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Co-benefits of urban climate action: Leveraging high spatial resolution of cities

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Abstract

Urban climate action can generate multiple co-benefits, however, without accounting for socioeconomic and demographic heterogeneity in their quantification, these benefits may be unequally distributed, reinforcing inequalities and widening existing socioeconomic gaps. This study seeks to estimate the delivery of co-benefits of urban climate action, while investigating the impact of spatial differences on their fair distribution.

An integrated framework linking supply and demand-side systems with socioeconomic data within energy systems modelling is developed and applied to the energy system of Gothenburg, where 147 statistical areas are aggregated into five sub-regions to capture spatial characteristics in TIMES city model. Varying income-dependent hurdle rates are applied to assess co-benefits distribution in terms of resource efficiency, local air pollution, and energy affordability.

Urban resource efficiency improves significantly over time, attributed to improvements in resource use for fulfilling residential buildings and passenger car services. Increased shares of solar PV, electrified heating, energy-efficient buildings and resource efficient district heating contribute to the overall resource efficiency. Passenger transportation efficiency improvements are driven by EVs, while emissions obligations drive independence from fossil fuels. Economic benefits are, however, not equally distributed. Under base and high hurdle rates, more than 15% of households are projected to experience energy burdens exceeding 3% by 2045, compared to around 4% in the base year.

Overall, this study emphasizes the role of accounting for socioeconomic and demographic characteristics at high spatial resolution within cities, using clustering of regional statistical areas to enable analysis on the distributional impacts of urban climate action.

Keywords: Co-benefits, Hurdle rates, Distributional impacts, Regional statistical areas, Urban climate action

1 Introduction

Cities need to mitigate their climate impacts to reach net-zero emissions by mid-century [1]. By taking action to reduce greenhouse gas (GHG) emissions cities can gain multiple co-benefits. Integrating co-benefits into climate action planning at the city level enables cities to address multiple challenges, encourage support from key stakeholders and enhance public acceptance. This can help cities accelerate their climate actions. At the city level, the co-benefits of climate action are highly impactful, as policy measures lead to noticeable improvements in residents' daily lives [2]. Delivering climate actions that also provide other positive outcomes can encourage buy-ins from stakeholders, promote equitable implementation of actions, and provide solutions to multiple city challenges simultaneously and cost-effectively. Furthermore, highlighting co-benefits from climate action as community benefits achieved through mitigation behaviors can be used to motivate the climate change skeptics to adopt mitigation actions [3].

Energy and transportation systems are important to climate change mitigation in cities. Key socio-economic benefits of transitioning to net-zero energy and transportation systems are characterized as security of energy supply, reduced material footprint, increased green employment, reduced cost of living, and health benefits [4]. At the city levels, some of the key co-benefits reported include a shift towards sustainable behaviors, improved resource efficiency, improvements in the quality of air and water, their associated health benefits, and resilient energy systems [5]. However, mitigation actions need to be carefully designed, and their co-benefits quantified; otherwise, they may result in unintended negative consequences and exacerbate inequalities [4,6]. Without adequate financial support mechanisms, low-income households are often unable to afford renovations, or such renovations may place an increased financial burden on their incomes. Another example is that the adoption of electric vehicles (EVs) may increase non-exhaust emissions, potentially leading to higher levels of local air pollution [7]. Decarbonization 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 [8].

Quantifying the co-benefits of local mitigation actions enables cities to make evidence-based decisions about the most appropriate mitigation measures. Health and environmental benefits arising from the decarbonization of the transportation system have been the most assessed co-benefits. When reporting co-benefits, actions from the transportation and agriculture, forestry, and other land-use (AFOLU) sectors were 5-8 times more likely to report health co-benefits compared to other sectors [9]. Applying quantitative modelling to assess the multiple benefits of low-emission transport systems, studies demonstrated that transportation decarbonization measures can achieve substantial air-quality and associated health benefits [10–13]. Another study, investigating the co-benefits of physical activity and improved air quality from a macro-economic perspective,

demonstrated substantial decrease in morbidity and mortality with increased physical activity and reduced pollutant exposures [14]. Additionally, low-carbon passenger transportation actions show further benefits with reduced oil-demands thus increasing energy security of urban systems [15]. In the transportation sector, reducing travel demand can generate significant co-benefits, yielding substantial environmental and economic gains in Chinese cities [16]. More broadly, analyses of cross-sectoral interactions indicate that urban energy exchange strategies coupled with compact urban development can yield significant air-quality–related health benefits, with impacts varying across cities in China [17]. While air quality and associated health co-benefits are well documented in the literature, other benefits of urban climate mitigation remain underrepresented. These include improvements in urban resource efficiency through higher productivity and energy efficiency, as well as enhanced energy affordability and social equity, as mitigation measures are expected to reduce household energy cost burdens.

Urban climate action can deliver significant societal benefits, but climate policies may also have unintended negative consequences. This highlights the importance of a just transition, which calls for the decarbonization of energy systems while ensuring social justice and an equitable distribution of the associated benefits and burdens. Incorporating justice considerations into energy system modelling (ESM) can therefore help inform policymakers and the wider society about how long-term transitions may affect different social groups and how inequalities can be minimized [18]. Previous studies demonstrate the importance of accounting for socioeconomic and demographic heterogeneity at high spatial resolution when assessing the deployment and impacts of decarbonization measures. The spatial representation of the city's demographics was utilized to represent techno-economic parameters based on spatial disparities, with results highlighting the different levels of adoption of decarbonization measures at sub-city levels [19]. A national-level study on the decarbonization of passenger fleet implemented a multi-regional representation of the transportation sector to capture region specific infrastructure characteristics, and consumer heterogeneity, presenting insights into regional diffusion of electric vehicles [20]. Differences in socioeconomic circumstances may expose lower-income households to greater economic burdens from energy and transportation services as cities transition toward decarbonized energy systems [21,22].

A growing body of research has also examined specific dimensions of energy equity, particularly affordability and distributional impacts. Energy burdens, commonly defined as the ratio of household energy expenditure to available income or budget, are increasingly used to assess affordability and identify groups disproportionately affected by energy transitions [23]. Evidence also suggests that ambitious decarbonization policies can generate regressive distributional impacts, disproportionately affect lower-income groups and potentially increase energy inequality across income classes [24]. At the household level, socioeconomic analyses have further identified substantial energy inequities and a significant prevalence of energy poverty, with up to 16% of households affected in some contexts (Scheier & Kittner, 2022). These findings underscore that

the social consequences of decarbonization extend beyond technological deployment and require explicit consideration of how transition costs and benefits are distributed across population groups.

However, there is a gap in the scientific literature investigating how these co-benefits are spatially distributed across in socioeconomic and demographic characteristics [21,22]. Research on urban energy transitions consequently emphasizes that achieving sustainable and inclusive outcomes depends not only on technological advancement but also on policies that explicitly address social equity considerations [25]. Insufficient consideration of social consequences due to socioeconomic differences, such as who bears the burden and who reaps the benefits of climate change, risks reinforcing inequities and widening socioeconomic gaps within urban populations [6,26]. Thus, this study seeks to identify and quantify the principal co-benefits and negative consequences of the implementation of climate mitigation policies and actions at higher spatial resolution within cities, guided by the following research question:

- How do the energy transition measures aimed at achieving climate goals deliver co-benefits beyond emission reductions; and how do socioeconomic and demographic factors shape the distribution of these co-benefits at high spatial resolution?

Cities are often subdivided into smaller statistical units to support more effective administration, planning, and data-driven resource management. This study introduces a methodology for spatial representation of socioeconomic and demographic differences based on existing statistical divisions of the cities to enable sub-city level representation of techno-economic parameters driven by spatial differences. This regional characterization is integrated into an energy systems optimization model to examine the deployment of decarbonization measures and the resulting distribution of co-benefits.

The novelty of this study lies in integrating environmental, social, and economic co-benefits into urban energy systems modelling, with a particular emphasis on their distribution at high spatial resolution. By quantifying the co-benefits of climate-change mitigation actions, the framework enables cities to quantitatively assess the suitability of climate strategies and make informed decisions about which actions deliver fair distribution of benefits, allowing climate action to address multiple urban priorities simultaneously. Such a framework is essential to ensure that decarbonization pathways do not exacerbate existing inequalities but instead create opportunities for inclusive and systemic transformation [27]. Inclusive energy policies that simultaneously address environmental and social dimensions are therefore crucial for ensuring an equitable distribution of transition co-benefits across society [28].

2 Methodology

This study employs an integrated modelling framework that links high-spatial-resolution supply, demand, and socioeconomic databases with policy-oriented long-term energy system planning to investigate the distribution of climate action co-benefits and unintended negative consequences. Regional statistical areas are grouped into sub-regions based on similarities in population density and income levels using a clustering algorithm. Following the clustering, residential building and passenger transport datasets are processed at the sub-regional level to estimate service demands in each area. In addition, supply-side parameter assumptions are guided by sub-regional differences. The resulting database is then used as input for an integrated long-term city energy systems model. Key policy measures are incorporated, and future assumptions are applied to support long-term energy systems planning. With income-dependent hurdle rates, representing socioeconomic disparities, model outcomes are evaluated using key indicators to assess how co-benefits are distributed across the city with the application of policy measures and decarbonization targets. The proposed methodology is graphically illustrated in Figure 1 and described below.

2.1 Socioeconomic and demographic characterization

Statistical divisions of cities are used to capture the city's socioeconomic and demographic characteristics at high spatial resolution. In the first step, regional statistical areas are arranged into a manageable number of groups to enable effective analysis and representation of spatial data in the energy systems model. Clustering techniques are employed to group similar objects based on specified distance measures [29]. The K-Means clustering algorithm is then applied to partition the data into k clusters, grouping the statistical areas into homogeneous sub-regions.

To represent socioeconomic and demographic characteristics, spatial clustering is applied based on population density and average income levels. Population density is calculated using the population and land area of each statistical unit. Total land area can overestimate the inhabited space as it may include uninhabitable features such as parks and lakes. To address this, the intersection between urbanized areas and statistical boundaries are used to estimate the inhabited land area for each unit. Population density is then derived using the population and the adjusted land area. The resulting population density values, together with data on average income by statistical area, are used to cluster the statistical areas into smaller sub-regions.

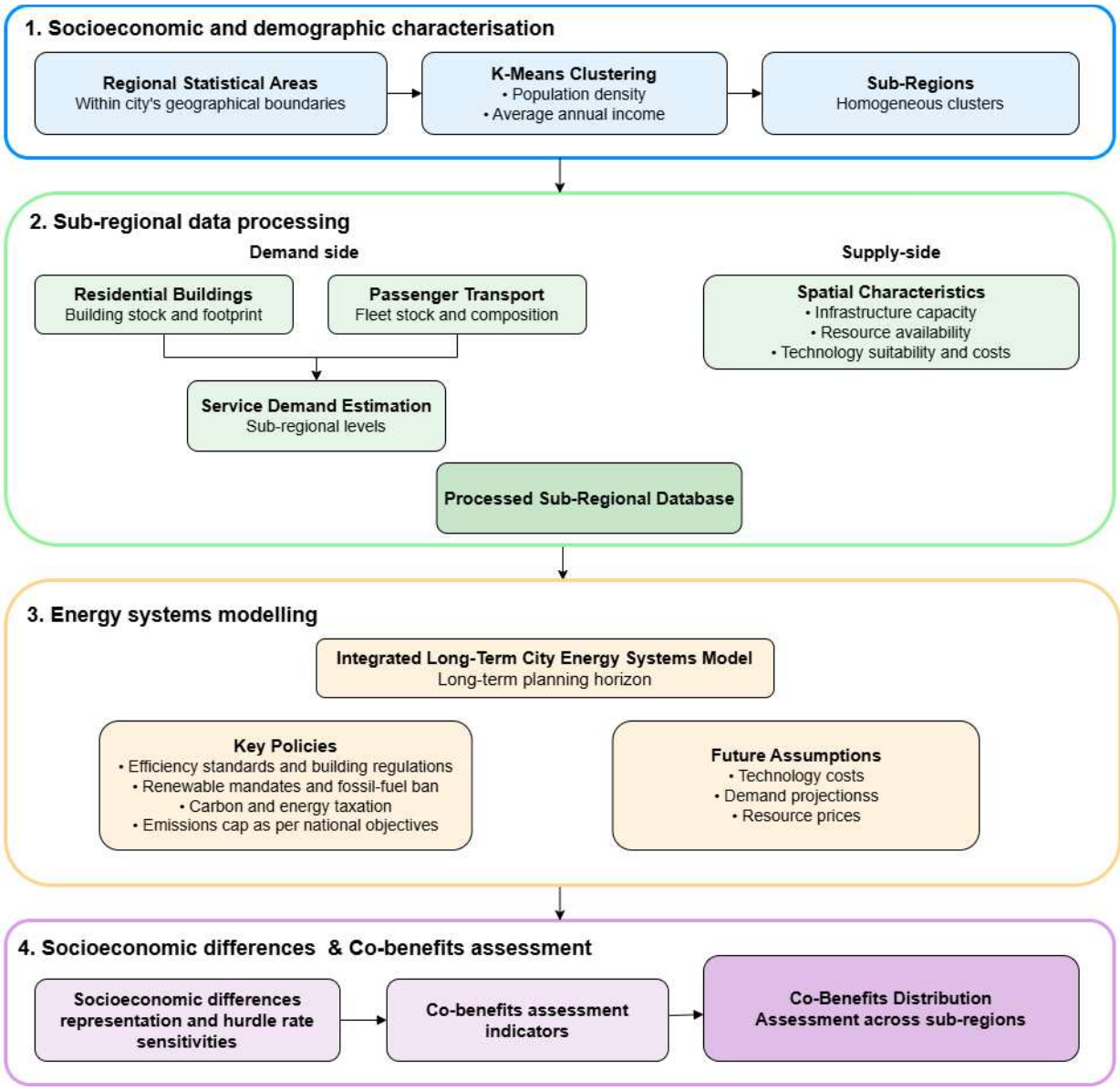


Figure 1: An overview of the workflow for the developed methodological approach.

2.2 Sub-regional data processing

After clustering, regional statistical datasets on residential buildings and passenger transportation are processed to estimate service demands at sub-regional levels. Additionally, techno-economic parameters of key technologies are defined based on spatial differences. Residential building databases include building archetypes and their associated stocks, along with the building footprint. Building archetypes include single family housing (SFH) and multi-family housing (MFH). Passenger transportation databases include total number of registered cars, cars in traffic as well as fleet composition by fuel type.

Dwelling stock by region and average dwelling floor area for SFH, and MFH are used to estimate existing end-use service demand for residential buildings. Service demands for residential buildings are then coupled with specific energy needs to estimate the associated energy needs. Building footprints are used to calculate the rooftop solar photovoltaic (PV) potential. To estimate the footprint for residential buildings, available spatial datasets on the residential building stock are used. Residential buildings by archetype are first allocated to the clustered sub-regions. In the next step, building geometry is utilized to estimate the footprint for SFH and MFH by sub-region. Assuming building footprints represent rooftop area, along with an average fraction of roof space available for PV installations, and average space requirement per MW_e PV, rooftop PV potentials for each sub-region per building archetype are estimated.

Sub-regional data for the passenger car fleet are estimated based on vehicle registry at regional statistical levels. To account for fleet composition by sub-regions, an equal distribution of the fleet stock is assumed for all vehicle types. Furthermore, the annual vehicle activity is highly dependent on the population density and location of different sub-regions compared to the city center [30,31]. Due to differences in population density and location, different levels of annual vehicle activity are assumed.

The supply-side technological parameters defined according to spatial characteristics include the distribution system and the charging infrastructure. The existing electricity grid capacity is estimated based on the base-year peak loads in each sub-region. Network costs for new district heating (DH) networks are dependent on the heat demand density and housing archetype. Based on population density, assumptions on DH network costs are made for connecting SFH and MFH. Finally, electric vehicle charging behavior is represented through user-specific charging profiles, defined by the mix of available charging options and differentiated across sub-regions according to population density and housing composition. User-specific charging profiles include socket user, wall box user, average user and commercial user as defined in the study analyzing the levelized costs of EV charging [32].

2.3 Energy systems modelling

The processed sub-regional database is then integrated into the long-term energy systems planning tool. The TIMES (The Integrated MARKAL-EFOM System) model generator, a long-term cost-optimization model, is used to develop the city energy systems planning tool [33]. The modelling framework is formulated as a linear cost-optimization problem under an assumption of perfect foresight. The objective function of the optimization problem minimizes total system costs over the modelling time horizon (Eq. 1). The social discount rate ($d_{r,y}$), applied to discount future costs and benefits to the base year is calculated using (Eq. 2) to derive the socially optimal solution, based on the OECD report [34].

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

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

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

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

The model includes existing and future energy supply and demand dynamics, while also incorporation existing policy and plans for the long-term development of the city energy system.

2.4 Socioeconomic differences and Co-benefits assessment indicators

The socioeconomic differences at the sub-regional levels are represented through residential consumers' willingness to make new investments. In this respect, varying levels of implicit discount rates are used to reflect residential consumers' income levels. In energy system models, these discount rates, often referred to as technology-specific hurdle rates, are used to represent the range of factors that influence individual investment decisions [35]. These rates are shaped by household preferences, policy environments, uncertainties, and access to financial resources [36].

With the application of socioeconomic differences through hurdle rates and demographic characterization, co-benefits of urban climate action are analyzed through a set of assessment indicators.

2.4.1 Hurdle rates representing socioeconomic differences

Hurdle rates are typically assumed to be inversely correlated with the socio-economic conditions of individual investors. In this context, median hurdle rate is assumed to represent consumers with median income levels, with an inverse relationship between income and hurdle rates used to capture socioeconomic differences at sub-city levels. Eq. 3 estimates hurdle rates' dependence on income levels.

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

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

The magnitude of the relationship between socioeconomics and hurdle rates is not well defined and is shaped by heterogeneous preferences, behavioral responses, and external barriers [36]. As a result, quantifying this proportionality within energy system models remains challenging and relies on simplifying assumptions. Hence, a sensitivity analysis on hurdle rates is conducted with variation in the hurdle rates associated with median income and different proportionality levels associated with hurdle rates dependence on income levels, represented by α values. An α value of 1 indicates a direct inverse proportionality between hurdle rates and income. Values of α greater than 1 imply a stronger dependence on income, which disproportionately favors higher-income groups, while values of α less than 1 indicate weaker income sensitivity.

2.4.2 Co-benefits assessment indicators

Model outcomes are analyzed to examine the development of key indicators and address research questions on the distribution of co-benefits of urban climate action. The key indicators identified to assess co-benefits at the sub-regional level are presented below.

Urban resource efficiency

Cities are major consumers of energy and resources. Urban climate actions targeting renewable energy deployment, demand-side measures, and transportation sector decarbonization are expected to reduce per-capita energy and resource consumption, thereby enhancing urban resource efficiency, and contributing to more secure and resilient energy systems. Improvements in resource efficiency are one of the most reported co-benefits by city authorities and are defined as meeting the urban service needs with lower resource inputs [5]. From the perspective of energy systems analysis, resource inputs to fulfil energy service demands for residential buildings (kWh/m^2), and passenger car transportation (kWh/PKM), are defined as urban resource efficiency. Changes in the urban resource efficiency over the modelling time horizon across sub-regions of the city are investigated to evaluate co-benefits of city-level climate action.

Local air pollution concentrations

The transportation system is a major contributor to GHG emissions and local air pollution in cities [14–16]. With the application of decarbonization measures aimed at reducing the climate impact of the transport sector, transition measures are reported to improve local air quality. In the dense urban context, local air pollution includes direct exhaust emissions from vehicles as well as non-exhaust emissions from road, brake, and tire wear. With high vehicle and fuel standards, the

exhaust emission share is expected to be low, while increased usage of heavier vehicles will significantly contribute to non-exhaust emissions [7]. In this aspect, changes in tailpipe exhaust emissions and average particulate matter (PM) emissions from exhaust and non-exhaust sources are investigated. Tailpipe exhaust emissions include carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). PM emissions include exhaust, road wear, tire wear and brake wear. The local air pollution concentration is measured through changes in exhaust emissions in kilograms/capita, and PM emissions from exhaust and non-exhaust sources in grams/capita. As the population exposure is strongly influenced by the characteristics of a location and can differ between rural areas and urban centers, the co-benefits analysis is therefore limited to relative changes in pollutant emissions. Emission concentrations and population exposure are not included in the analysis.

Energy affordability (Economic efficiency)

Increased energy affordability refers to a lower share of income allocation to pay for energy services. With improved resource efficiency, shifts towards electrification and renewable sources, households' income exposure to energy services is expected to reduce, however, to reduce its climate impacts, certain socioeconomic groups may face higher burdens on their disposable income. In the context of energy equity, energy affordability has been identified as an important indicator to account for the fair distribution of climate action co-benefits [37]. Energy affordability is estimated as the ratio of average annualized cost of energy services and average annual income for each statistical area, accounting for the changes in energy costs relative to income in the long-term planning horizon. The share of income allocated to energy services (%) presents the changing energy affordability over the time horizon with the application of decarbonization measures. Average annual incomes at the RegSO level for the year 2023 are used to assess both current energy affordability and its evolution over time. Detailed description of the adopted methodology to calculate energy affordability is presented in the **Appendix A.1**.

3 Method application to the city of Gothenburg

Sweden has committed to achieving net-zero GHG emissions by 2045 and recognizes municipalities and regions as key actors in its climate efforts. Many local initiatives contribute towards the country's national climate targets [38]. The city of Gothenburg is the second largest city in Sweden and is expected to grow rapidly over the next decades. The city has set ambitious climate goals and adopted environmental and climate programs to reach sustainable emissions by 2030 [39]. Gothenburg also possesses a diverse energy system, with potential to adopt several technological measures to advance decarbonization while enhancing the efficiency and affordability of the energy system. With ambitious climate objectives, coupled with a diverse energy system, Gothenburg has been identified as a suitable case to apply the methodology introduced in Section 2. This study thus builds upon the analysis on policy-based city energy systems planning for the city of Gothenburg [19,40] and investigates spatial distribution of co-benefits with the application of current policies and national decarbonization targets.

3.1 Socioeconomic and demographic characterization

To account for socioeconomic and demographic characterization of the city, RegSO ("Regionala statistikområden": Regional statistical areas) level data was analyzed. RegSO divides Sweden into 3,363 areas, with municipalities divisions varying from 2 to 147 statistical areas [41]. The city of Gothenburg is divided into 147 RegSO. For clustering the RegSO into sub-regions, K-means clustering was applied to the RegSO level population density and income datasets. For the calculation of population density, the intersection of urban areas in Gothenburg and RegSO boundaries were used, and inhabited areas calculated as shown in Figure 2.

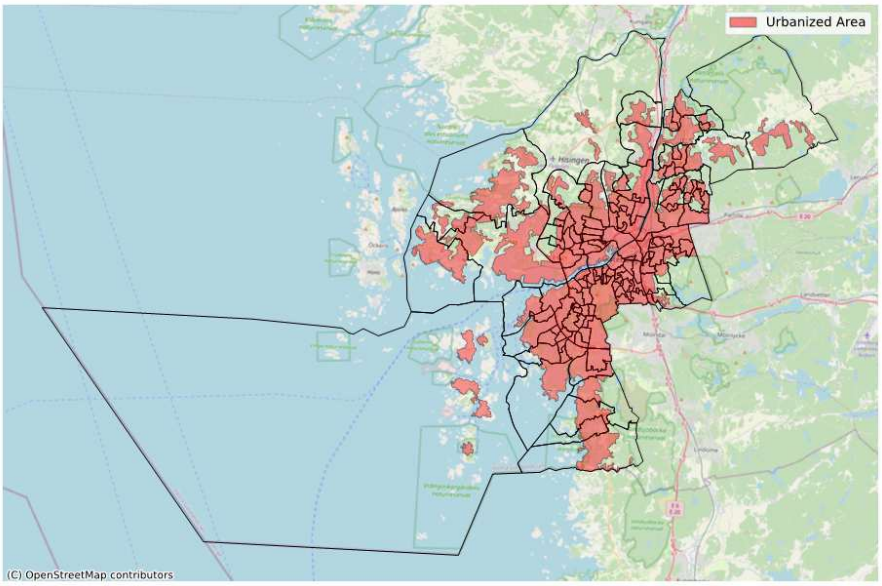


Figure 2: Gothenburg division into 147 RegSO, with the red shades showing the inhabited areas in each RegSO.

Using population by RegSO and calculated urban land area, population density by RegSO was calculated. With population density and average annual income, the 147 areas were clustered into five sub-regions using the K-Means clustering algorithm, grouping the areas with similarities in population density and annual incomes (Figure 3). The graphical output of the clustering is presented in Figure 4 and results presented in Table 1.

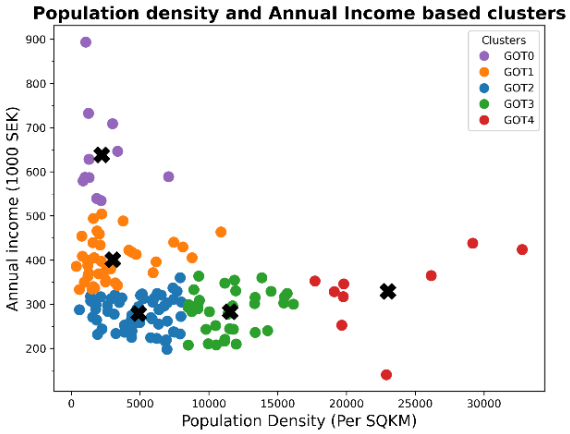


Figure 3: K-Means Clustering of the 147 RegSO, with centroids used to represent population density and average income associated with each of the sub-regions.

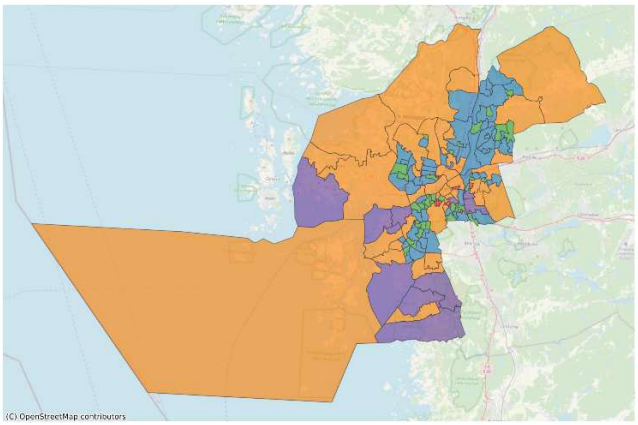


Figure 4: Graphical illustration of grouping the 147 RegSO into five sub-regions with same color coding as shown in Figure 3.

Table 1: Results of the sub-city level clustering with Population density and Average income.

Sub-region	No. of RegSO	Population density (per square kilometers)	Average Income (1000 Swedish Krona per annum)
GOT0	11	2206	638.63
GOT1	37	3024	400.81
GOT2	56	4887	278.90
GOT3	34	11539	283.43
GOT4	9	23011	329.14
Median value		5796	316.7

3.2 Sub-regional data processing and associated assumptions

Upon clustering the RegSO into five sub-regions, key datasets processed include data associated with the residential buildings stock and passenger car fleet to estimate the current and future service demands. Additionally, key technological parameters were characterized at sub-city levels.

Building stock by sub-region was processed using RegSO level buildings and dwellings database [41]. Building footprint was estimated based on Lantmäteriet spatial database on buildings. Database for existing buildings and associated building footprint for 2023 is presented in Figure 5. Key assumptions associated with the buildings stock database for energy and service demand estimations, and rooftop solar PV potential are presented in Table 2. For future projections on

residential building demands, per capita floor space is coupled with historical population growth for each sub-region.

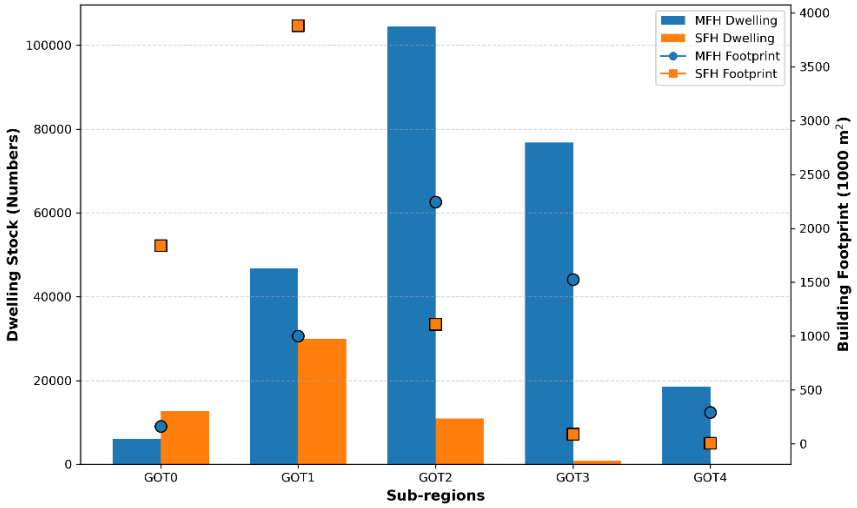


Figure 5: Dwelling stock and building footprint by building archetype for each sub-region.

Table 2: Key assumptions associated with the buildings database to estimate service demands, and rooftop solar PV potential.

Serial Number	Parameter description	Assumptions	Source
1.	Average dwelling floor area (SFH)	127.5 m^2	[41]
2.	Average dwelling floor area (MFH)	65 m^2	[41]
3.	Specific heating energy needs (SFH)	149.625 kWh/m^2/year	(Own estimations)
4.	Specific heating energy needs (MFH)	118.125 kWh/m^2/year	(Own estimations)
3.	Effective roof area for PV Installations	19%	[42]
4.	Space requirements (Irradiance)	5.12 (1000 m^2/MW_e)	[43]

The passenger transportation database includes the total number of cars in traffic by RegSO. Fleet composition by fuel type is available at the city level and equal distribution of fleet stock is assumed for all vehicle types except electric vehicles. Findings from previous work suggest more favorable conditions for EV adoption in the high-income sub-regions with single family housing [19]. Hence, higher shares of EV stock were assumed to be in the GOT0 (18.7%), and GOT1 (14%) sub-regions compared to the city-level (9.35%) EV stock. Vehicle activity is dependent on the population density, and proximity to the city center. Higher population density and proximity to the city center generally leads to reduced car use [30,44,45]. Differences in population density and geographic location were used to assign varying annual vehicle mileages across sub-regions. For the GOT2 sub-region, an average annual mileage of 11,000 kilometers per vehicle is assumed. Activity levels were adjusted relative to GOT2, with 10 percentage-point increases from GOT2 to GOT0 and 10 percentage-point decreases from GOT2 to GOT4. Vehicle fleet composition and

associated annual mileage at sub-regional levels is shown in Figure 6. For future projections of passenger car fleet, per capita fleet per sub-region is coupled with the historical population growth of the associated region.

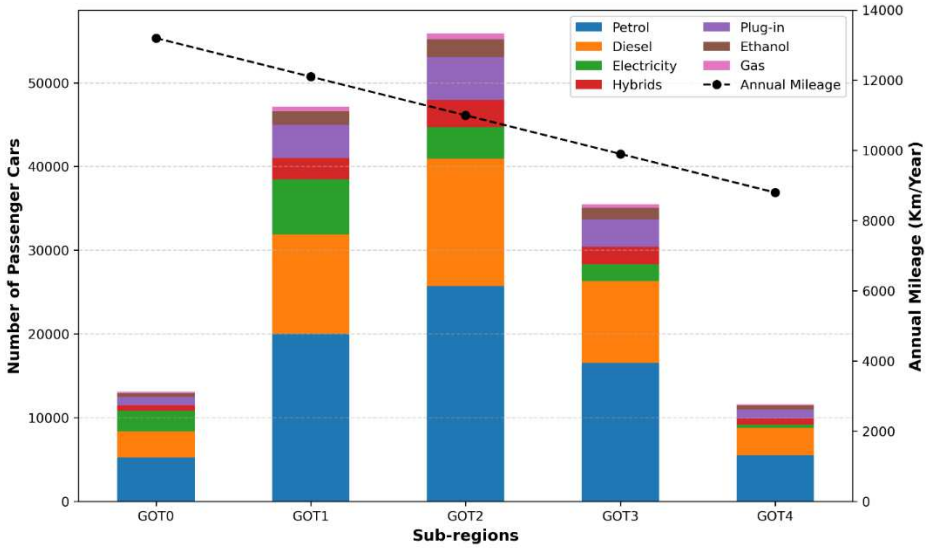


Figure 6: Passenger vehicle fleet number by sub-region on Y axis along with assumptions on annual mileage per car on the secondary Y axis.

3.3 TIMES_NE City model

The TIMES_NE city model was used to investigate the delivery of co-benefits with applied policy measures, and impact of spatial differences on their distribution. The TIMES_NE model is based on the TIMES model generator, representing a northern-European city with high heating and transportation demands. A detailed description of the model development is presented in [40] and the methodology adopted to account of spatial characterization of techno-economic parameters at sub-city levels is presented in [19]. The base year for the model setup is 2023, and modelling time horizon up to 2050 in line with different decarbonization objectives. The time horizon was divided into smaller time periods up to 2030 followed by 5-year periods. Each year was further divided into 12 × 24 time slices to capture seasonal (12) and daily (24) variations. Thus, the temporal resolution is hourly, with one representative day used for each month. The social discount rate ($d_{r,y}$) applied to discount future costs and benefits for the base year, was estimated at 3.5% and calculated using Equation 2 and the following assumptions stated below:

- **δ** was assumed to be 0.5, rate of pure time preference.
- **μ** was assumed 1.26, elasticity of marginal utility.
- **g** was assumed 2-2.5%, average expected growth rate.

The system incorporated in the city model includes energy supply and distribution infrastructure to fulfill the end-use service demands for buildings and road transportation. Supply system includes primary resources and conversion technologies to produce heat and electricity. Heating

systems comprise of centralized heat production facilities as well as individual heating systems for households. Electricity production systems include combined heat and power plants (CHPs) and distributed production using solar PVs. The distribution system comprises a representative low-voltage electricity grid, DH network, infrastructure for transport fuel delivery, including electric vehicle charging facilities and gas-filling stations.

3.4 Policy instruments and future developments

Key policy instruments considered for the long-term development of the city energy system include efficiency standards and building regulations for new buildings, carbon dioxide (CO_2) and energy taxes for the consumption of fuels, and reduction obligations for gasoline and diesel use in the transportation sectors. Furthermore, emissions cap on territorial emissions were applied in line with the Integrated National Energy and Climate Plan of Sweden [38]. Table 3 states the policy instruments included in the analysis.

Table 3: Key policy measures incorporated into the long-term development of the city energy system.

Serial Number	Policy Instruments	Policy Implementation	References
1.	Integrated National Energy and Climate Plan	• 85% reductions in net territorial GHG emissions in 2045 compared to 1990. • 70% reductions in the transport sector emissions (fossil emissions) in 2030 compared to 2010.	[38]
2.	Buildings regulations	• 75 kWh/m² (Multi-Family Housing) • 95 kWh/m² (Single-Family Housing)	[46]
3.	Carbon Dioxide Taxes	CO_2 tax on fossil emissions (134 €/tonne, 2025)	[47]
4.	Energy Taxes	Energy tax on energy commodities, as per Swedish taxation system.	[47]
5.	Reduction obligations	• 7.6% Gasoline, 30.6% Diesel (2023) • 6% Gasoline & Diesel (2024) • 10% Gasoline & Diesel (2025)	[48]

Given the long-term modelling horizon, several assumptions were made to represent the future development of the city's energy system. Assumptions were made associated with the available future technologies along with their investment costs and operational parameters. Technological choices include centralized and decentralized heating options, distributed electricity production using rooftop solar PV, and utility solar PV, alternative fuel vehicles fleet and demand-side measures including building renovations and battery storage.

3.5 Sensitivity analysis of hurdle rate assumptions and income sensitivity

Model runs were conducted with distinct levels of median technology-hurdle rate and α values associated with hurdle rates sensitivity on income levels, coupled with policy instruments stated in Section 3.4. In the base hurdle rate assumption, a median hurdle rate of 12%, and α value of 1 was used. This corresponds to a lower average hurdle rate compared to previous applications, which typically assumed average values in the range of 12–18% [20,49]. Sensitivity analysis on hurdle rates was conducted with high and low hurdle rates with reference to the base case. A policy environment with a high level of policy and economic uncertainties is represented by high hurdle rates, using higher level of median hurdle rate, and $\alpha > 1$. A lower level of median hurdle rate is used to represent more favorable conditions for individual's investment making with $\alpha < 1$, as low hurdle rate case. The different parameters associated with hurdle rates assumptions for different cases are presented in Table 4. Hurdle rates associated with different sub-regions of the city of Gothenburg are presented in Figure 7. In addition to the hurdle rates, annual deployment levels of buildings renovations and rooftop PV were also fixed for each model run to 3% annual deployment of the estimated potential.

Table 4: Hurdle rate assumptions and income sensitivity. The changes in hurdle rates from high to low case, are representative of improvements in willingness to make new investments, policy effectiveness, and sustainable behaviors.

- Willingness to make new investments (socio-economic conditions)
- Policy effectiveness
- Sustainable behaviors



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

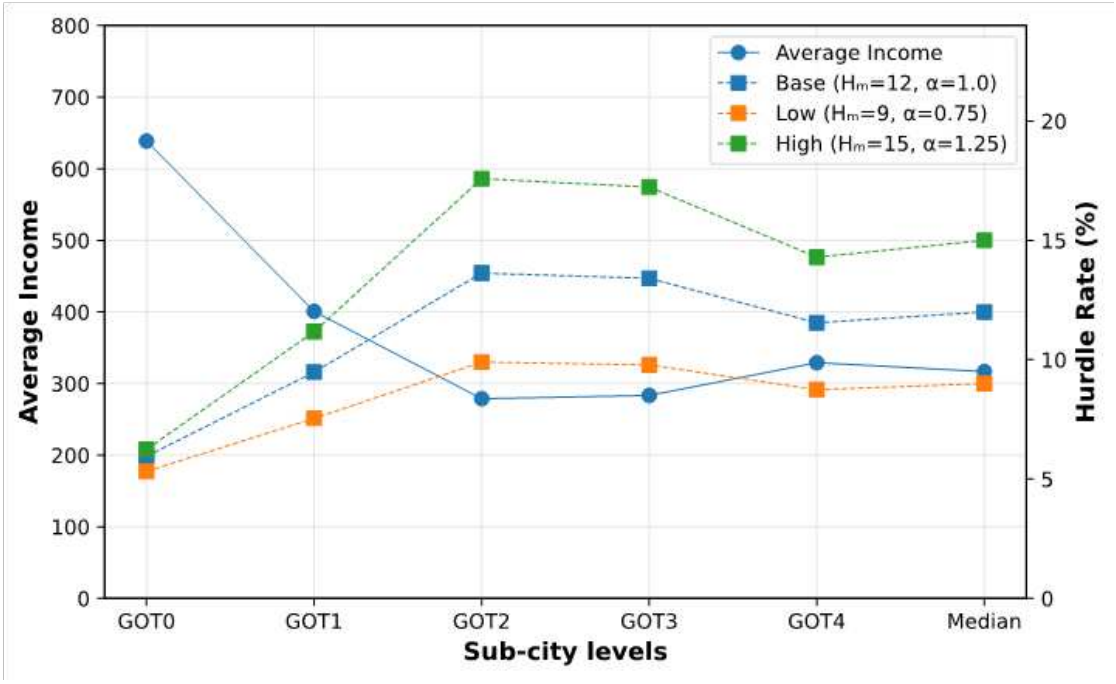


Figure 7: Median hurdle rates and their dependence on the average income for the different sub-regions in Gothenburg under the three hurdle rate assumptions.

4 Results and analysis

This section presents how implementation of city energy systems transition measures delivers co-benefits beyond the binding emission reduction targets to achieve the national climate goals. Section 4.1 presents the improvements in urban resource efficiency for residential buildings and passenger transportation over the modelling time horizon across the sub-regions for the base hurdle rate case. Relative changes in the local air pollutant concentrations with the adoption of transportation sector decarbonization measures are presented in Section 4.2 considering the base case. Section 4.3 highlights the impact of changing system development aligned with national decarbonization targets on the affordability of energy services for the base case and sensitivity analysis with high and low hurdle rate assumptions.

Urban resource efficiency developments are presented in per unit of service demands, and local air pollutant concentration changes are presented on a per-capita basis. Service demand at sub-regional levels is different for GOT0-4, based on existing database on per-capita dwelling stock, cars per-capita, floor space by dwelling type and assumptions on passenger activity. For a better understanding of the city-wide impact of sub-regional changes in the co-benefit assessment indicators, Table 5 presents service demands on a per-capita basis, as well as population by sub-region. GOT0, with the largest share of SFH, has the highest per capita floor space followed by GOT4. Passenger activity gradually decreases between GOT0 and GOT4, derived by per capita fleet share ranging from 0.38 to 0.21 cars per capita and assumptions on changing vehicle activity driven by population density (Figure 6).

Table 5: Per capita service demands for residential buildings and passenger car transportation and population at sub-regional levels.

Service demands	**GOT0**	**GOT1**	**GOT2**	**GOT3**	**GOT4**
Building floor area (m^2/capita)	41.35	39.40	35.5	34.83	40.14
Passenger car activity (1000 PKM/capita)	7.88	6.2	4.43	4.14	2.88
Population, 2023	47528	166352	219550	141998	29188

4.1 Urban resource efficiency

With the adoption of transition measures aimed at decarbonization of residential buildings energy use, the energy required to meet building service demands gradually decreases, thereby contributing to improved urban resource efficiency. The trend of improvements in buildings' resource efficiency is driven by the combined effect of electrified heating (heat pumps), energy efficiency building renovations for MFH, and new construction based on building regulations. Increased electricity production with rooftop PV production also reduces the need for grid electricity, while battery deployments help with reduced peak loads. Furthermore, DH production

in the city is estimated to be highly resource efficient, based on centralized heat pumps, and waste heat recovery.

Overall, building energy use comprises grid electricity for heating and electricity, DH use for heating, electricity produced using rooftop PV and peak load balancing with battery storage. In 2025, energy use per square meters of floor space ranged from 127 kWh/m2 in GOT0 to 159 kWh/m2 in GOT3. With 70% single-family houses using heat pumps in Sweden, sub-regions with high SFH shares have lower energy inputs per m2 of floor space. By 2045, buildings' energy use reduces by 27.5% in GOT4, to a minimum 11% improvements in the GOT2 sub-region. Apart from the highly dense sub-region GOT4, electrification of heating is the primary driver of improvements in building energy use. In GOT4, however, building renovations play a more dominant role in driving efficiency gains. Figure 8 shows the development of residential buildings energy use over the modelling time horizon for different parts of the city under the base hurdle rate assumption.

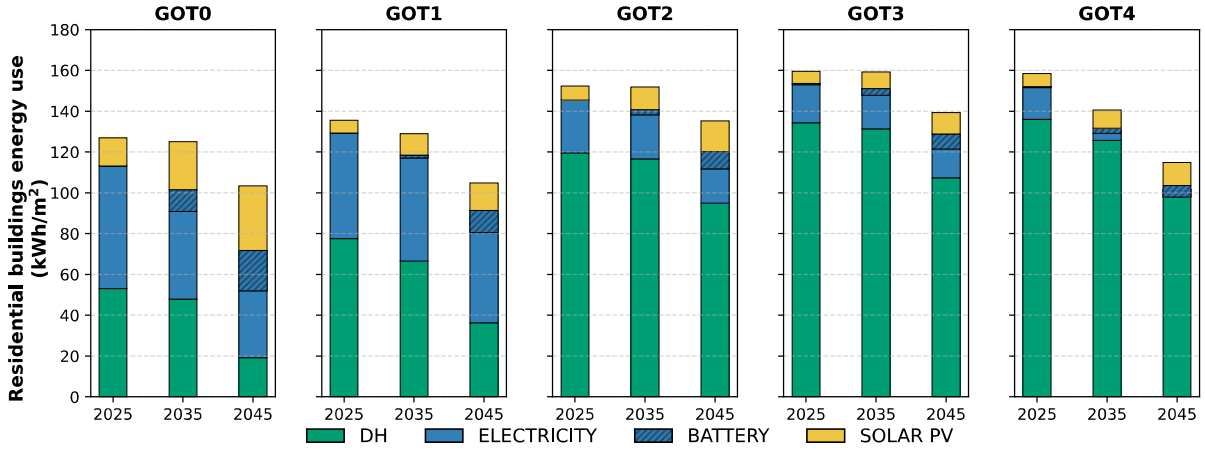


Figure 8: Energy use per unit service demand for residential buildings (m^2 of floor space) for each sub-region for the Base hurdle rates.

Different levels of adoption of measures contributing to improved overall urban resource efficiency are impacted by the spatial characterization of technological parameters, coupled with hurdle rates representative of socioeconomic differences. Between 2025 and 2045, significant developments are estimated for all sub-regions. In GOT0, electricity end-use increases from 72 kWh/m2 to 84 kWh/m2, driven by increased electrified heating, with solar PV share increasing from 16% to 42%. At the same time, DH use decreases from 54 kWh/m2 to 19 kWh/m2. Similar changes are observed in GOT1. In the regions GOT2, 11% improvements are observed, attributed to the use of heat pumps, however high hurdle rates limit the adoption of buildings renovation. In GOT3, both electrification and building renovation drive improvements, whereas in GOT4 the largest gains are primarily attributable to building renovations. The deployment of measures that improve buildings energy use are impacted by spatial differences in demographic characteristics, while adoption in lower-income regions is constrained by high upfront investment barriers.

Resources used to fulfil passenger car service demands significant change over time, driven by bounds on GHG emissions and economic competitiveness of electric vehicles (EVs). Fleet electrification and improvements in the fuel efficiency of conventional vehicles deliver the co-benefit of improved urban resource efficiency. Additionally, the use of fuels with high biofuel blending to meet emission targets gradually reduces fossil fuel dependence, followed by complete electrification by 2045.

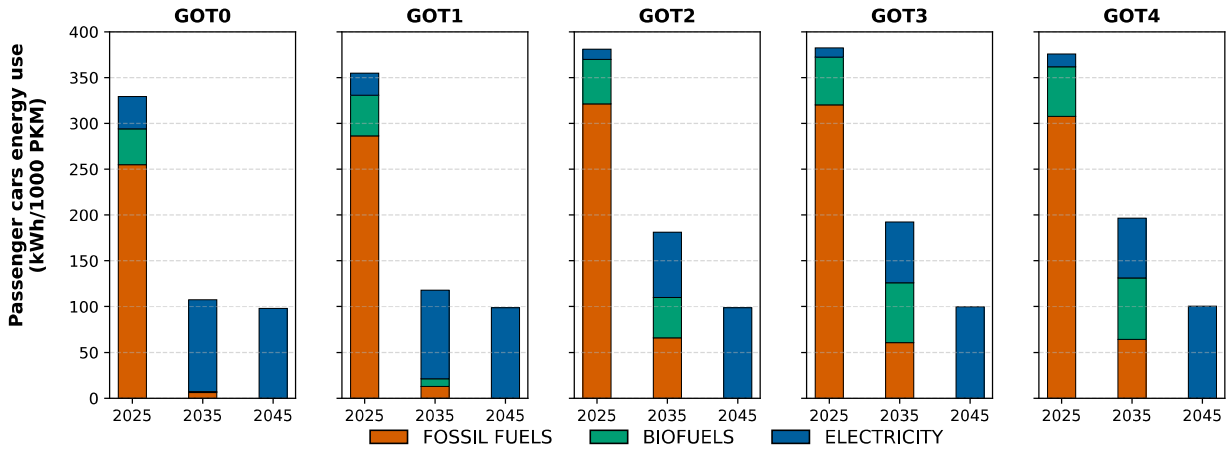


Figure 9: Energy use per unit service demand for passenger cars (1000 passenger kilometers) for each sub-region for the Base hurdle rates.

Resource efficiency developments at sub-city levels are largely impacted by economic conditions, along with impacts on operational costs due to differences in population density and housing types. GOT0 and GOT1 exhibit the fastest electrification rates, with all new cars being electric in GOT0 in the first future modelling year (2027). New EVs start appearing in 2035 for all sub-regions, as EV investments reach parity with conventional vehicles. In 2045, 100% of the city's car fleet is expected to be electrified. In the GOT2-4 sub-regions, higher barriers to upfront investments coupled with higher operational costs due to their charging profiles, slow down the electrification of passenger cars, with large share of fossil fuel and biofuel use in the intermediate years. The transition toward electrification and biofuels significantly reduces dependence on oil imports, with fossil fuel use declining by approximately 85% by 2035 compared to 2025 and being fully eliminated by 2045, thereby enhancing resilience to external market shocks. Figure 9 presents the changing resource efficiency and resource use for passenger cars under the base hurdle rate assumptions, from 2025 to 2050 across sub-regions of the city.

To comply with the decarbonization targets, households with lower income levels face higher barriers to investments in EVs and are driven towards biofuel adoption despite their higher expected costs due to competition for limited bio-resources. In addition to the investment costs, investment decisions are impacted by the associated operational costs. Sub-regions with high shares of SFH have higher incomes (lower investment barriers) and infrastructure for in-house charging, as opposed to the high-density regions, which are more dependent on commercial charging infrastructure. With assumptions on different charging profiles based on population

density and housing composition, levelized cost of charging increase as we move from regions with high shares of individual housing to apartments.

4.2 Local air pollutant concentrations

In the base hurdle rate assumptions, tailpipe exhaust emissions per capita follow a steep downward trend only in the sub-regions exhibiting the fastest rates of fleet electrification. Trends in relative emission changes are aligned with the evolving energy mix for transportation services, as shown in Figure 9. Tailpipe exhaust emissions decline to negligible levels from GOT0 and GOT1 by 2035, because of complete electrification of passenger cars. In GOT2-4 sub-regions, the delayed fleet electrification leads to relatively higher emissions, with reductions attributed to partial electrification and reduced CO emissions primarily driven by shifting from gasoline to hi-biofuel blend diesel fuel to meet the climate objectives. Changes in the per capita contribution to tailpipe air pollutant emissions with base hurdle rate assumptions across sub-regions are presented in Figure 10.

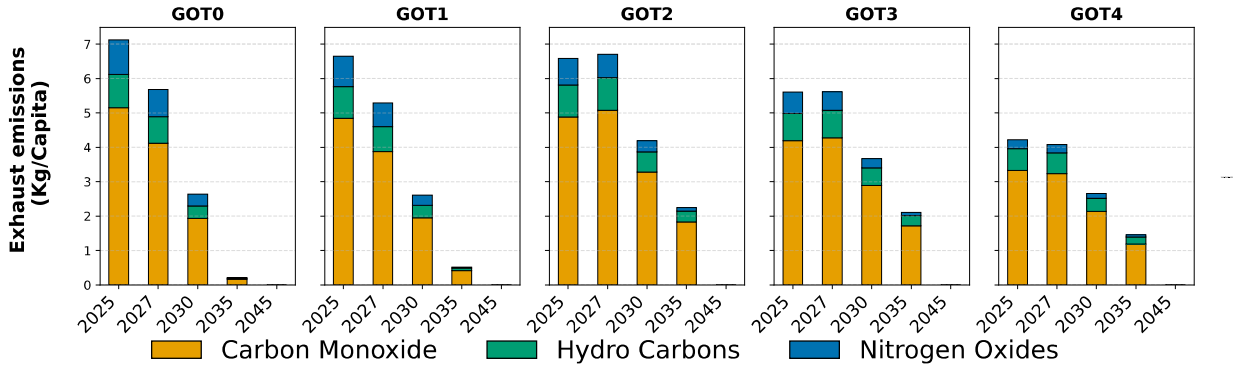


Figure 10: Tailpipe emissions associated with passenger car activity for different sub-regions under the base case, high and low hurdle rate sensitivity on per capita basis.

Over time, PM emissions are expected to persist in the city, as urban climate actions alone are unlikely to deliver benefits associated with reduction of PM concentrations, unless mitigation strategies also incorporate reduced vehicle activity and promote adoption of active transportation modes. Most PM emissions today originate from non-exhaust sources rather than tailpipe emissions and are largely dependent on vehicle activity rather than fleet composition. Vehicle activity associated with GOT0 is the largest contributor to PM emissions followed by GOT1-4. At the sub-regional level, differences in non-exhaust PM emissions can be attributed to per-capita passenger activity across sub-regions as shown in Table 5. While fleet electrification contributes to reduced PM emissions due to regenerative braking, higher vehicle curb weights of EVs compared to conventional vehicles may lead to increase in road and tire wear. Per-capita PM emission contributions from passenger car activity across sub-regions is presented in Figure 11..

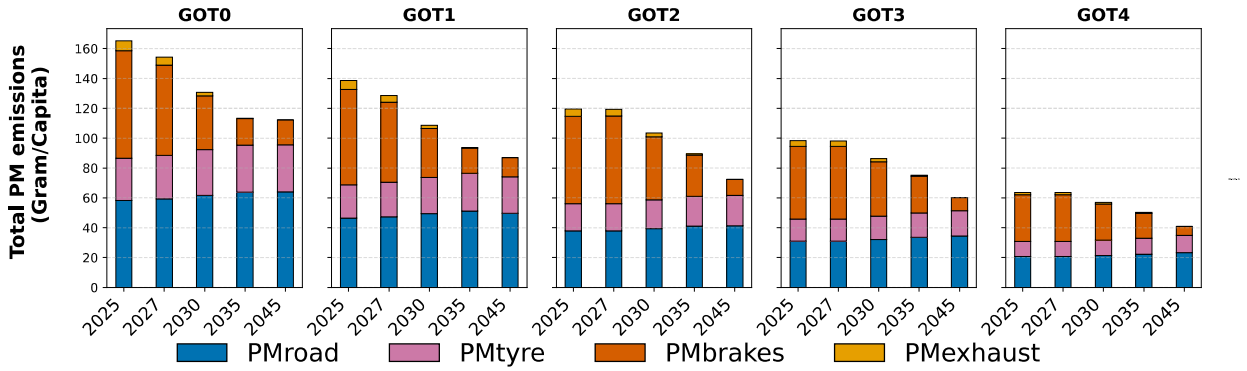


Figure 11: Particulate matter (average) emissions from exhaust as well as non-exhaust emission sources associated with passenger car activity for different sub-regions under the base case, high and low hurdle rate sensitivity on per capita basis.

4.3 Energy affordability

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

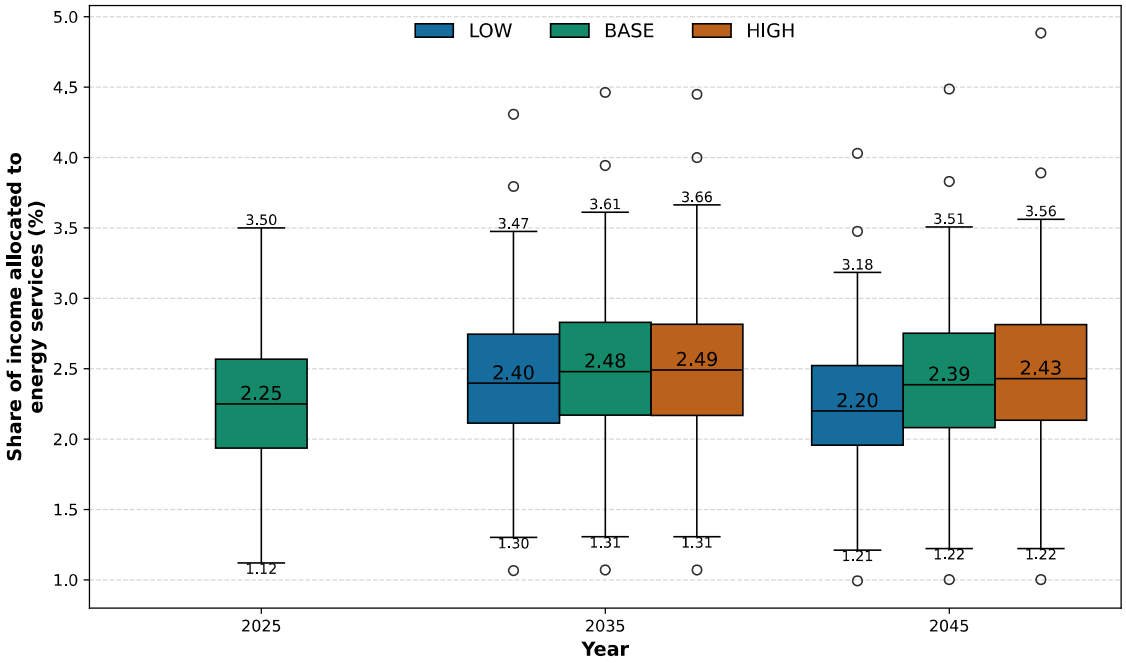


*Figure 12: Share of income utilized to fulfil the energy service demands in 2025, along with income allocation for the low, base, and high hurdle rates in 2030 and 2045. The box represents the interquartile range (25th–75th percentile), with the central line indicating the median. Whiskers extend to the minimum and maximum values (1.5*Inter-quantile range), including outliers.*

In the base year, shares of income allocated to energy services ranged from 1.1% to 3.5%. Higher hurdle rates prioritize upfront investment costs over long-term operational benefits when identifying cost-optimal solutions. Additionally, hurdle-rates influence the decisions of lower-income households more than those of higher-income households. In all cases, increased energy costs are observed in the intermediate year 2035. On progressing towards 2045, median income allocation increases by 6% and 8% respectively for the base and high hurdle rates, while it decreases by 2.2% in the case of low hurdle rates. Furthermore, outliers exceeding an income allocation of approximately 4–4.5% are observed in the dataset, indicating an increased financial burden for certain RegSOs. At the city level, the share of the population experiencing an energy burden exceeding 3% increases from 4.1% in 2025 to 15% by 2045 in under high hurdle rate assumptions. In contrast, under low hurdle rate assumptions, the proportion of the population allocating more than 3% of income to energy remains stable at around 4%. Policy environments that support investments in decarbonization measures with higher upfront cost premiums can enhance overall energy affordability by prioritizing long-term operational cost savings. The annualized cost of energy services as a share of annual income for the Year 2025, and the impact of changing resource use on energy affordability and its distribution over the different statistical areas is shown in Figure 12 for all hurdle rate assumptions.

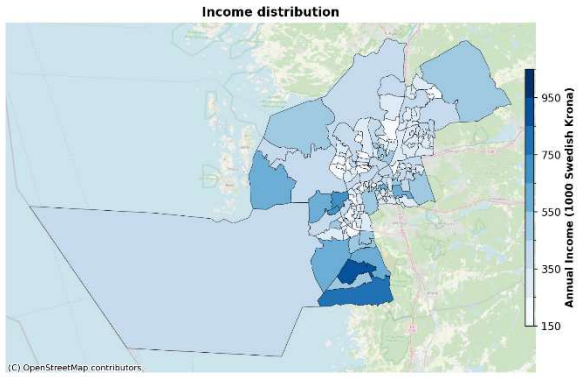


Figure 13: Income distribution by RegSO in Gothenburg, representing average annual income in Year 2023.

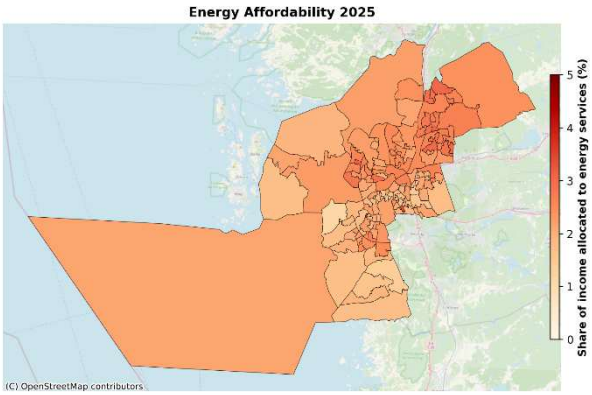


Figure 14: Spatial distribution of the share of income allocated to energy services across RegSO in Gothenburg, in the base case for the Year 2025.

Figure 13 presents the annual income distribution across RegSO in Gothenburg, and the associated spatial distribution of income allocated to energy services (%) for 2025 is presented in Figure 14. While the income range is significantly large, the distribution of energy burden lies within a smaller range between 1.1% to 3.5%. Higher income groups utilize higher per capita resources thus leading to higher initial costs. It is therefore relevant to examine how energy burdens evolve over time across different income groups, both in the intermediate year 2035 and upon reaching national net-zero targets in 2045.

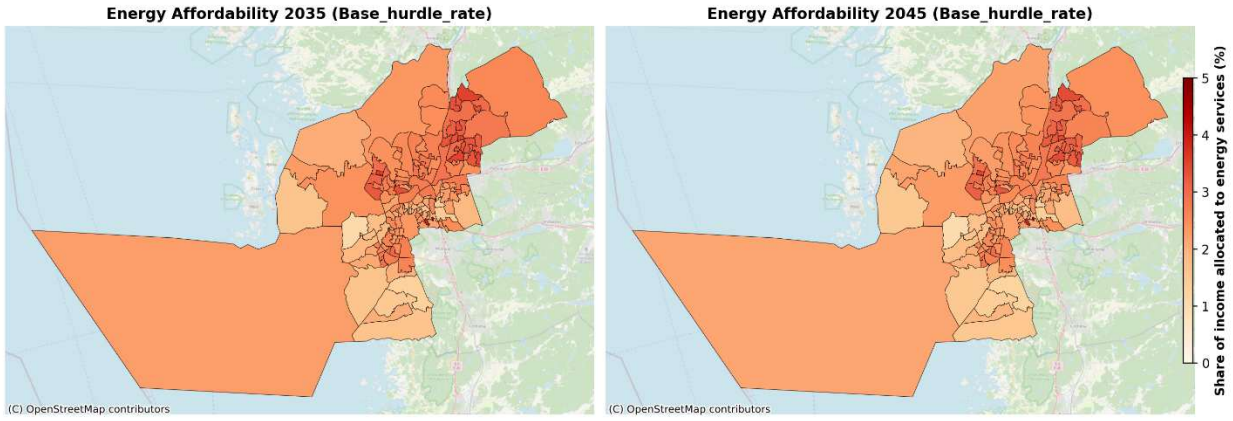


Figure 15: Spatial distribution of the share of income allocated to energy services across RegSO in Gothenburg, under the base hurdle rate case for the Year 2035 and Year 2045.

In the base case, increased energy costs are observed for all RegSO in the intermediate year 2035. On progressing towards 2045, areas associated with the GOT2 sub-region are estimated to be facing higher costs, while the costs are estimated to reduce especially for the RegSO associated with GOT0-1 sub-regions. Compared to 7 RegSOs in 2025, 21 RegSOs face energy burden more than 3%. Spatial distribution of share of income allocated to energy services for the base hurdle rates are presented in Figure 15. Similar trends observed under the high hurdle rates, but with larger increase in energy costs as depicted by darker shades on low-income groups, (Figure 16),

accounting for 23 RegSO facing higher energy burden. At the city scale, energy system transformation may appear to reduce household energy expenditures, however its distributional effects are uneven. While some regions benefit from additional co-benefits of climate action, others are projected to experience increasing financial burden on their incomes.

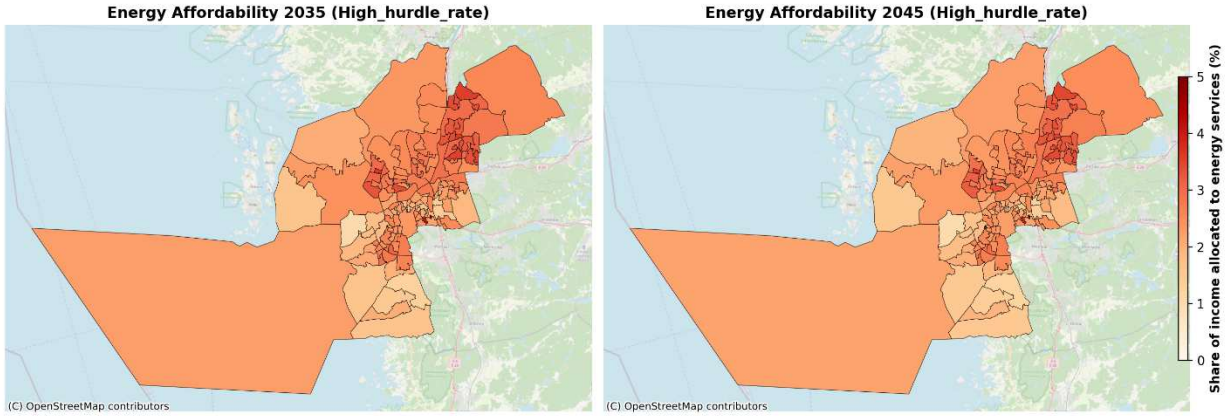


Figure 16: Spatial distribution of the share of income allocated to energy services across RegSO in Gothenburg, under the high hurdle rate case for the Year 2035 and Year 2045.

As depicted in Figure 12, under low hurdle rates, the inter-quartile range is estimated to narrow from 2025 to 2045 and median value is lowered. In this case, co-benefits of climate action are expected to be enjoyed by the majority of RegSO, with 7 RegSO facing more than 3% burdens Spatial distribution of share of income allocated to energy services for the low hurdle rates are presented in Figure 17.

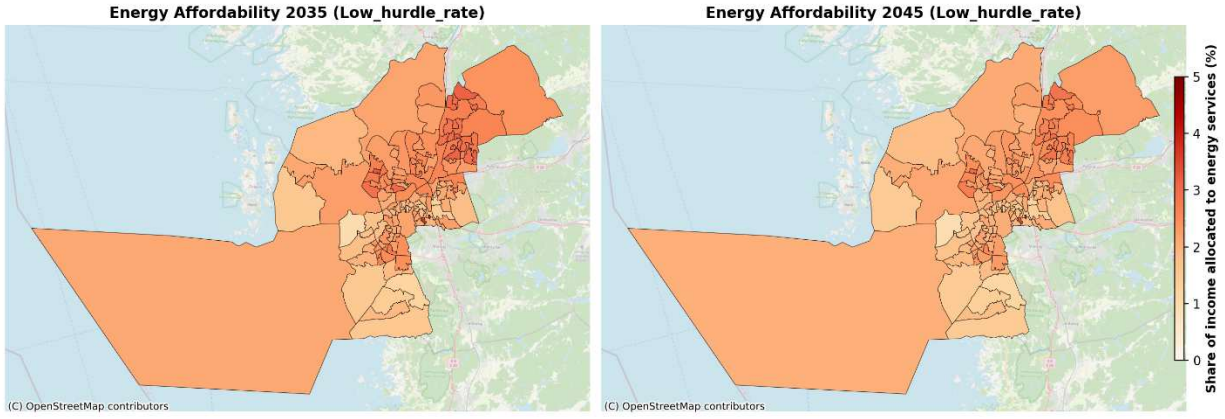


Figure 17: Spatial distribution of the share of income allocated to energy services across RegSOs in Gothenburg under the low hurdle rate case for the Year 2035 and Year 2045.

5 Discussion

This study emphasizes the importance of socioeconomic and demographic differences at high spatial resolution in long-term energy systems planning. It enables the assessment of distributional impacts of urban climate action across socioeconomic groups, supporting equity-oriented approach. With bounds on greenhouse gas emissions in line with the national decarbonization targets, and using income dependent hurdle rates to reflect socioeconomic differences across the city, the results indicate system wide benefits such as improved resource efficiency and associated resilience through reduced dependence on imported fossil fuels, improvements in local air quality, while certain socioeconomic groups experience disproportionately higher income burdens associated with energy service provision.

Resource efficiency improvements in residential buildings are observed through increased shares of distributed solar PV, renovations and building regulations, load shifting through battery storage, and deployment of heat pumps. Local DH production is expected to be highly resource efficient, primarily due to the use of centralized heat pumps and waste heat recovery, consistent with findings from previous studies investigating the operation of the city's future DH system [50,51]. System-level developments in the building sector are primarily driven by housing composition, population density and socioeconomic situations across sub-regions. Choice of decarbonization measures is driven by demographic characteristics; level of resource efficiency improvements is directly correlated to the income levels. Given that heating and electricity are already highly decarbonized, improvements in resource use are influenced less by climate targets and more by the increasing economic competitiveness of alternative measures. Transportation sector resource use developments are primarily driven by increasing penetration of electric vehicles and high biofuel blending. Fossil fuel use in passenger cars in the city is estimated to be reduced by more than 85% by 2035, with the remaining consumption concentrated in sub-regions where conditions for electric vehicle (EV) adoption are less favorable Complete phase-out is projected by 2045, aligning with national short-term climate targets and the net-zero objective. Through findings on lower resource input per unit floor space, and reduced reliance on oil imports, improvements in urban resource efficiency are estimated to contribute to enhanced systemic resilience and energy security, and reduced dependence on external market mechanisms.

Technology-specific hurdle rates are used to represent consumer investment behavior shaped by socioeconomic differences, and policy environment across the city. Previous studies have adopted similar approaches to represent consumer behavior at the national scale [20,36]. Hurdle rate variations impact investment decisions particularly on electric vehicles due to their high upfront costs. High upfront costs constrain adoption in lower-income areas; consequently, adhering to decarbonization objectives in these contexts leads to greater reliance on biofuels to meet passenger service demands. Furthermore, charging profiles in such areas comprising large shares of commercial charging increases the operating cost of electric vehicles. Households in low-income,

high-density areas are likely to face greater challenges in adopting fleet electrification as a transition pathway unless electric vehicles reach price parity with conventional vehicles, thereby delaying their ability to benefit from the lower operational costs of EVs. Favorable conditions of EV adoption in certain parts of the city have led to rapidly increasing shares of new EVs, however the market penetration may slow down once large share of high-income single-family households have already electrified their fleet. This study highlights the importance of representing diverse consumer groups shaped by spatial income disparities when analyzing different dimensions of the transport system transition. Projections of future market shares and charging demand based solely on historical trends may provide misleading insights, considering the differences between early adopters and future EV owners. The Swedish climate policy council (2025) also reports that the pace of electrification in Sweden during 2023–2024 has been slower than projected by government estimates [48].

Improvements in local air quality are directly linked to electrification of passenger car fleet, and declining exhaust emission concentrations following the trend of electrification across sub-regions. GOT2-4 sub-regions contribution to exhaust emissions persist until 2035, due to partial electrification and biofuel use contributing to reduced CO emissions. Furthermore, non-exhaust emissions are expected to persist even with a fully decarbonized vehicle fleet. Many studies have highlighted the persistent challenge of non-exhaust emissions, particularly in urban areas where PM emissions impose substantial health and economic burdens [7,52]. Estimations on non-exhaust emissions emphasize the need to reduce vehicle use coupled with fuel-shifts to achieve the desired resource quality benefits of passenger transport decarbonization.

Energy affordability, defined as the share of annual household income spent on energy expenditures, is widely recognized as a key indicator of energy equity, and improvements in energy affordability resulting from energy system transformations are identified as an important socioeconomic co-benefit [37]. Under high hurdle rate assumptions, a larger proportion of the population is expected to face increased income burdens to meet their energy needs, whereas these burdens remain comparatively lower under low hurdle rate assumptions. These findings underscore the long-term operational benefits of decarbonization measures once barriers to upfront investments are addressed. For instance, when barriers to EV investments persist, efforts to meet climate targets shift towards greater reliance on biofuels to mitigate emissions, thereby increasing operational costs. On the other hand, policy environment representative of low hurdles to consumer investments facilitates a more equitable distribution of benefits associated with increased energy affordability due to reduced barriers to investment premiums.

Sweden has ambitious climate objectives, with its municipalities committed to rapid decarbonization [38]. Also, Sweden stands out as the European country with fastest growing levels of inequalities, mainly due to housing related reforms during the last decades [53]. It is thus important to address socio-spatial differences, ensuring access to alternative solutions to all

communities. Lower hurdles to investments, especially for low-income groups, are essential to ensure that upfront cost premiums do not hinder access to long-term operational and system-wide benefits. Otherwise, limited access to resource-efficient measures would leave segments of the urban population vulnerable to exogenous shocks, such as ongoing market disruptions linked to conflicts in West Asia in the long-term.

The contribution of this work lies in the integration of high-resolution socioeconomic and demographic heterogeneity into integrated energy system modeling to support the analysis of urban futures aligned with climate neutrality objectives. Decarbonization efforts aligned with the principles of social equity and justice ensure that transition benefits all segments of society. This requires inclusive energy policies that address both environmental and social dimensions, rather than focusing solely on technical or economic outcomes. As previously highlighted, transformation of urban energy and mobility systems concerns positive reinforcement of socio-spatial inequalities in access to decarbonization measures and their associated benefits [54]. In this context, incorporating socio-spatial disparities into research and policy decisions should be a priority, enabling more equitable and effective long-term urban energy systems design.

Within the scope of this work, certain assumptions are made to simplify the representation of socioeconomic and demographic characterization at high spatial resolution. Some of these simplifications constitute limitations of the analysis and should be considered when interpreting the results. When representing the different dwelling types, and associated socioeconomic conditions, the tenancy type of dwellings is not accounted for. For certain tenancy types, investments may not depend on households' financial resources. Furthermore, uncertainty about the distribution of incentives often limit building owners' willingness to invest in improving buildings' energy performance [55]. This may limit households' capacity to realize improvements in resource efficiency and energy affordability. Sub-regional developments in air pollution concentrations are based on the location of vehicle-ownership rather than its activity, due to challenges associated with vehicle-activity tracking. It limits the accounting of health and economic impacts associated with changing air quality, as it is largely impacted by the location of local emissions. Depending on whether it's an area of dense or sparse nature, population exposure per unit of pollutant emissions varies significantly [56]. In this study, constant demand for energy services is assumed throughout the modelling horizon. Service demand changes associated with behavioral changes, changes in living space requirements and avoid-shift strategies in the transportation sector can significantly contribute to delivering resilient climate-neutral urban systems [57,58]. However, reductions in end-use service demands are not included in the analysis. Although consumer behavior is partially captured through investment decision-making assumptions (e.g., hurdle rates), broader behavioral responses that influence consumption patterns over time remain outside the scope of this work. Advancing approaches to quantify behavioral responses such as reduced service demands, shared mobility, changes in living space requirements would allow for more comprehensive assessments of urban decarbonization pathways.

6 Conclusions

This study evaluates the delivery of urban climate action co-benefits, aimed at achieving national decarbonization objectives, and investigates the distributional impacts of applied policies and mitigation targets at high spatial resolution. Regional statistical areas are clustered into sub-regions based on similarities in population density and average income, allowing spatial differences in socioeconomic and demographic characteristics to be incorporated into city energy system planning. Differences in socioeconomic conditions are represented through income-dependent hurdle rates for private investment decisions, enabling the integration of spatial heterogeneity into long-term energy system optimization–based planning. With the integration of spatial differences, the co-benefits assessment is conducted for the city of Gothenburg under the application of policy measures and national climate targets.

Energy transition measures aimed at achieving national decarbonization targets, deliver co-benefits through improved in urban resource efficiency, and better air-quality in the long-term. Improvements in building resource efficiency are attributed to electrification of heating, building renovations, regulations on specific energy use. In GOT0-1, buildings energy use is expected to reduce by 18.5% to 22.6% in 2045 compared to 2025, attributed to increased electrification. With the renovation of apartments in GOT4, 27.5% reduction is observed. GOT2-3 with the highest investment hurdles, energy use reduced by 11-12.5% respectively. Improvements in the resource use for passenger cars are directly correlated to fleet electrification. In line with emission reduction targets, electricity dominates energy use in the passenger car fleet in sub-regions GOT0–GOT1. In contrast, other sub-regions exhibit slower electrification, with a combined use of electricity and biofuels observed in 2035. As electric vehicles reach price parity with conventional vehicles, full electrification of the passenger car fleet is expected across all sub-regions by 2045. Electrification of passenger cars contributes to significant reductions of exhaust emissions; however, slower electrification delays the expected improvements in local air quality. With more than 60% of the city population in the GOT2-3 sub-regions, barriers to EV adoption would mean delayed benefits of climate action on local air quality. On the other hand, non-exhaust emissions are expected to remain under the assumptions of constant passenger vehicle activity. Although modal shifts are not considered in this analysis, a shift towards public transport and active travel modes is deemed necessary alongside fuel switching to further reduce exposures to PM emissions in urban areas.

To reach the long-term climate objectives in 2045, energy burdens are expected to increase in sub-regions with lower incomes in the base and high hurdle rate assumptions, similar levels of burdens are expected in the low hurdle rate assumptions. On the other hand, highest income groups are expected to have similar or lower levels of energy burden in all cases. When mapping energy burdens at the RegSO levels, 21 and 23 RegSOs are expected to allocate more than 3% of their income on energy services in 2045 compared to 7 RegSOs in 2025 in the base and high hurdle rate assumptions respectively. With low hurdle rate assumptions, 7 RegSOs are expected to allocate

more than 3% in 2045, with median energy burden reducing by 2.22%. The findings from the low hurdle rate assumptions highlight the long-term operational benefits of decarbonization measures when barriers associated with upfront investment premiums are adequately addressed in decision-making processes. Incorporating sub-regional socioeconomic representation enables a detailed assessment of the distributional impacts of climate action and supports policymakers in identifying areas that are particularly vulnerable to increased economic burdens under emission reduction obligations in the absence of additional incentives.

Acknowledgements

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Appendix

Appendix A.1

Calculations for the cost of energy services

To calculate the cost of energy services, results on annualized costs are analyzed, and the results attributes included in the cost calculations are presented in Table A6. Values for all results except the Cost_Inv and Cost_Inv+ are directly included in the calculations. The results on Cost_Inv and Cost_Inv+ are further processed and are described below.

Table A6: TIMES Results attributes that are included in the cost evaluation for energy services.

Results attribute	**Description**
Cost_Act	Annual variable activity costs
Cost_Com	Annual commodity costs
Cost_Comx	Annual commodity taxes/subsidies
Cost_Flo	Annual flow costs
Cost_Flox	Annual flow related subsidies/taxes
Cost_Fom	Annual fixed operating and maintenance costs
*Cost_Inv	Annualized investment costs
**Cost_Inv+	Annualized investment cost premium, due to tech hurdle rates.
Cost_Ire	Annual implied costs of endogenous trade

***Cost_Inv:** Investment costs, taxes and subsidies, excluding portions attributable to hurdle rates more than the general discount rate.

- Cost_Inv for all technological investments are accounted for, as annualized investment costs.
- Residential buildings and cars are treated in the model as expected services to fulfil the service demands, hence the investment costs associated with these required services are not included in the cost calculations.
    - The above assumption is straightforward applied in the case of residential buildings, because no additional investment cost is included for new buildings, and all buildings are assumed to be the same.
    - In the case of passenger cars, there are different options to choose from, and a cost is associated with any new car that is incorporated into the system. For this reason, the approach considers incorporating cost differentials as part of the cost required to meet service demand when higher-cost options are selected. Figure A1 illustrates the variation in annualized costs per vehicle type. Accordingly, the methodology accounts for the difference between gasoline cars and alternative vehicle types as part of the cost of service demands in the analysis.
- Annualized costs for the investments, that are represented as existing capacity available in the base year, are not included in the analysis.

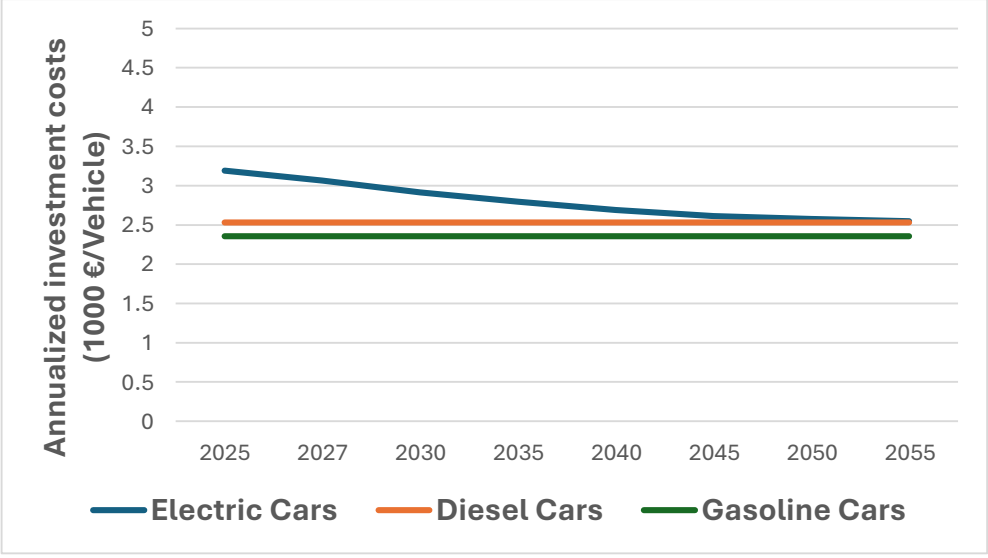


Figure A1: Annualized costs for different cars included in the analysis.

****Cost_Inv+:** Investment costs, taxes and subsidies, portions attributable to hurdle rates in excess of the general discount rate.

- In the case of non-residential (commercial or utility) investments such as district heating connections or commercial charging infrastructure, hurdle rates reflect expected returns on investment. These costs are assumed to be passed on to consumers utilizing these services to meet their energy-related demands. The additional investment costs (Cost_Inv+) for commercial investments are thus included in the cost calculations, as the expected profit-making is expected to be passed on to the consumers as a cost.
- In the case of investments made by residential consumers, hurdle rates are used to represent the range of factors that influence individual investment decisions. For investments undertaken by residential consumers such as rooftop solar PV systems and electric vehicles, hurdle rates are used to represent individual willingness to invest and associated upfront barriers. The additional investment costs (Cost_Inv+) are thus not included in the cost calculations, as they serve to reflect initial investment constraints rather than costs incurred after the adoption decision. Once the investment is made, these barriers no longer directly contribute to the ongoing costs borne by the consumer.

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