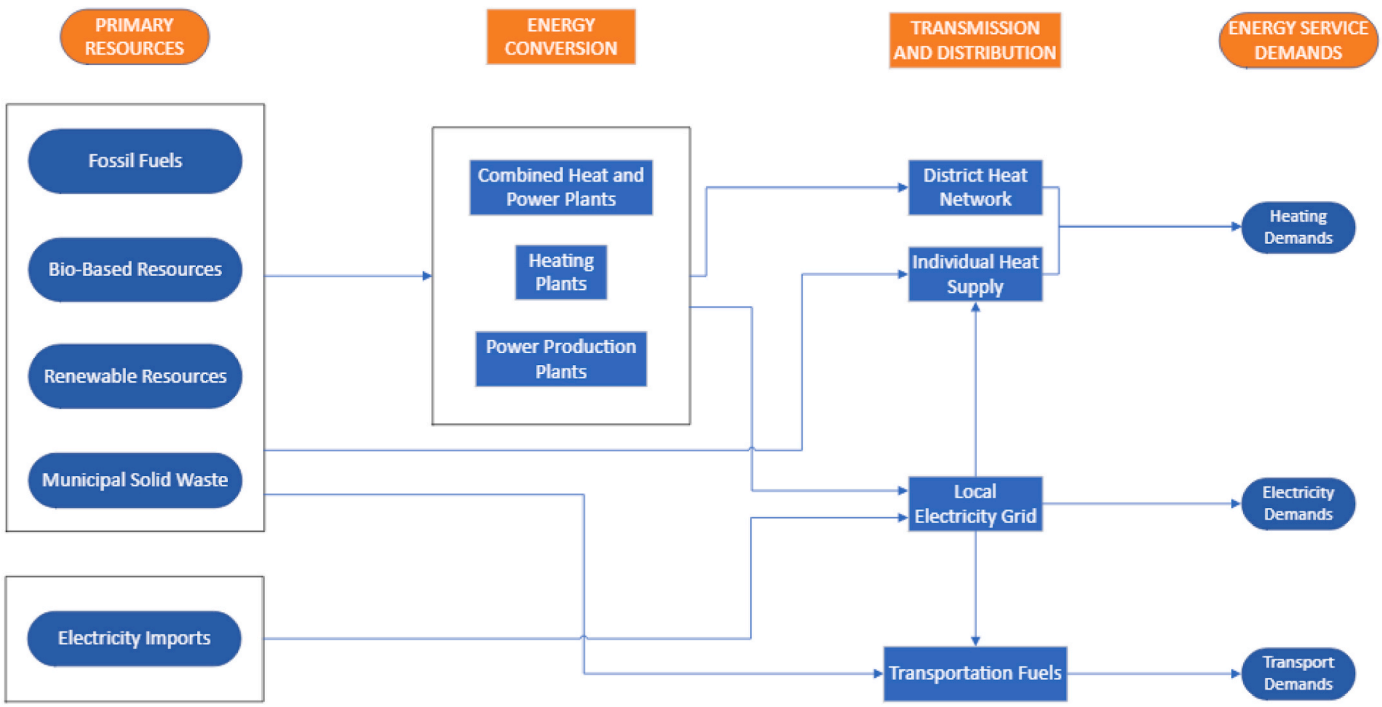

Fig. 2. TIMES-NE city model structure.

power. The heating supply includes two supply options: DH, based on centralized heat production facilities, and individual heating options, including heat pumps, fossil or biomass boilers, and direct electrical heating. A regional electricity grid and DH network are also modeled to distribute the heat and electricity produced to the end-users.

The fuel supply infrastructure for the transport sector includes the existing infrastructure for distributing conventional fuels. The model also includes the existing infrastructure of gas filling stations and charging stations with existing capacity estimation to fulfil base year demands. For future electricity and gas supply for transportation, options for investment in charging infrastructure and gas stations are included.

2.2.2. *End-use service demands*

End-use sectors include the built environment and urban transportation. End-use service demands are exogenously calculated for the modeled sectors.

Building energy demand accounts for a large share of the final energy consumption in cities and is thus considered an essential part of this modeling framework. The buildings included are residential, commercial, and industrial. Furthermore, residential buildings are disaggregated based on dwelling types and energy needs. Considering the northern European city setup, buildings' energy demands include space heating, hot water, and electricity use for appliances and lighting. The energy demand for buildings is endogenously calculated based on their service demands and specific energy requirements.

In the TIMES_NE, road transportation, including passenger and freight transportation, is modeled. Passenger transport includes passenger cars and public transit buses. Freight transport includes light commercial vehicles and urban heavy freight. Transportation service demands are expressed in passenger kilometers (PKM) and tonne kilometers (TKM) for passenger and freight transportation. The associated energy consumption is endogenously calculated in the model following the method described in Fig. 3.

End-use services growth rates are assumed to follow historical growth rates and demographic projections to account for future energy demands. Due to the uncertain nature of residential buildings' service

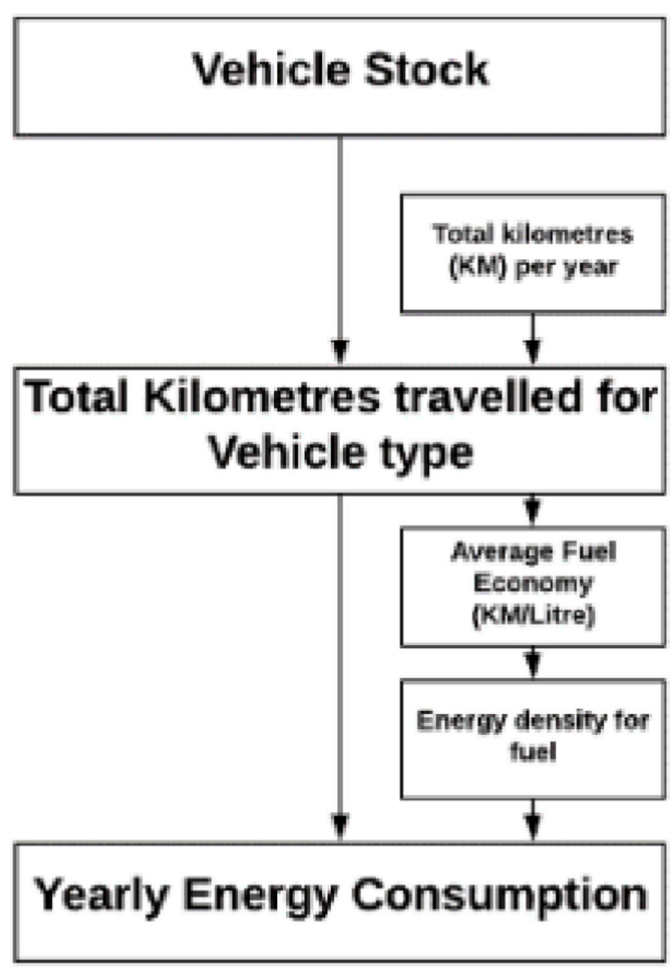

Fig. 3. Transportation energy demand calculation methodology.

needs, two methodologies are adopted to estimate the future building stock growth. In the first case, average historical growth rates of building stock are used for future stock projections. In the second case, the correlation between historical building stock and population growth rates is used to project future building stocks based on population projections. Future demand for commercial and industrial buildings is assumed based on historical trends and a literature review of future energy demand for the service sectors. Future transportation service demands are estimated based on the official prognosis of future traffic works.

3. Case description and modeling assumptions

This section presents a detailed description of the selected modeling case, followed by data and assumptions for the design of the energy system of the chosen case.

3.1. Outline of the modeled case

The city of Gothenburg was selected as the case study for applying the novel modeling framework. Gothenburg is the second largest city in Sweden, with a population of 583 thousand and a regional gross domestic product amounting to 400.8 billion Swedish Krona in 2020. The city is rapidly expanding, and its population is expected to grow by almost 60 thousand between 2020 and 2030 [32]. Gothenburg municipality (Göteborg Stad) has decided to set goals to limit the climate impacts and reach a sustainable and fair level of GHG emissions by 2050 [33]. Gothenburg municipality is a key player in energy systems planning, with access to its own properties and the possibility of influencing the local energy utility company.

The city of Gothenburg is selected as a representative case for a Northern European city setup. Gothenburg has a well-established heating system with options to use an extensive DH network or individual heating solutions. Simultaneously, the heating system of Gothenburg is in the planning stage, with major plants reaching retirement age and uncertainty around the continuation of the use of biomass and excess 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 city model.

According to the Municipal Energy Planning Act (1977:439), all municipalities in Sweden must have an energy plan that includes supply, distribution, and use of energy in the municipality. The city energy plan was adopted in accordance with the Municipal Energy Planning Act to promote the implementation of measures that would lead to the city of Gothenburg reaching its environmental goal [34]. The environmental and climate program 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 as per the Environment and Climate Program.

The implementation of the city energy plan is driven and coordinated by the Environmental and Climate Committee. Within the energy plan, the city has interim goals for the climate.

- Reduction of energy use in homes and premises: Making our energy use more efficient is a prerequisite for an energy system that has no negative environmental and climate impact.
- Production of energy from renewable sources: The City of Gothenburg, through Göteborg Energi AB, owns heating and co-generation plants that produce heat and electricity partly from fossil fuels.
- Reduced climate impact of transport: Gothenburg has excellent opportunities for a higher proportion of sustainable transport modes than Sweden.
- Reduce the climate impact of purchasing.

The plans cover the energy produced or used within the municipal geographic area, the energy produced by the city of Gothenburg, and the energy used by municipality employees when traveling outside. Key measures identified under the city energy plan are described in Table 1 [34].

3.2. Data and assumptions

This section presents key modeling assumptions and data associated with the development of the Gothenburg energy system model. The developed model's time horizon is from 2018 to 2050. To represent the seasonal variations for the Gothenburg energy system, each year is divided into 13 time slices. The 13-time slices include 12 months and a set of 3 days representative of peak heating demand days. Fig. 4 shows the heating load profile for the 13-time slices. On a spatial level, the city boundaries within the jurisdiction of Gothenburg municipality are identified as one region. The model assumes a system-wide discount rate of 5 % [29]. A list of key modeling assumptions is presented below in Table 2.

The sections below elaborate on the primary data sets, including energy prices, service demands, and supply infrastructure.

3.2.1. Energy prices

Fuel prices for the city of Gothenburg are based on the average annual national energy prices provided by the Swedish Energy Agency [35]. The electricity prices correspond to the spot market price in 2018 for the electricity price area SE3. The electricity price profile follows an average monthly variation based on the price profile of 2018. The overall price for electricity use includes.

- Spot price
- Network fee (Fixed network contract fee is excluded from the price. Only variable fee based on the electricity consumption is included.)

The prices associated with energy resources are further categorized based on the end-user to account for the consumer's perspective in investment decisions. This includes different prices for household types and commercial users of energy services. **Appendix A** presents data associated with fuel and electricity prices.

3.2.2. Energy supply infrastructure

The energy supply infrastructure for Gothenburg includes existing power plants, a distribution network, and fuel supply infrastructure. Existing heating supply options include CHP units, heat-only boilers, municipal solid waste (MSW) incineration, and refinery waste heat. Future investment options include DH production units and individual heat supply options. Key technology parameters for existing technologies and future investment options are based on the technology database [36].

Distribution systems within the city boundaries include a distribution network for DH, electricity, and transportation energy supply. The

Table 1
Targets within the city energy plan.

Serial no.	Sectors	Sector	Reference value	Target 2030
1	Building energy efficiency	Residential buildings	117 kWh/m2 (2017)	95 kWh/m2
2	Share of renewable sources	Electricity	20 % (2018)	100 % (2025)
3	Share of renewable sources	District heat	69 % (2018)	100 % (2025)
4	Transport decarbonization	Transport	999.9 kilotons of $CO_{2,\ equivalent}$ (2010)	90 % lower than in 2010
5	Road traffic (Motorized vehicles)	Transport	Based on demand calculations (2020)	25 % lower than in 2020

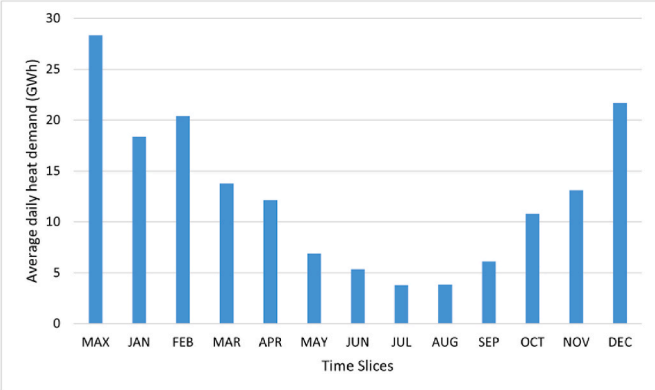

Fig. 4. Heating demand profile for Gothenburg in 2012, with heating demand averaged over the months.

Table 2
Key Modeling assumptions.

Serial no.	Modeling parameters	Assumptions
1.	Base year	2018
2.	Time horizon	2018–2050
3.	Temporal resolution	13 time slices
4.	Spatial resolution	City as a region
5.	Discount rates	5 %

existing capacity of the DH network is estimated based on the current demand for DH. Future investments in DH networks allow different residential consumer types to connect to the DH grid. The distribution network for electricity is assumed to fulfill all the existing and future electricity needs without additional investments. Transport systems include filling stations for biomethane and charging infrastructure for electric vehicles. The cost structure and associated technology parameters for filling stations are based on [37], and charging infrastructure is based on [38]. The fuel supply mix for Gothenburg's transportation sector includes conventional fuels with existing biofuel blending shares. In the long term, options with existing and future high blends are available [39].

3.2.3. End-use service demands

For residential buildings, the demand for heating and electricity is considered. Heating demand includes demand for space heating and hot water. Electricity demand corresponds to the demand for appliances and lighting on the premises.

The residential building stock is disaggregated based on the building type.

- Multi-Family Housing (MFH)
- Single Family Housing/Detached Housing (SFH)

MFH building stock is further disaggregated based on age and energy class to account for future renovation strategies. More than 90 % of the existing heating demand for MFH is fulfilled by DH; hence, the existing MFH building stock is assumed to be connected to the DH network. Data regarding heat demand calculations for MFH is acquired from energy performance certificates [40] and building statistics [41]. The model can choose between DH and individual heating options for future service demands. In the case of SFH buildings, aggregated heat demand based on the final heating supply option is modeled using Gothenburg's energy balance [42]. Existing SFH heat demand is disaggregated based on DH, biomass boilers, heat pumps, fossil boilers, and direct electrical heating. Existing and new buildings can switch between DH and individual heat supply options to fulfill their heating needs. Due to the limited potential for developments in the electricity demand-side changes for residential buildings, aggregated electricity demand is modeled based on Gothenburg's energy balance [42]. For commercial and industrial services, aggregated heating and electricity demands are considered based on the energy balance [42]. The load profile for heating demand is assumed to follow monthly variations, including peak demand for coldest days. The seasonal load profile is generated based on the actual heating demand for Gothenburg, available for the year 2012, as presented in Fig. 4. The load profile represents the seasonal temperature variations in Gothenburg and is assumed to follow the same temperature variations over the modeling time horizon. Considering limited seasonal variations in the electricity end-use, average annual demands are modeled.

For the city of Gothenburg, transport modes and vehicle types included are presented in Table 3. Transportation through tram services is assumed to be constant throughout the modeling horizon. The existing stock for vehicles in different transport modes is based on [43]. The residual stock for passenger cars follows the lifespan-based age profile based on the Weibull distribution curve [44], combined with age-wise vehicle stock in Sweden [45]. For other modes of transport, a linear profile following the assumed lifespan of vehicles is used to estimate the residual stock of existing vehicles.

Service demands in PKM and TKM for the city are evaluated using data on existing vehicle stock [43] and annual vehicle mileage. Energy requirements are endogenously calculated using end-user demand calculation methodology (Fig. 3). In the transport sector, average annual demands are modeled due to limited seasonal variations.

3.3. Future assumptions

The main future assumptions include energy price developments, demand projections, applied national policy instruments, and emissions. Unless stated in the scenario description, the same assumptions are applied to all scenarios.

3.3.1. Energy prices

Different approaches for energy price development are considered depending on the fuel type and based on data availability. Energy price developments for crude oil and natural gas correspond to the New Policy Scenario of the World Energy Outlook 2016 [46]. Prices for bio-based resources are expected to increase by 50 % by 2050 compared to 2018, based on historical trends. The future diesel and gasoline prices are based on Sweden's projected fuel prices [39].

It is difficult to identify a trend in the historical spot prices of electricity as seen in Fig. 5. Due to the uncertainty associated with electricity prices, it is challenging to make assumptions about their developments. Hence, spot prices are assumed to be constant throughout the modeling period, and variations in electricity prices are studied with the implementation of price sensitivities. Network fees follow historical trends for future projections [35]. **Appendix A** provides data associated with assumed future price projections.

3.3.2. Demand projections

Future demands for residential buildings follow two approaches. In case 1, annual growth in the building stock is considered based on historical growth rates of building stocks [41]. Case 2 includes a two-step

Table 3
Transport modes and vehicles by fuel types in Gothenburg.

Serial no.	Transport modes	Vehicle types
1.	Passenger cars	Gasoline
2.	Urban public transport buses	Diesel
3.	Light commercial vehicles (<3.5 Tonnes)	Electric
4.	Heavy urban freight (>3.5 Tonnes)	Hybrid and plug-in hybrid
5.		Biofuel
6.		Gas/Biogas

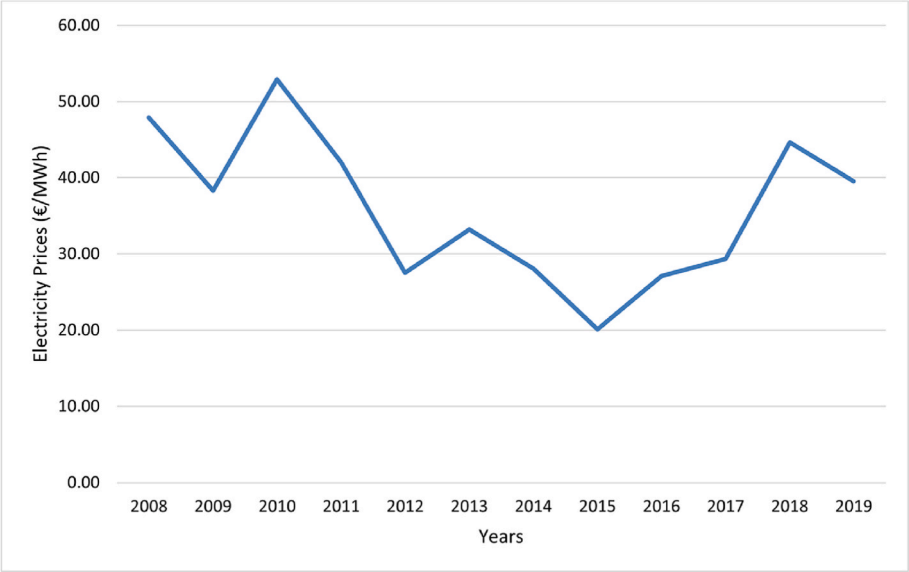

Fig. 5. Historical electricity spot prices for the SE3 region of Sweden.

process. Firstly, the correlation between the historical growth rate in building stocks and the population growth rate is identified. In the next step, population projections for Gothenburg [47] are used along with historical correlations to estimate the future growth in the building stock.

Service demands for the commercial and industry sectors are assumed to be constant over the modeling time horizon based on historical trends and decoupling of economic growth with energy use [48]. Forecasts of future transportation needs are based on the Swedish Transportation Agency's freight and passenger transport forecasts [49, 50]. Existing service demands and future projections are presented in **Appendix B**.

3.3.3. *National energy policies*

National policy instruments considered in the modeled scenarios include.

- Carbon tax associated with the use of fossil-based primary energy resources.
- Energy tax for energy consumption. Different energy taxes are applied based on consumer categories.
- Building regulations for new buildings' specific energy demands.

3.3.4. *Emissions*

Key assumptions concerning the emission calculations are mentioned below.

- In this study, CO_2 emissions associated with the use of primary energy resources to fulfill the end-use service demands are considered.
- MSW is assumed to be carbon neutral in the heating system, considering the emissions associated with the fossil waste allocated to the different end-uses.
- Only CO_2 emissions are considered. Local air pollutants are beyond the scope of current analysis. Key assumptions regarding the emission factors of different fuel types are based on [51].
- Emissions associated with the use of electricity are assumed based on the CO_2 intensity of the Swedish Electricity mix and do not include imported electricity from the connected system, which may be of fossil origin.

3.4. *Scenario description*

The reference (REF) scenario continues the base year model into the future. The City Energy Plan (CEP) analyses the role of short-term energy plans set by the city authorities on long-term energy system developments.

3.4.1. *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.

3.4.2. *City Energy Plan (CEP)*

The City Energy Plan scenario extends the reference scenario presented above. The energy policies and plans stated under the City Energy Plan 2022–2030 [34] are applied in this scenario. With the incorporation of policy measures to describe possible consequences of strategic decisions, this scenario is identified as an explorative strategic scenario per the scenario typology [52]. Strategic scenarios are recognized as a suitable methodology for environmental assessment, combining external factors and internal policy decisions [53].

The sector-wise system development measures deployed in this scenario are based on the Gothenburg city energy plan [34]. A 3 % annual renovation of existing multi-family housing stock is applied for improved building energy efficiency. With the application of renovation measures, the building energy requirements reach the levels of energy requirements as per the building regulations from their existing class. A 100 % share of renewable fuels in the production of heat and electricity is implemented by banning the use of natural gas and oil for energy production. The percentage of biogas in the gas grid is assumed to reach 100 % by 2025. To represent the emission reduction target of the transport sector, the allowed fossil emissions are constrained to 10 % in 2030 compared to 2018. Transport modal shift is exogenously applied to the model, implying 25 % fewer passenger vehicle kilometers in 2030 compared to 2020. The excess demand for PKM is allocated to public transport and active transport modes, ensuring that PKM demand is fulfilled with fewer vehicle kilometers. The applied constraints are extended beyond the short-term targets up to the end of the modeling time horizon.

3.5. System uncertainties and price sensitivities

As with any other energy system, the city of Gothenburg's energy system also faces system-related uncertainties. Based on stakeholder discussions and considering the modeling assumptions, a set of uncertainties and price sensitivities have been identified and are described below.

Gothenburg's heating system heavily depends on the waste heat from refineries and municipal solid waste incineration. With the transport sector transitioning towards electricity and alternative fuels and additional regulations on solid waste processing, the amount of waste heat available to the city's DH network could be significantly reduced. The study thus identifies availability of waste heat as a system uncertainty. Future service demand projections for residential buildings are also recognized as system uncertainty. Table 4 presents the identified system uncertainties.

With increasing ambitions to reach decarbonization targets, it has been observed that there is a move towards a stronger dependence on bio-based resources [54]. The authors foresee increasing resource competition with the increasing demand for bioresources in different sectors, thus driving the biomass price increase. Also, electricity prices are always uncertain and beyond the control of the local system boundaries. Thus, any fluctuations in electricity prices could lead to different developments in the energy sector. Hence, variations in electricity and biomass prices are tested as price sensitivities. Table 5 presents the identified price sensitivities.

The policy scenarios are further investigated with the inclusion of system uncertainties and price sensitivities. Fig. 6 gives an overview of the scenario development process with the applied uncertainties and sensitivities.

4. Results and analysis

The TIMES_NE model is applied to the Gothenburg case study to analyze long-term energy system development pathways. To answer the research question on the impact of the city energy plans, the development of the heating and transport sector with the application of scenarios is presented. Resource allocation among the sectors is presented and analyzed based on the results on electricity and biomass utilization among the heating and transportation sectors.

4.1. Impact of city energy plan

The impact of the CEP scenarios on Gothenburg's energy system is presented through long-term development pathways for the heating and transportation systems. The outcome of heating sector development includes heating demand for residential buildings, district heating production mix, and heating supply solutions. The future transport sector is analyzed by calculating the fuel share in the TFEC.

4.1.1. Heating system

For the existing building stock, with the implementation of renovation measures for MFH, the annual demand for heating will be reduced by 16 % in 2050 compared to the reference scenario. Two demand projection approaches have been adopted to deal with uncertainties in future building service demands. With demand projections based on historical trends and demographic projections, additional annual heating demand for residential buildings will reach 449 GWh by 2050, while a historical average growth approach leads to an additional annual heating demand reaching 882 GWh by 2050. Demand developments for the existing and future stock of residential buildings are shown in Fig. 7.

Table 4
Identified system uncertainties.

Serial no.	Uncertainty	Descriptions
1	**Demand projections**	Demographic projections (Low growth) Historical (High growth)
2	**Waste heat availability**	Constant Low availability (50 % capacity in 2050 compared to 2018)

Table 5
Price sensitivities.

Serial no.	Price sensitivity	Descriptions
1	**Bio-resources price**	Base price (Constant during the modeling horizon) High future (Doubling in 2050 compared to 2018)
2	**Electricity price**	Base price (Average annual price 2018) High (Average annual price 2021)

The district heating production mix for the REF scenario and CEP scenarios with system uncertainties is presented in Fig. 8. The base heating load in the DH system of Gothenburg is based on the waste heat from refineries and MSW incineration. Biomass and gas CHP, biomass boilers, and heat pumps fulfill the rest of the DH needs. As the existing capacities start to retire, new investments begin to appear in the system from 2025, with significant investments from 2030. With carbon taxes in place and competitive alternative solutions, natural gas-based heating solutions do not attract new investments with or without a fossil ban. The reference and policy scenarios show a similar DH production mix. The second measure applied in the policy scenarios is building renovation, which reduces the demand for district heat in 2050 by more than 10 % compared to the REF scenario. With the application of system uncertainties, the future heating production mix is significantly impacted. Reduction of available waste heat leads to considerable investments in both biomass CHP and heat pumps, as seen in Fig. 8 (c). Higher DH production is attributed to the higher heating demand with historical demand projections.

Energy prices have a significant impact on the investment and operations decisions of the heating system. With the assumption of constant bio-resource prices and high average electricity prices, the DH system is dominated by biomass CHP units, with DH production reaching up to 4.98 TWh in 2050 compared to 3.5 TWh in 2018. High electricity prices combined with low bio prices make heat and electricity production from biomass CHP a cost-efficient solution. On the other hand, with high future biomass prices and base electricity prices, the DH production mix is dominated by centralized heat pumps and small shares of biomass CHP to fulfill the heating demands. Also, DH production in 2050 will be reduced by 1.4 TWh compared to the first case. With assumptions of high energy prices, the system initially invested in biomass CHP in 2025 but started using higher shares of heat pumps as bio-resources prices gradually increased. Fig. 9 presents the effect of variations in the electricity and bio-resource prices on the DH production mix compared to the CEP_2 scenario with low available waste heat.

The changing need for district heat production between the three price sensitivities in Fig. 9 can be allocated to the changing mix of heat supply solutions.

Fig. 10 presents the heat supply solution mix for single-family houses under CEP_2 with low available waste heat and three price sensitivities. In all scenarios, direct electrical heating is not an economically feasible solution and is immediately replaced by DH connections. DH connections are a favoured option in the beginning, considering the existing capacity of DH production units. However, as the existing plants retire, individual heat pumps become cost-competitive with DH-based heating at different rates. Under the CEP scenario, no new DH connections are observed after 2025, and individual heat pumps cover new heating demands. Similar trends are observed with high biomass price, with either base or high electricity prices; however, heat pumps start replacing DH connections at different rates later in the time horizon. In the case of

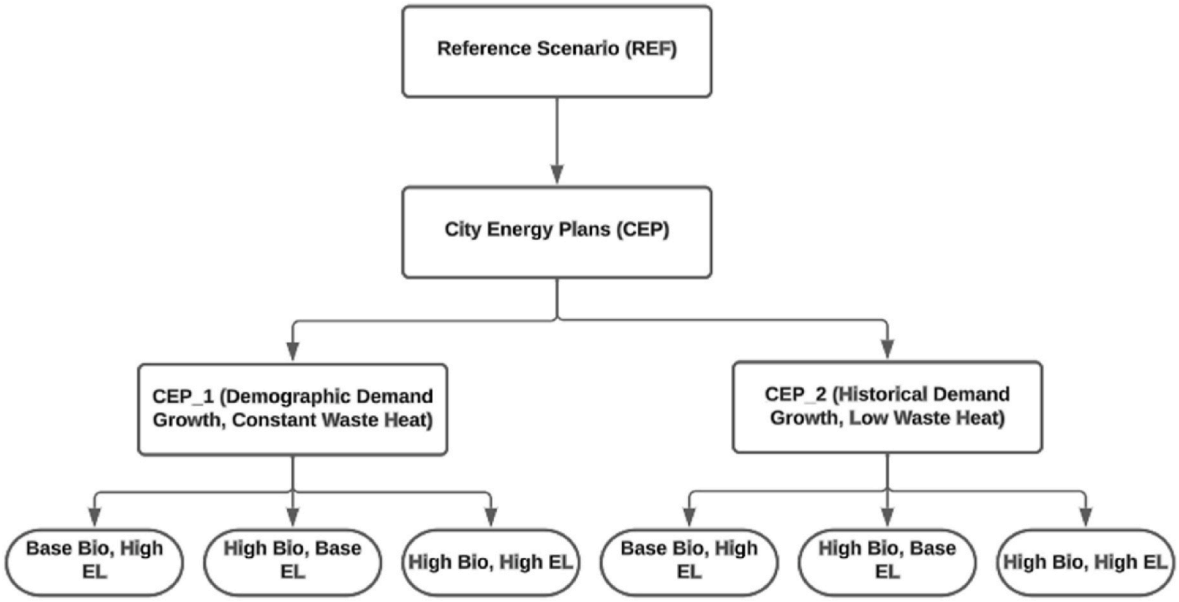

Fig. 6. Scenario extension with the application of system uncertainties and price sensitivities.

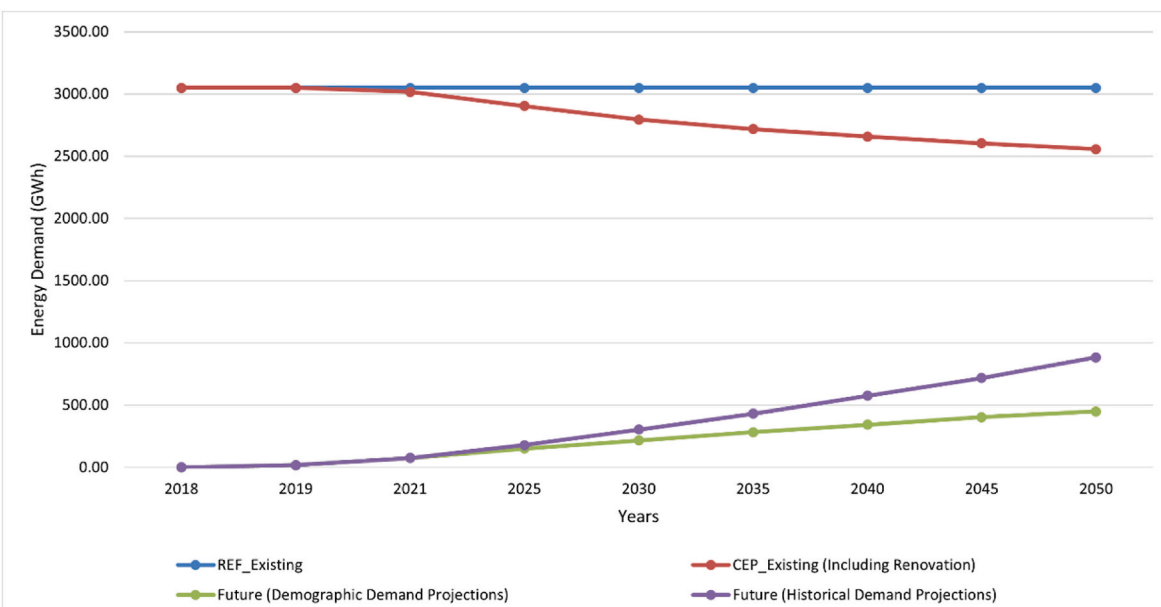

Fig. 7. Existing and future demands for Residential Buildings. Variations in existing demand due to renovation of existing building stock and variations in future demands due to the two approaches for future demand projections.

base price for bio-resources, the heating supply mix of single-family houses is dominated by DH, with some penetration of biomass boilers in the future.

4.1.2. Transportation sector

The modeling results provide insights into the development of the transportation sector for the city of Gothenburg. For the decarbonization of the transportation sector, city energy plans play a significant role. With emission reduction constraints and passenger transport modal shift, the main developments observed are associated with higher deployment of alternative fuel vehicles and associated energy demand reduction due to high-efficiency vehicle deployment. With the assumed growth rates, the demand for passenger and tonne-kilometers increased by 71 % and 84 %, respectively, from 2018 to 2050. At the same time, the total final energy consumption reduced significantly, reaching 42 % reductions in 2050 compared to 2018 in the reference scenario with the assumed efficiency improvements and vehicle electrification. In the CEP scenario, final energy use reductions reach 57 % due to improved vehicle efficiency and modal shifts for passenger transportation. Fig. 11 presents the results for the transport sector. Diesel vehicles are chosen as the most economical solution without any emission reduction targets, and electric vehicles are starting to penetrate the vehicle mix after 2030. With emission constraints, biofuel-based vehicles start penetrating the transport system with a large share of biodiesel and high-blend diesel and gasoline to reach short-term goals. In the later half of the time horizon, electric vehicles will start becoming more economical, resulting in 90 % electrification of the transport sector by 2050. The freight transport running on gasoline and diesel consumes the rest of the allowed 10

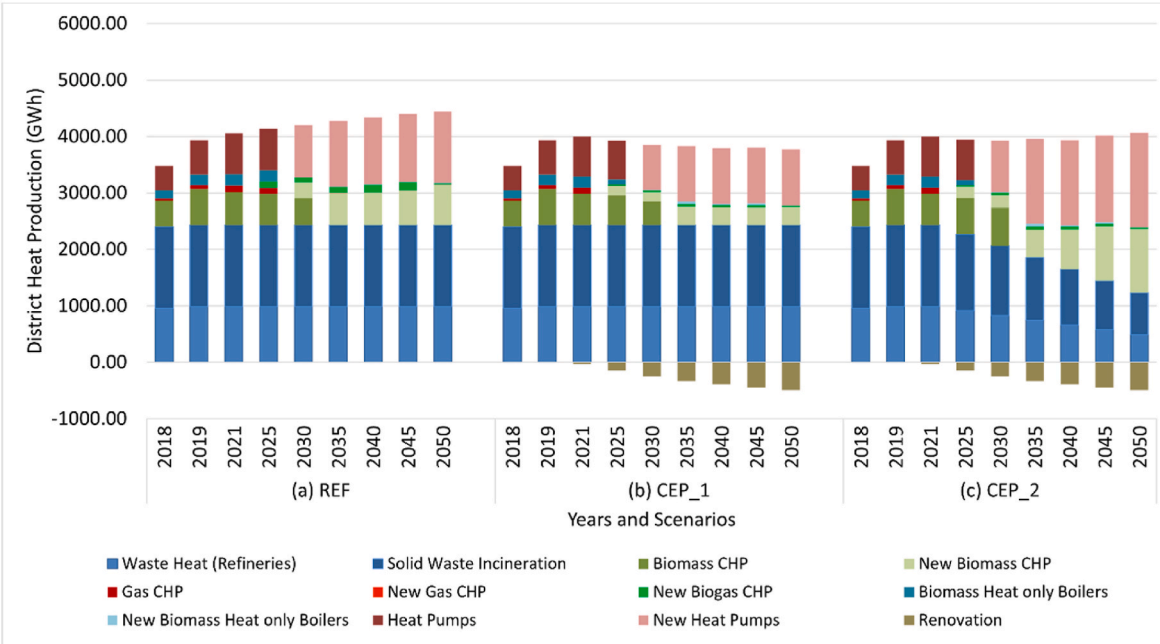

Fig. 8. District heating production mix under (a) Reference Scenario, (b) City Energy Plans scenario with demographic demand projections and constant available waste heat, and (c) City Energy Plans scenario with historical demand projections and low availability of waste heat.

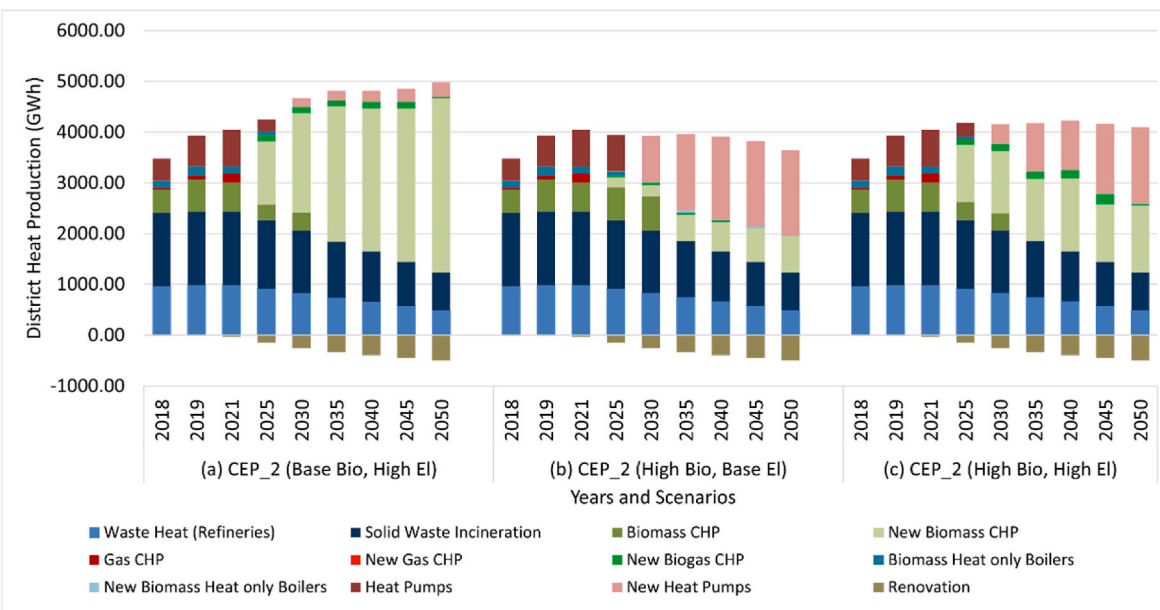

Fig. 9. Impact of price sensitivity on the district heating production mix for city energy plans scenario with low available waste heat and historical demand growth. Three price sensitivities for City Energy Plans scenario with historical demand projections and low available waste heat: (a) Base Bio, High El, (b) High Bio, High El, (c) High Bio, High El.

% emissions. An important observation starting in 2048 is the electrification of freight beyond the emission constraints, highlighting the economic competitiveness of electrified freight transport compared to conventional vehicles.

Variations in energy prices significantly change the techno-economic pathway for the transportation system of Gothenburg, as seen in Fig. 12. Apart from the price sensitivity of base bio prices (b), leading to a transport system dominated by biofuels, similar trends are seen for (c) and (d) in Fig. 12 compared to the CEP scenario.

4.2. Sectoral interactions

In this section, the results of the allocation of resources in the sectoral development are presented to investigate the sectoral interactions in their long-term development pathways. In the CEP scenario, high penetration of EVs and residential heat pumps is observed, leading to a more than 43 % increase in electricity needs in 2050 compared to 2018. Sector-wise, the share of heat pumps and EVs in the final electricity use is 14.5 % and 25 %, respectively. Similar results are observed for high bio price with base electricity price sensitivity, with electricity use

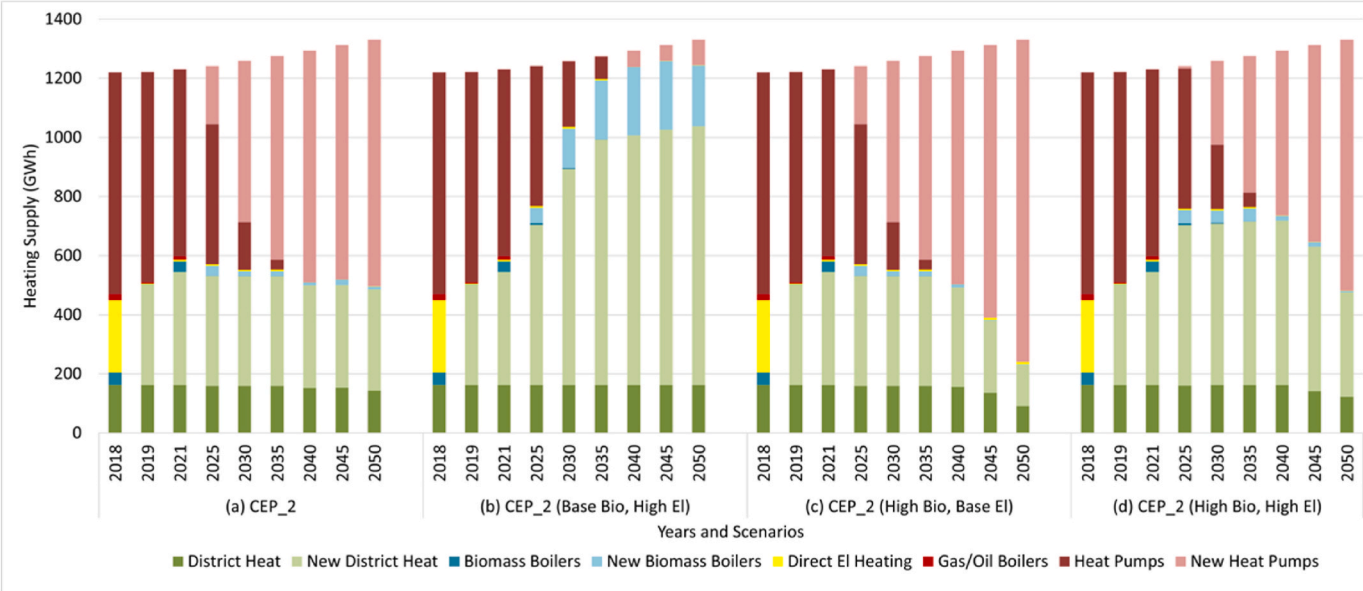

Fig. 10. Heating supply mix for SFH under (a) City energy plans scenario with low available waste heat and historical demand growth followed by three price sensitivities (b) Base Bio, High El, (c) High Bio, High El, (d) High Bio, High El.

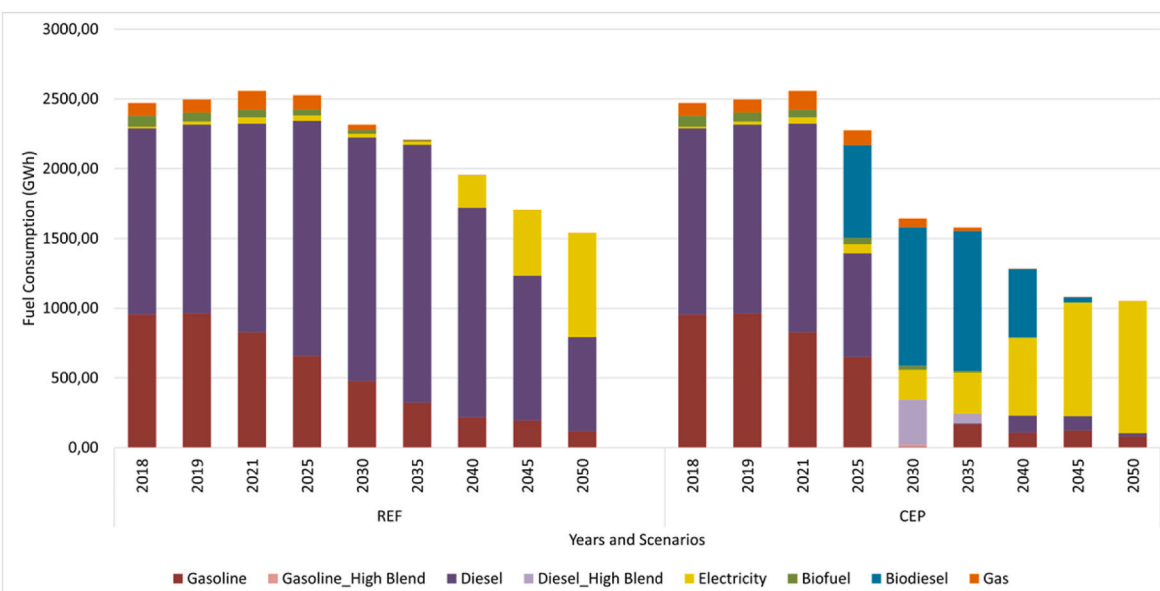

Fig. 11. Fuel consumption for the transport sector under the (a) Reference and (b) City energy plans scenarios.

increasing by 56 % with 19 % and 24 % contribution from heat pumps and EVs, respectively. Fig. 13 presents the development of electricity uses for residential buildings electricity use, residential heat pumps, and passenger cars.

Base bio-price assumptions lead to a future transport system dominated by biofuels with only a small share of electrification, as shown in Fig. 10. Since the heating sector is also dominated by DH production from biomass CHP with no penetration of individual heat pumps, this leads to a significant increase in the demand for biofuels and biomass. Bio-resource utilization could reach up to 4.8 TWh in 2050 compared to 0.9 TWh in 2018, thus putting pressure on the availability of bio-resources. Under the other price assumptions, bio-resource use will increase around 2030 to fulfill the emission reduction targets of the transportation sector but reduce again as electrification becomes a more favorable alternative. Fig. 14 presents the sector-wise growth in the demand for bio-resources under the different price sensitivities within the CEP scenario.

5. Discussion

With the implementation of city energy plans combined with national policy instruments, the results show that biofuels and electrification drive developments in the heating and transportation sectors. The heating sector has historically evolved towards fossil-free heat production and continues to follow the same route in the future in the reference scenario. The city energy plans further contribute to the development of heating systems with improved building stock and complete elimination of fossil fuels. The energy plans' main contribution to emissions mitigation lies in the decarbonization of the transport sector.

Emission constraints must be translated into practical measures to

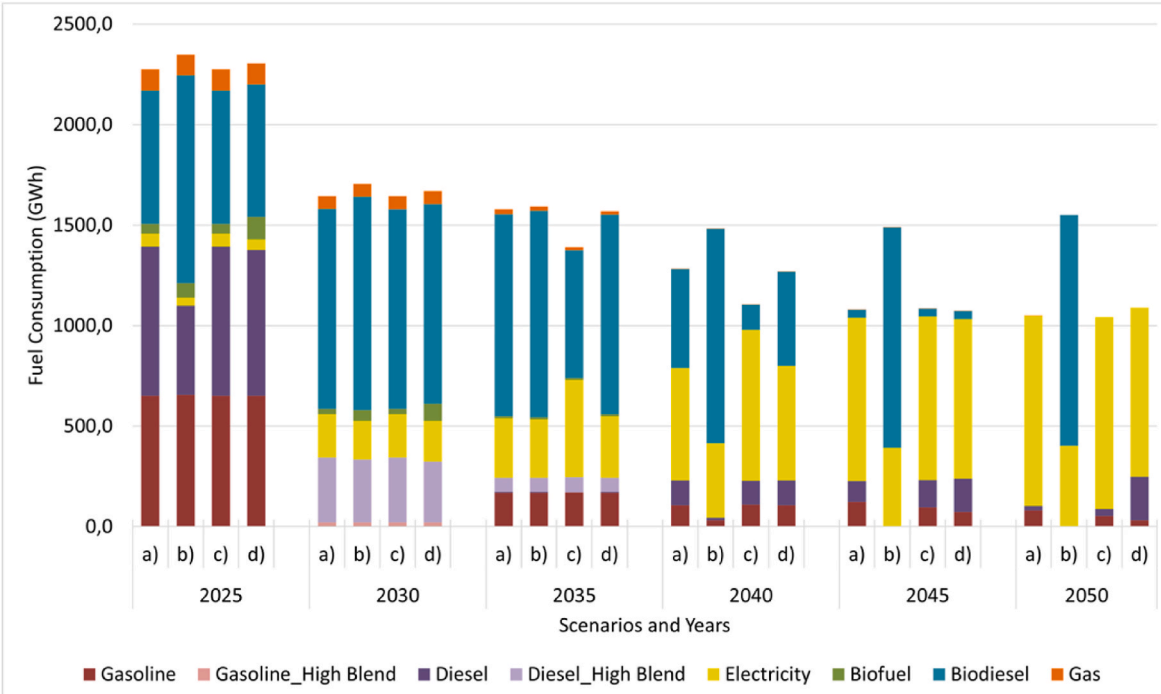

Fig. 12. Fuel consumption for the transport sector with (a) City energy plans along with the three cases of price sensitivities (b) Base BIO, High EL, (c) High BIO, Base EL, and (d) High BIO, High EL.

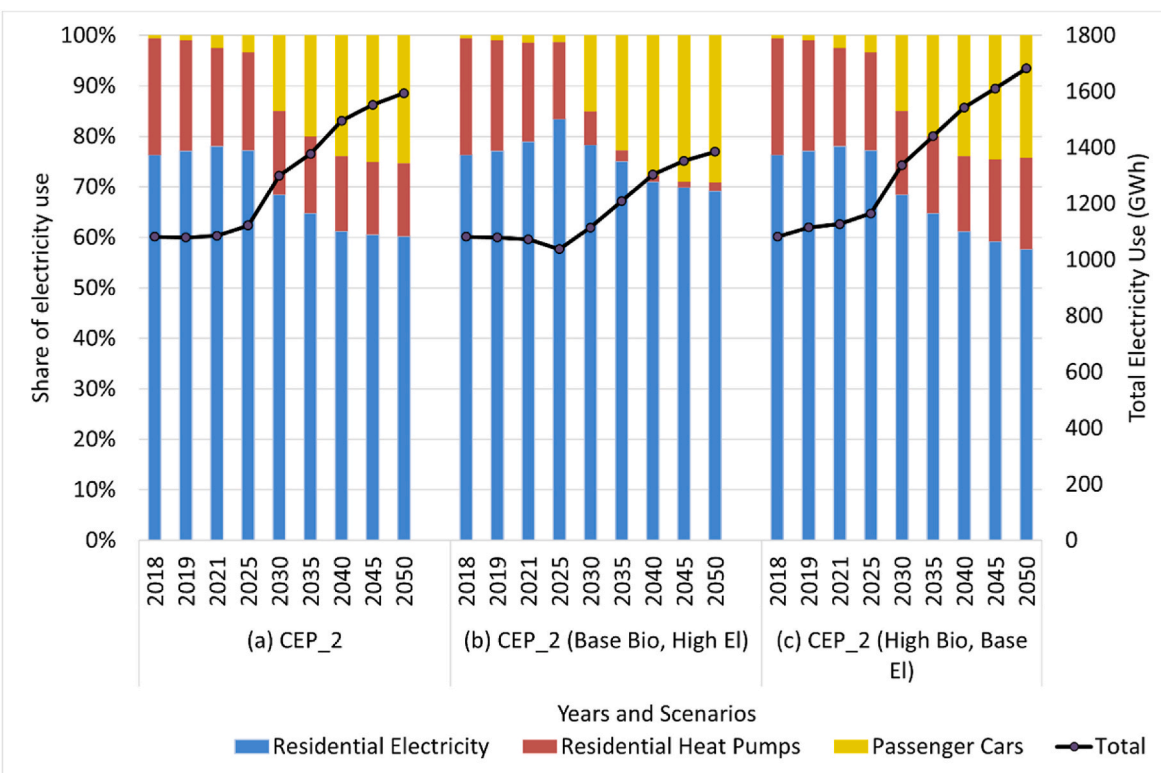

Fig. 13. Electricity use for residential electricity needs, heat pumps, and passenger cars under a) City energy plans with low waste heat and historical demand, along with two cases of price sensitivities, b) Base BIO, High EL, and c) High BIO, Base EL price.

reach the decarbonization of the transportation sector. To reach the emission reduction targets set under the city energy plans, the model outcome shows the extensive deployment of biofuel-based vehicles in the short term, followed by EV penetration. Under the scenario of low biofuel prices, biofuel deployments will continue, apart from passenger cars. While EVs already started becoming economically competitive, further EV deployments depend on investments in charging infrastructure. With the current utilization rates and charging profiles, the

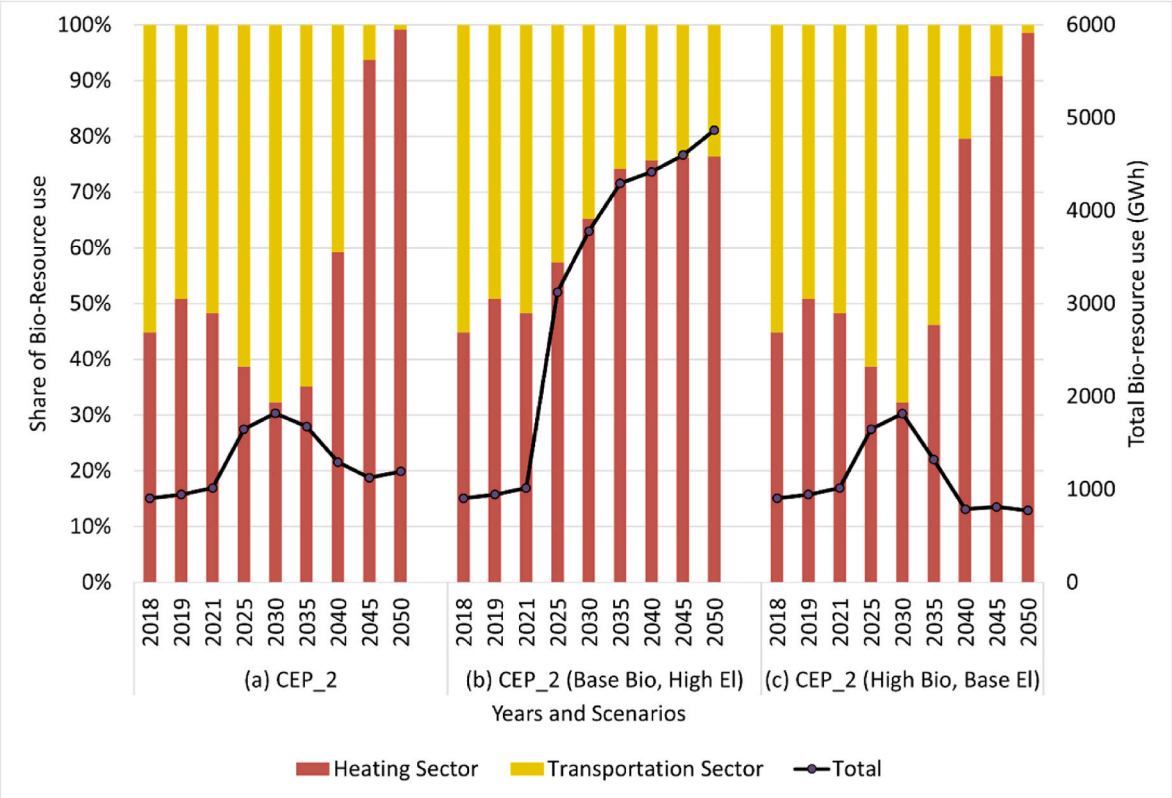

Fig. 14. Bio-resource utilization under a) City energy plans with low waste heat and historical demand, along with two cases of price sensitivities, b) Base BIO, High EL, and c) High BIO, Base EL price.

charging infrastructure has a large share of the levelized cost of charging, thus impacting the economics of EVs, primarily passenger cars [38]. Similarly, the need for additional infrastructure for gas-filling stations makes the deployment of biogas vehicles uneconomical from a systems perspective. Schemes supporting higher infrastructure utilization and flexible charging profiles driven by low electricity prices could be a driving force. To reach the 2030 CEP targets, cost-competitive biofuels are essential in the short term to mitigate transport sector emissions rapidly. Furthermore, transport mode shifting could support the transition in the urban setting by ensuring reduced vehicle kilometers through public transport usage, active transport modes, and shared mobility. However, this option is not fully represented in the model due to the challenges associated with including behavioral changes in modeling work.

From the supply perspective, DH is chosen as a future cost-optimal solution for new MFH. However, in the case of detached housing with spatially dispersed heating demands, the optimal solutions are more sensitive to energy prices. Optimal systems can switch from a high share of DH to an increased deployment of individual heat pumps under different uncertainties. Similar results are observed for new housing connections [55] further validating the model outcome presented in this study. Thus, from a systems perspective, strategies combining a diverse mix of individual and centralized heating solutions are necessary for an optimal heating system under system uncertainties.

As with any other system, Gothenburg's energy system faces uncertainties. Gothenburg DH is fed mainly by heat from waste incineration and refineries. Increasing recycling rates/regulations of waste incineration could reduce the amount of waste available for heating. Also, the decarbonization of the transport sector would significantly reduce the operation of refineries. Considering developments in world biomass markets and historical price developments, constant future biomass prices are improbable. Similarly, electricity prices are highly volatile and determined outside the local energy systems' boundaries, limiting the study's capacity to make estimates on future electricity prices. The assumption of constant future electricity prices could impact the optimality of suggested long-term planning strategies. Hence, scenario development, including uncertainties and sensitivities, provides knowledge and background for complex decisions when designing the future heating supply. System uncertainties and price sensitivities offer alternative strategies to energy planners responsive to the changes in the system.

The model outcome presents insights into the allocation of resources among the sectors in their transition toward carbon neutrality. Increased demand for electricity at the distribution level could significantly increase peak demands, thus exhausting the existing hosting capacity limits. Biomass is also identified as a limiting resource with growing competition among sectors to achieve rapid decarbonization. Comparing alternating pathways with a whole systems perspective is particularly important considering the increasing integration of heating and transport sectors with high shares of biofuels and electrification. Grid reinforcement costs with exogenously fixed technology shares are estimated for a Swiss case study [56]. Hence, incorporating costs for reinforcing distribution grid capacities and demand-elastic fuel prices in long-term planning models would further shed light on inter-sectoral integration accounting for resource allocation. Details on the economic representation for analyzing resource competition among sectors is identified as an avenue for future research.

Apart from the heating and transport sectors, there is an increasing interest in biomass use and electrification in the industrial sector. Industries also present opportunities to supply low-temperature heat into the heating system. The existing model includes aggregated demands for the industrial sector. Adding other urban sector development pathways can provide a broader overview of energy and economic resource allocation in the city energy plans.

Local energy systems, identified as socio-technical systems, are affected by multi-scale aspects, i.e., temporal and spatial scales. The

temporal resolution of the existing model is representative of seasonal variations in the heating system. Due to limited seasonal dependencies, transport and electricity demands are modeled annually. In an integrated approach, including electricity and transport systems, low time resolution can underestimate the importance of variations in the respective sectors. Applying a high temporal scale to account for variations in electricity and transport would be interesting from the perspective of integrated assessment. On the spatial scale, the city is identified as an aggregated region. A significant driver of investment and operational costs is the transmission and distribution system for a DH system. As the results indicate, spatial resolution has a limited impact on heating systems with high linear heat density, representative of an urban heating system [11].

This modeling study enables decision-makers to assess various possible energy system transition strategies and their economic competitiveness. The model outputs provide valuable insights for the urban decision-making process and provide an understanding of the contribution of local short-term policy on long-term decarbonization pathways. Longer lifetimes of assets lead to investment lock-ins, thus making it essential to analyze short-term plans from a system-wide long-term perspective. Without a long-term perspective, investment decisions are beneficial in the short term, contrasting with long-term national climate ambitions. Additionally, it would be crucial to identify the contribution of short-term city plans in achieving long-term national decarbonization targets. While this study does not identify city energy plans' contribution to national targets, it has been identified as an avenue for future research.

The modeling framework is designed to be applied to cities with colder climates and high heating needs, representing a Northern European city. Due to the unique geographical scope of the case study, this study possesses a shortcoming regarding the general applicability of the modeling outcomes. However, with slight structural modifications, the framework could be applied to cities with different energy system designs. Using this framework to investigate the long-term impact of energy plans for cities with different demand and supply compositions would be interesting. It would give essential insights into the versatility of this modeling framework for varied applications.

The study's results are based on a cost-optimization model assuming perfect foresight. Decisions on future investments are solely based on the cost-effectiveness of technologies. However, investment decisions are also influenced by behavioral characteristics and market designs [57]. A shortcoming of this study is the lack of representation of behavioral characteristics. Another shortcoming is associated with the availability of data at the city level. Due to the limited availability of city-specific data, national or global averages have been used to represent technological parameters at the city level. Additionally, the impact of climate change on seasonal temperature variations and its influence on heating demands is excluded from this analysis. In this study, the emission scope is limited to the indirect emissions associated with the utilization of resources for energy end-uses. Within the limited scope of emissions, it is rather complex to account for the impact of applied transition measures on the associated GHG emissions. Hence, analysis of CO_2 emissions is not included in this study.

6. Conclusions

This study evaluates the impact of city energy plans on the long-term development of the city energy system and investigates sectoral interactions in its transition pathways. A methodology based on energy systems optimization modeling was developed, and a set of policy-driven scenarios combined with uncertainties and price sensitivities were applied. With the application of the modeling framework to the city of Gothenburg, the model outcomes provide optimal mixes of technology deployments for long-term energy system development. Sectoral interactions are studied based on the model outcomes on the allocation of resources among the heating, transportation, and electricity sectors.

With the introduction of the CEP scenario, no significant changes are observed in the heating system developments compared to reference scenarios, apart from reduced needs for DH due to applied renovation. However, emission reduction targets set within the CEP lead to rapid, short-term penetration of biofuels in the transport sector, followed by gradual electrification after 2030. With the extension of the CEP scenario with system uncertainties and price sensitivities, different mixes of district heat production and supply solutions are identified as cost-optimal. Under the assumption of constant future bio-resource prices, a large deployment of biomass CHP and penetration of biofuels in transport modes other than passenger cars is observed. In other cases, different mixes of CHPs and heat pumps are observed, thus providing stakeholders with alternating energy systems planning strategies.

From an inter-sectoral perspective, the model outcomes give information on the allocation of electricity and bio-based resources among the heating and transportation sectors. Electricity use in the residential sector, including EVs and heat pumps, could increase up to 56 % in 2050 compared to 2018. Bio-resource utilization could reach up to 4.8 TWh in 2050 compared to 0.9 TWh in 2018 under constant future bioresource price scenarios. Combined sectoral development gives an understanding of the need for strategic planning to ensure efficient resource allocation among sectors.

CRediT authorship contribution statement

Kushagra Gupta: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Kenneth Karlsson:** Methodology, Writing – review & editing, Supervision. **Erik O. Ahlgren:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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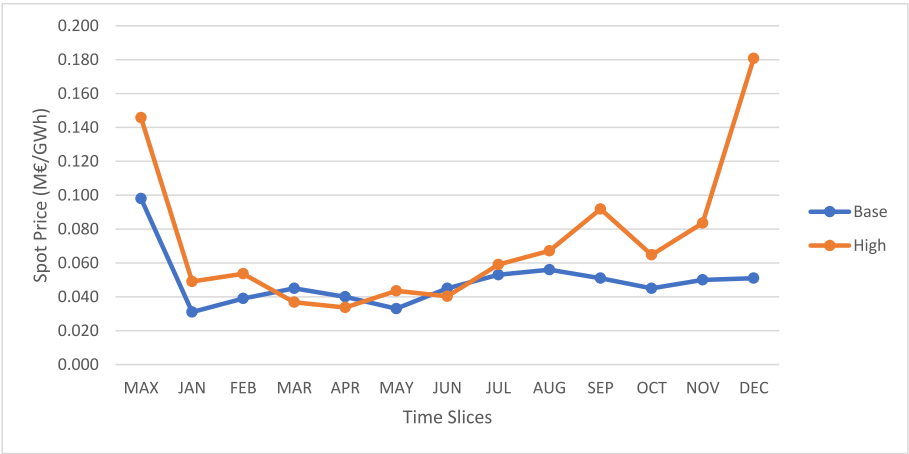
Appendix A

Appendix A provides data sets associated with fuel prices.

Appendix A 1

Electricity prices for SE3 region, along with network price and electricity tax for different customer types.

Customer type	Electricity price		Network price			Electricity tax		
	Base	High	2018	2030	2050	2018	2030	2050
Spot price (Average SE3 region)	0.045	0.066						
Multi-family housing	0.069	0.101	0.021	0.030	0.044	0.032	0.044	0.063
Single family housing w/o Heating	0.060	0.088	0.015	0.020	0.029	0.032	0.044	0.063
Single family housing with heating	0.055	0.081	0.015	0.020	0.029	0.032	0.044	0.063
Commercial	0.045	0.066	0.015	0.020	0.029	0.005	0.005	0.005



Appendix A2 Spot Price profile for the Base and High Electricity Price scenario derived from average monthly electricity price. The base price corresponds to the electricity price and profile of 2018. The high price corresponds to the electricity price and profile of 2021.

Appendix A 3

Price for bio-based resources in M€/GWh. The price for the base year is based on [35] with future reference and high prices based on the author's assumptions with a price increase by 1.5 and 2 times in 2050 for the future reference and high price.

Bio resource	Base	Future (Reference)			Future (High)		
	2018	2030	2040	2050	2030	2040	2050
Biomass (Pellets)	0,029	0,036	0,039	0,043	0,036	0,043	0,057
Biomass (Woodchips)	0,019	0,024	0,027	0,029	0,024	0,029	0,039
Biomass (Residential)	0,067	0,084	0,093	0,101	0,084	0,101	0,135
Biogas	0,025	0,031	0,034	0,037	0,031	0,037	0,050
Biomethane	0,126	0,158	0,173	0,189	0,158	0,189	0,252
Ethanol (E85)	0,125	0,156	0,172	0,188	0,156	0,188	0,250
Biodiesel	0,125	0,156	0,172	0,188	0,156	0,188	0,250

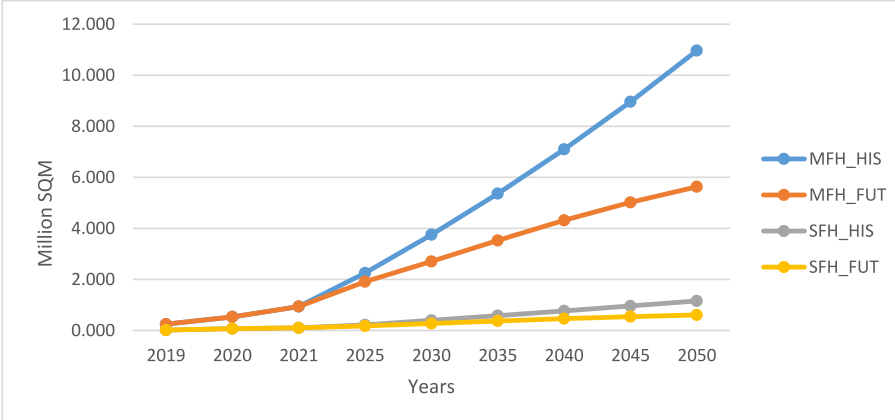
Appendix A 4

Price of fossil fuels in M€/GWh. 2018 prices are based on [35]. Future prices of oil and gas are based on [46], and future prices of diesel and gasoline are based on [39].

Fossil fuels	2018	2030	2040	2050
Oil	0.032	0.055	0.062	0.062
Natural gas	0.023	0.030	0.033	0.033
Gasoline (B5)	0.132	0.156	0.181	0.208
Diesel (B23)	0.116	0.142	0.163	0.183
Gasoline high blend	0.132	0.182	0.235	0.274
Diesel high Bbend	0.116	0.158	0.197	0.230

Appendix B

Appendix B provides data associated with future energy service demand projections.



Appendix B1. Future service demands for MFH and SFH in Million SQM, based on the two adopted methodologies for future demand projections.

Appendix B2

Future assumptions on service demand growth rates for different transport modes based on [49] for passenger transportation and [50] for freight transport for the city of Gothenburg.

Transport sector	Service demand growth rate
Passenger cars	1.10 %
Bus	0.70 %
Heavy freight	1.44 %
Light commercial vehicle	1.68 %

Data availability

Data will be made available on request.

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