THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

A Participatory Energy Systems Modeling Approach

– Insights on the Local Dynamics of Passenger Car Decarbonization

MARIA DE OLIVEIRA LAURIN

Department of Mechanics and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

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MARIA DE OLIVEIRA LAURIN

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Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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MARIA DE OLIVEIRA LAURIN

Division of Maritime Studies
Department of Mechanics and Maritime
Chalmers University of Technology

Abstract

While some literature incorporates a local energy systems perspective in energy transition analyses, describing these transitions as context-specific processes, this local perspective is often overlooked in existing studies on road transport decarbonization. This raises the question of how to address this transition locally.

This thesis, by developing and applying a new framework – participatory energy systems modeling – aims to evaluate road transport decarbonization at the local level. Specifically, it investigates the influence of socio-geographical contexts and their specific characteristics on the decarbonization of road transport, with a particular focus on passenger cars. The proposed framework advances an Energy Systems Optimization Model (ESOM) that integrates local spatial dynamics by assessing different local modeling scenarios. These scenarios stem from a participatory approach (PA), where pathways are developed based on discussions with local stakeholders, such as municipal officials. The significance of local spatial dynamics is further explored by comparing the evolution of the passenger cars system at both the national (i.e., country) and local (i.e., municipality) levels, as well as in urban and non-urban municipalities.

At the national level and within urban contexts, where annual average mileages and trip distances are typically low, the model tends to favor vehicles with lower upfront costs. Conversely, in non-urban contexts with longer trip distances, the emphasis shifts towards vehicles that enhance fuel economy and low fuel cost, despite their higher upfront purchase costs. Furthermore, the analysis of the modeled local scenarios emphasizes the importance of fleet electrification. However, it also highlighted the necessity of integrating fleet electrification with developing a resilient electric grid capable of accommodating the growing demand for electricity from variable renewable energy sources (VRESs). While non-urban areas can manage increased electricity demand through renewable energy production, urban areas may face challenges in meeting their demand solely with VRESs. Consequently, due to stringent local electricity production constraints, urban areas are likely to rely more on imported fuels such as biofuels and hydrogen.

Overall, this thesis concludes that while a national perspective can adequately prescribe long-term solutions, it often overlooks the importance of local specifications in road transport decarbonization. Incorporating local spatial dynamics in ESOM becomes essential for accurately describing the transition and creating inclusive, resilient transport systems. This thesis advocates, thus, for tailored approaches over "one-size-fits-all" strategies, aligning with the European Commission's call to engage local authorities.

Keywords: Fossil-free Road Transport; Local Energy Systems; Local Spatial Dynamics; Participatory Modeling; Socio-geographical Contexts; Sweden; TIMES Cost-optimization Model.

List of publications

Paper I

de Oliveira Laurin, M., Selvakkumaran, S., Ahlgren, E.O., Grahn, M. (2024). Are decarbonization strategies municipality-dependent? Generating rural road transport pathways through an iterative process in the Swedish landscape. *Energy Research & Social Science*, 114: 103570. https://doi.org/10.1016/j.erss.2024.103570

Maria de Oliveira Laurin credit author contribution: Writing - original draft, Writing - review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Paper II

de Oliveira Laurin, M., Aryanpur, V., Farabi-Asl, H., Grahn, M., Taljegard, M., Vilén, K. Road Transport Decarbonization: A comparison between urban and non-urban municipalities applying a participatory approach (*manuscript submitted to Nature Scientific Reports, under review*)

Maria de Oliveira Laurin credit author contribution: Writing - original draft, Writing - review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

List of additional publications and reports

A. de Oliveira Laurin, M., Taljegard, M., Ahlgren, E.O., Generating and validating non-urban road transport decarbonization pathways: How to integrate a participatory approach into energy system modeling?, *presented at the World Conference on Transport Research (WCTR), Montreal, Canada,* July 17-21, **2023**.

B. de Oliveira Laurin, M., Farabi-Asl, H., Grahn, M., Taljegard, M., Future fuel mix for passenger cars in different socio-geographical contexts: Results from energy systems modeling, *presented at the Transport Research Arena (TRA), Dublin, Ireland*, April 15-18, **2024.**

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Maria de Oliveira Laurin

Contents

Abbreviations, acronyms, and description of concepts used in this thesis

Abbreviations and acronyms

BEVs	Battery Electric Vehicles
CO_2	Carbon Dioxide
CH	Charging at Home
CW	Charging at Work
E4	Energy, Economy, Environment, and Engineering
ECost	Electricity Cost
EFOM	Energy Flow Optimization Model
ESM	Energy Systems Modeling
ESOMs	Energy Systems Optimization Models
ESR	Effort Sharing Regulation
ETSAP	Energy Technology Analysis Program
EU	European Union
ETS	Emission Trading System
FC	Fast Charging
FCEVs	Fuel Cells Electric Vehicles
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEVs	Hybrid Electric Vehicles
HVO	Hydrotreated Vegetable Oil (Biodiesel)
ICEVs	Internal Combustion Engine Vehicles
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MaaS	Mobility as a Service
MARKAL	Market Allocation
MCA	Multi-criteria Analysis
NPV	Net Present Value
O&M	Operation and Maintenance
PA	Participatory Approach
PHEVs	Plug-in Hybrid Vehicles
pkm	Passenger-kilometers
RED	Renewable Energy Directives
RES	Reference Energy System
SALAR	Swedish Association of Local Authorities and Regions
SDGs	Sustainable Development Goals
SP	Standard Public Charging
TIMES	The Integrated MARKAL-EFOM System
UN	United Nations
VRESs	Variable Renewable Energy Sources

Description of concepts used in this thesis

Biofuels are fuels produced from biomass. In this thesis, both biogas and liquid biofuels – ethanol and Hydrotreated Vegetable Oil (HVO) – were considered.

Biogenic is a term used to distinguish between fossil carbon and carbon that is recycled in a much shorter timeframe. The biogenic carbon is cycled between being absorbed in growing biomass, from the atmosphere, and released back into the atmosphere again through e.g., the combustion of biofuels. In this thesis, the biofuels were considered to be fully non-fossil, meaning that only biogenic carbon is emitted from the combustion of biofuels and therefore also defined as carbon neutral.

Bottom-up Models are typically defined as technology-explicit models, offering extensive technological details, while emphasizing how to achieve load balance in response to exogenous demand from a technical perspective. These models, such as The Integrated MARKAL-EFOM System (TIMES) model developed and applied in this thesis, often rely on linear correlations and engineering data, encompassing techno-economic data to define different technologies and their activity.

Climate Neutrality defines an equilibrium between emitting carbon and absorbing carbon from the atmosphere in carbon sinks.

Deterministic Linear Programming Models are set as "black-box" models that mathematically represent a problem, where the constraints, as well as requirements, are expressed through linear equations, and the goal is evaluated according to a linear objective function.

E4 Models stand for Energy, Economy, Environment, and Engineering models, and are described as bottom-up models, providing a high techno-economic detail. These models provide a highly detailed representation of energy systems while offering a simplified perspective on their interactions with the broader economy.

Energy Carriers are the mediums used to transfer energy from one form to another. For simplicity reasons, in this thesis, energy carriers such as electricity and hydrogen are included in the term transport fuels.

Energy Systems Modeling is a tool that mathematically represents possibilities and challenges related to energy conversions in energy systems. As a tool, it can represent energy systems at different temporal, sectoral, and spatial resolutions.

Energy Systems Optimization Models as part of the Energy Systems Modeling (ESM) family, offer detailed and context-specific insights on energy systems, according to a techno-economic perspective and a cost-optimized objective function.

Feebate System, also referred to in this thesis as a **Green Tax Shift,** is a policy tool used to encourage environmentally friendly practices by imposing fees on less efficient or more polluting options and providing rebates or incentives for more efficient or less polluting ones. The term "feebate" is a combination of "fee" and "rebate".

Fossil Fuels are fuels origin from ancient organic materials (millions of years ago) including coal, natural gas, crude oil, and their derivatives as petroleum products, coke, and derived gases. Also, non-renewable wastes are defined as fossil. Fossil energy sources are characterized by their finite nature. Carbon emitted from fossil fuels adds to the existing atmospheric CO_2 concentration.

Hard-to-abate Sectors refer to industries or energy sectors that face significant challenges in decarbonization, due to the nature of their operations, processes, as well as involved stakeholders, and thus these sectors show heavy reliance on fossil fuels.

Hurdle Rate while inversely related to GDP, is defined as an individual discount rate specific to a technology, envisaging the reluctance of an individual to invest in less mature technologies compared to fully established ones.

Hydrotreated Vegetable Oil is a renewable diesel synthesized from renewable oily raw materials, like soy, rapeseed, and tall oil as well as from waste and residues, as used cooking oil and animal fats. In this thesis, HVO 100 was considered, representing a biodiesel composed of 100% renewable raw material.

Load Balance refers to the required equilibrium of matching the generation output (i.e., supply) with the load (i.e., demand).

Local is used in this thesis to describe a socio-geographical cluster composed of various nodes, located close to each other (e.g., municipality).

Local Energy Systems are dynamic networks connecting energy supply and demand within specific socio-geographical contexts, focusing on local end-users in a defined area. They highlight how demand-side actions impact the local energy balance.

Local Resources are energy resources available locally, within a specific socio-geographical area or community (e.g., municipality).

Micromobility, also known as active mobility, refers to transporting people and goods through non-motorized vehicles, based on human activity (e.g., walking and biking).

Modal Shift refers to the transition of a given transport demand from one transport mode to another.

Modeling Scenarios are used in the modeling exercise to provide an overview of the transition of a given pathway (e.g., fleet electrification), reflecting on how the system might evolve from the current situation (e.g., fossil fuel-dependent road transport) to the desired end-point (road transport decarbonization).

Municipality refers to a single administrative division with legal status and the authority for self-governance, as conferred by national and regional laws to which it is subjected. In this thesis, a municipality is further described as a socio-geographical cluster, encompassing different nodes closely located, providing, thus a local perspective.

National refers to the whole country and its population.

Net-zero Emissions refer to overall climate neutrality's goal, referring to the balance between the amount of greenhouse gases (GHGs) released with an equivalent amount sequestered or offset, or buying enough carbon credits to make up the difference.

Non-urban Municipality refers to every municipality that, in this thesis and according to the Swedish Association of Local Authorities and Regions (SALAR), is not defined as being a "larger city".

Net Present Value is a financial tool that evaluates an investment's profitability. It compares the value of money that can be expected to be received from the investment (i.e., return) in the future to the initial cost of the investment, adjusted for the time value of money (i.e., money is worth more today than in the future).

Partial Equilibrium Models focus exclusively on achieving equilibrium within the energy sector, without considering potential impacts or adjustments in the broader economy.

Participatory Approach is a method described through an active involvement, collaboration, and engagement of stakeholders, particularly those affected by or involved in a decision-making process. As a method, it facilitates a continuous dialogue throughout the research process, engaging stakeholders in collecting and analyzing findings.

Participatory Energy Systems Modeling Approach refers to the specific framework developed and applied in this thesis, as combining a participatory approach (PA) with an Energy Systems Optimization Model (ESOM).

Pathways refer to different strategies (e.g., fleet electrification) that can be employed to achieve a well-defined goal (e.g., road transport decarbonization).

Perfect Foresight is a model characteristic that assumes "perfect" information, at all iterations when running the model, during the entire modeling horizon. Accordingly, the model is provided with a comprehensive knowledge of all the market dynamics and related parameters, today and in the future.

Reference Energy System is a comprehensive network illustrating the flow of energy among various end-use activities, fueled by a wide array of energy sources.

Regional relates to a region composed of different municipalities.

Revealed Preferences involve inferring individual preferences based on their observable choices.

Salvage Value refers to the estimated "scrap value" of an asset at the end of its useful life (i.e., resale value, representing the amount of money that is expected to be received from selling an asset or its parts once it is no longer productive or needed for operations).

Semi-structured Interviews use predetermined open-ended questions to explore participant-centered narratives and insights, allowing flexibility for follow-up questions and detailed exploration of specific topics of interest.

Socio-geographical Context refers to the interplay between social and geographical factors influencing and characterizing a specific local area.

Socio-technical Systems describe energy systems and their transition as a product of integrating and balancing the complexities associated with social and technical elements. These systems are characterized by their interactions and interdependencies between human actors (e.g., individuals, organizations, and communities) and technical components (e.g., machines, infrastructure, and processes).

Spatial Dynamics describe the interaction between energy-society and the evolution of energy patterns — supply and demand — along with infrastructure availability and environmental factors across different socio-geographical contexts.

Standalone System is a self-sufficient system that operates without considering interactions with other systems and its surroundings.

Stated Preferences refer to the preferences that individuals express verbally or in surveys when asked directly about their choices or opinions.

System Integrators encompass local resources, technologies, and processes applied across various segments of a local energy system. Identifying these integrators helps reveal potential synergies and conflicts among different local subsystems. In this thesis, biomass, biogas, and Variable Renewable Energy Sources (VRESs) – wind and solar – play a system-integrator role.

Urban Municipality is referred to every municipality, that in this thesis, and according to the Swedish Association of Local Authorities and Regions (SALAR), is defined as being a "larger city" (i.e., in a Swedish context, having a population of at least 200,000 inhabitants in the largest urban area).

1. Introduction

In 2015, 197 parties signed the Paris Agreement, as a common commitment to limit the increase in global temperature to below 2°C above pre-industrial levels, with efforts to keep it to 1.5°C [1]. In light of the Paris Agreement, in 2019, the European Commission introduced the European Green Deal, emphasizing that timely achievement of climate neutrality needs a broad contribution of all society and thus, energy sectors [2].

All energy sectors have responded positively to the required climate efforts by proposing clear changes within their activity. However, as shown in Figure 1, despite its climate neutrality willingness, the transport sector remains worldwide heavily reliant on fossil fuels-based oils, which constitute 91% of its final consumption [3].

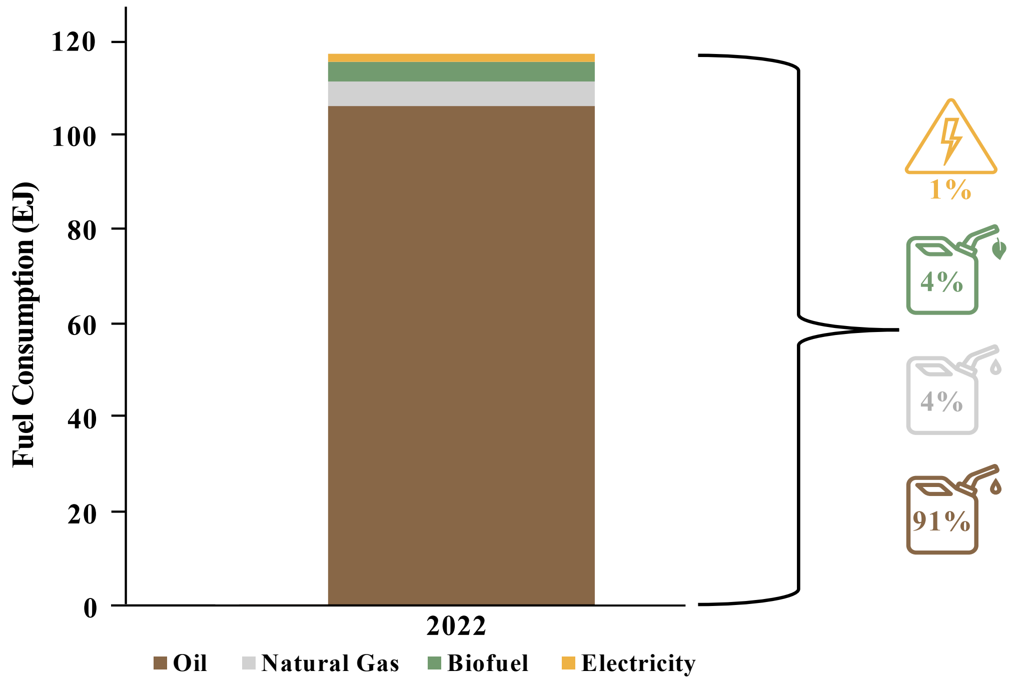


Figure 1. Worldwide transport fuel consumption (EJ) registered in 2022. Road transport, international maritime transport, aviation, and rail are the transport segments considered. Data retrieved from [3].

The same trend is seen also at the European level, where, as depicted in Figure 2, transport represents 66% of the whole oil products consumption, becoming the least diversified sector in terms of primary energy supply [4]. Due to its significant reliance on petroleum products, the transport sector is responsible for one-quarter of total European greenhouse gas (GHG) emissions [5]. Therefore, it must reduce its emissions by 80% to 95% from 1990 levels by 2050 to meet climate targets [6].

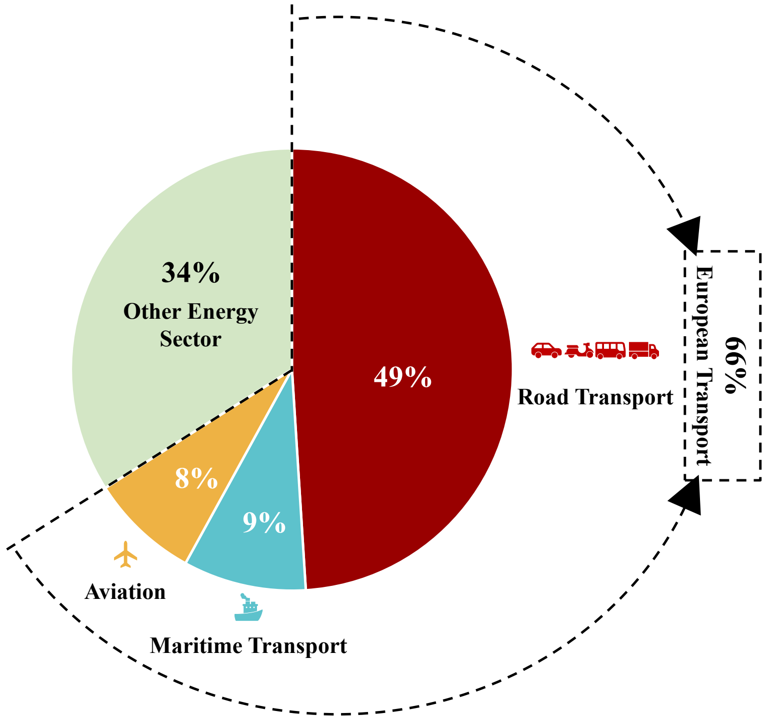


Figure 2. European petroleum products consumption disturbed in the different transport segments versus other energy sectors, as registered in 2022. Data retrieved from [4].

When planning the decarbonization of the European domestic transport sector, a special focus needs to be taken on road transport. Road transport is responsible for 72% of the total European domestic GHG emissions [7]. Subsequently, achieving the European transport sector's emissions reduction targets calls for a rapid decarbonization of road transport. In recent years, this urgency has driven numerous studies to investigate various strategies for overcoming the challenges associated with this energy transition, see e.g., [8],[9].

Existing studies on road transport decarbonization, see e.g., [10],[11], and specifically on passenger cars, often suggest strategies that include: (i) fleet replacement towards more energy-efficient vehicles; (ii) transport demand reduction through a modal shift to transport modes with lower emission per person; and (iii) fuel switching towards low carbon dioxide (CO_2) emission energy carriers, such as biofuels, electricity, and hydrogen.

Despite the great technical contribution that current literature offers to understand this transition, the scope of existing studies is often limited to an aggregated national, dismissing that road transport demand is predominantly defined at the local level. Such a limitation fails to capture that road transport depends on local spatial and socio-geographical conditions. Examples of these socio-geographical conditions, as listed in some studies [12]–[19], are (i) travel patterns; (ii) fleet composition; (iii) fuel consumption trends; and (iv) traffic regulations. Hence effectively tackling the decarbonization of road transport, like any energy transition, requires an understanding of the extension beyond theoretical and technical concepts. Road transport decarbonization calls indeed for being addressed as a context-dependent process and, thus, according to a local energy systems perspective [20].

This thesis, in line with the European Commission agenda [21], recognizes the frontier role that municipalities and local communities play in driving a sustainable and more socially inclusive transition. Accordingly, this thesis develops a framework that investigates the decarbonization of local road transport, specifically passenger cars. It applies a participatory energy systems modeling (ESM) approach. Such an approach was specifically developed in this thesis as a result of combining (i) an ESM, as integrating local spatial dynamics with (ii) a participatory pathway development, based on discussions with local and municipal officials. This thesis offers a unique perspective through its iterative process between ESM and stakeholder participation. As a result, this approach sheds light on the importance of assuming local spatial dynamics when decarbonizing passenger cars.

1.1. Motivation and research aim

Some existing literature highlights the significance of adopting a local energy systems perspective when examining energy transitions, especially in the electricity generation and heating sectors, see e.g., [22]–[25]. As a result of their local energy systems perspective, these studies emphasize that energy transitions are context-specific processes, influenced by the unique characteristics of the local systems being assessed. Despite this local perspective being often dismissed in existing road transport decarbonization studies, one might think about how to address this transition locally. Concretely, when addressing this decarbonization of road transport at the local level, attention must be drawn to attributes that are recognized to vary across socio-geographical contexts, underscoring the importance of viewing the decarbonization potential of fuel and mobility technologies through a context-specific lens.

The overarching aim of this thesis is to develop a new framework for assessing road transport decarbonization at the local level. Specifically, the proposed methodology was framed as assessing the impact that socio-geographical contexts and their specifications can have on the decarbonization of road transport, specifically passenger cars. The presented framework develops a techno-economic ESM incorporating local spatial dynamics, through applying different modeling scenarios. These scenarios are direct results of the participatory process of pathways development, based on discussions with municipal officials. The importance of local spatial dynamics is further investigated by comparing the development of passenger car systems under different climate policies and future energy systems assumptions at (i) the national (i.e., country) and local (i.e., municipality) level; but also in (ii) urban and non-urban municipalities.

The research questions addressed in this thesis follow four research aims:

> *RQ1: How can decarbonization of passenger cars be implemented at the local level, within Energy Systems Optimization Models (ESOMs), and what are the key considerations and modeling features required for such implementation?*

RQ1 will be assessed while developing a participatory energy systems modeling framework that can be applied to analyze how the decarbonization of passenger cars, at the local level, can be met cost-efficiently, while considering this transition as a context-dependent process.

RQ2: How can road transport decarbonization pathways be generated, when tailored to a specific local and socio-geographical context?

RQ2 will be assessed by generating and applying local road transport decarbonization pathways to the modeling framework, in order to better understand this transition at the local level and thus as a context-dependent process.

RQ3: What are the cost-effective options for the fleet composition and fuel mix of passenger car decarbonization, at the national level as well as within urban and non-urban municipalities?

RQ3 will be assessed through applying the developed participatory energy systems modeling framework to the national and municipal level, and test how the outcomes differ according to spatial dynamics (national versus local) and corresponding socio-geographical context(urban versus non-urban municipalities).

RQ4: What insights can be gained from incorporating local spatial dynamics as a modeling feature, and how does the modeling exercise benefit from this perspective?

RQ4 will be assessed by discussing (i) the influence of integrating local spatial dynamics into the modeling process through the modeling scenarios that envisage local pathways developed in a participatory manner; and (ii) how local spatial dynamics affect the modeling exercise, both the process and outcome.

1.2.Scope and delimitations

This thesis presents an introductory essay based on two appended papers, both focusing on road transport decarbonization at the local level of different types of municipalities (i.e., urban and non-urban). **Paper I** proposes a context-specific method that considers a local energy systems perspective when generating non-urban road transport pathways. **Paper II** develops a techno-economic ESM to test road transport decarbonization from a cost-effective perspective, through modeling scenarios that mirror the local pathways developed in a participatory manner. This thesis framework uses three non-urban Swedish municipalities as case studies in **Paper I**, whereas **Paper II** adds one urban municipality. For this thesis essay, the local modeling level was extended to also include a national perspective as a complement to appended papers.

Due to this thesis' research boundaries, different assumptions might be subject to discussion. In the bigger picture, one delimitation is that this study focuses on road transport, specifically passenger cars, as a standalone system. Such a sector limitation may potentially omit important factors that are related to other transport segments and energy sectors that can impact road transport decarbonization. Similarly, in this thesis a techno-economic ESM was developed and applied, built on assumptions, and thus, as all models, provides a simplified view of the "real world".

1.3. Contribution of the thesis

Paper I presents a socio-geographical municipality context-specific iterative method for generating local socio-technical pathways. The iterative aspect of this framework is related to the feedback loop established between different phases of the literature review and participatory approach (PA), which, through municipal officials' engagement, resulted in the identification of different local pathways. The primary contribution of this paper lies in its critique of the prevailing national perspective on road transport decarbonization, which often relies on aggregated data and travel patterns that disproportionately emphasize urban areas, while toning down non-urban settings. By advocating for a tailored approach that considers the specific context of each transition, this paper underscores the importance of aligning low-carbon solutions with local behaviors and socio-geographical characteristics. Overall, this paper highlights that a local perspective can enhance the effectiveness of decarbonization efforts, while contributing to more socially inclusive climate policies.

Paper II develops a techno-economic model to evaluate road transport decarbonization, when assessed at the local level of different socio-geographical municipalities. Local spatial dynamics is added as a core modeling feature, by integrating the local pathways identified in **Paper I** as modeling scenarios. The main contribution of this paper is the understanding of how road transport dynamics fit within cost-optimization models. This approach highlights that the optimal balance between upfront costs and more efficient technologies varies based on travel patterns across socio-geographical contexts. Consequently, urban and non-urban municipalities result in different optimal fleet compositions and fuel mixes, emphasizing the necessity of customizing decarbonization strategies to specific local contexts rather than relying on standardized approaches.

While this thesis provides an in-depth analysis of a Swedish case, its framework offers a universal message on creating more sustainable and inclusive road transport systems. This message is relevant to an international audience and diverse stakeholders, promoting a global dialogue on the crucial role of local authorities. Engaging local authorities is essential for accurately representing behavioral and consumption trends, climate actions, and the availability of local resources across various socio-geographical contexts. This dialogue underscores the pivotal role municipalities and local communities play in driving sustainable and inclusive transitions, not only in road transport but in the entire society.

1.4. Structure of this thesis

This thesis is structured in six chapters. Chapter 2 presents an overview of the background and related research according to which this thesis was built upon. Chapter 3 presents the participatory energy modeling approach developed and applied in this thesis. The applied case studies are also presented in Chapter 3. Chapter 4 presents the outcomes of applying the developed framework to the case studies. Discussion on the presented results and conclusions, as well as answers to the research questions of this thesis, can be found in Chapter 5. This thesis concludes with Chapter 6, which provides an overview of its limitations, while motivating future work.

2. Background and related research

Meeting the climate goals set by the Paris Agreement within the right timeframe requires the European domestic transport GHG emissions to decrease by 80% to 95%, compared to 1990 [6]. Albeit this target, Figure 3 illustrates that the European transport sector's domestic emissions, contrary to the GHG emissions reduction experienced in all other societal sectors, increased by 20% between 1990 and 2019 [26].

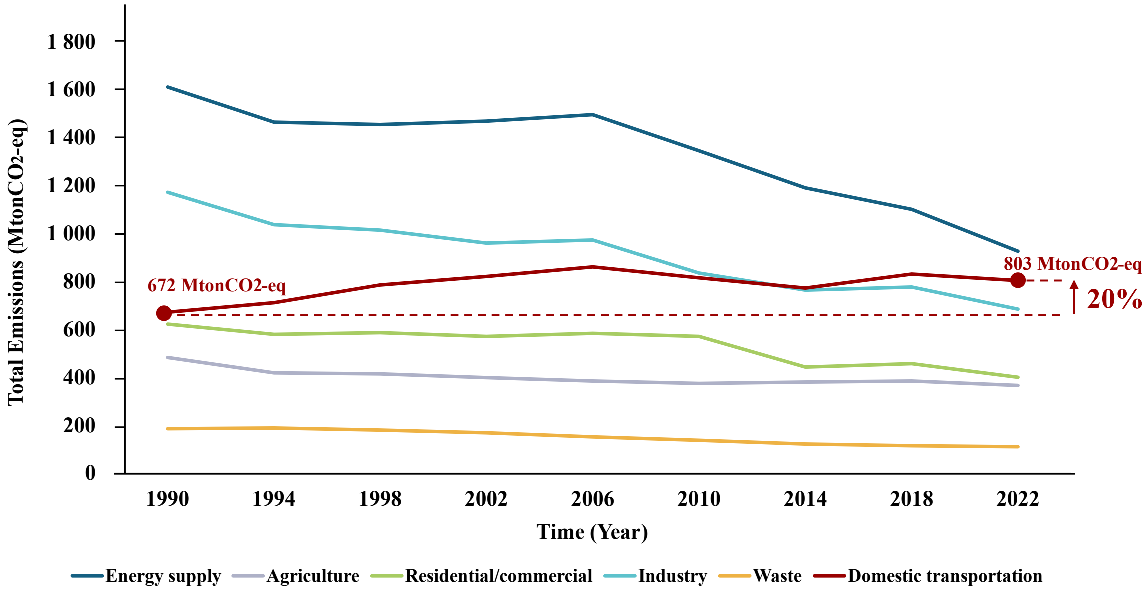


Figure 3. European domestic GHG emissions per energy sector, measured from 1990 to 2022. The dashed line represents the increase in domestic transport-related GHG emissions registered between 1990 and 2022. Domestic transport includes road and rail transport as well as domestic maritime transport and aviation. Data retrieved from [26].

Such a trend can be understood as a result of the European domestic transport sector being often described as a "hard-to-abate" energy sector [27]. As a "hard-to-abate" sector, the European domestic transport sector, contrary to other energy sectors (e.g., electricity and heating), presents high granularity, involving a wide range of actors (e.g., fuel producers as well as vehicle and infrastructure manufacturers), all of whom are required to coordinate their efforts [28]. This objection is further accentuated when thinking about the road transport sector, which, as depicted in Figure 4, currently represents 72% of the total European transport-related emissions [7]. The challenge, and therefore uncertainty, regarding the decarbonization of road transport, is correlated particularly to (i) its heavy reliance on fossil fuels [29] and; (ii) the fact that the energy demand within the transport sector has historically mirrored the upward trend of economic growth [30].

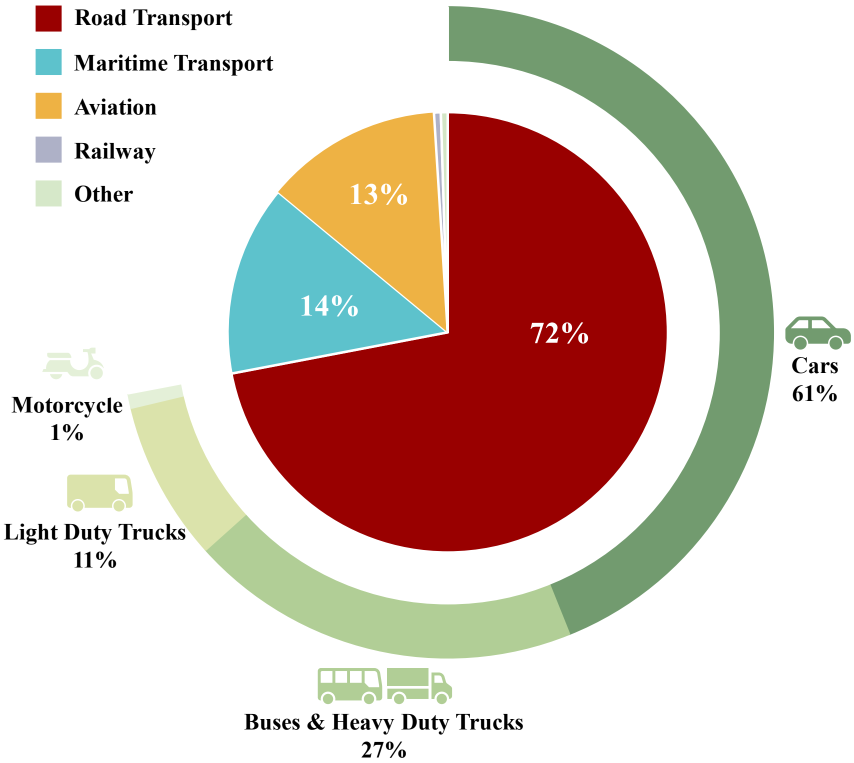


Figure 4. European transport-related GHG emissions distributed by transport segment registered as of 2019. Data retrieved from [7].

2.1.Energy systems modeling

Addressing the challenges of decarbonizing road transport, as in any transition, requires a comprehensive and holistic understanding of the entire system, which can be fulfilled using ESM tools [31],[32]. ESM is a powerful tool designed to assess how real-world energy systems might evolve under various stimuli, such as climate mitigation strategies [33]. This approach adds to understanding layers to future energy transitions: (i) a transitional perspective (i.e., how the systems need to develop to achieve specific objectives) and; (ii) a long-term view (i.e., what happens to the systems once these objectives are met) [34]. Among the extensive ESM family, ESOMs are particularly described as being effective at integrating techno-economic perspectives, providing a detailed representation of the entire energy system [33],[35].

ESOMs are often employed to investigate the decarbonization of road transport (e.g., [36]–[39]). However, these studies tend to adopt a more general and conceptual perspective, focusing mainly on the techno-economic aspects of energy transitions at the continental [36], national [37], regional [38], and large city [39] levels. This wide-angle approach fails to account for the significant impact of socio-geographical factors, like (i) travel patterns, (ii) vehicle characteristics, (iii) fuel consumption behaviors, and (iv) traffic regulations, which are local context dependents [18],[19],[40]. Given their socio-geographical nature, these conditions shape the decarbonization potential that fuel and mobility technologies have in different contexts. In contrast to urban municipalities, non-urban municipalities hold higher levels of reliance on cars, longer travel distances, and deficiencies in public mobility infrastructure and connectivity. These factors can exacerbate the challenges of decarbonizing transport systems in non-urban areas. Hence developing effective non-fossil fuel transport solutions calls for considering road transport as a socio-technical system and thus, treating its decarbonization as context-dependent. Accordingly, road transport decarbonization seeks to incorporate a socio-spatial dynamics perspective, reflecting the nuances and specifications of local energy systems.

2.2. Socio-technical systems and socio-spatial dynamics: A local energy systems perspective

Energy systems transitions are inherently complex, driven by intricate interactions and interdependencies among a wide range of social, technical, and contextual elements. Such complexity defines energy systems as socio-technical systems [41],[42], where humans are at the core of their transition [43]. Understanding energy systems transitions requires, therefore, a comprehensive grasp of the relationships between various actors involved [43]. Recognizing energy systems as socio-technical introduces a new layer of their transition – socio-spatial dynamics. This layer highlights that the links between energy and society are spatially dependent [44]. Accordingly, energy systems transitions are an outcome of reshaping social patterns influenced by diverse cultural, economic, and political factors, and everyday practices, all of which are defined as spatial-dependent characteristics [44]–[48].

Due to its socio-spatial dynamics, "optimum" solutions, often advocated for energy system transitions, might not be universally replicable across different contexts (e.g., national versus local) [40]. Accordingly, effectively tackling the decarbonization of road transport (like any energy transition) should be treated as a socio-technical system and thus, a reflection of its socio-spatial dynamics. Road transport decarbonization should, therefore, extend beyond theoretical considerations and be grounded in a local energy systems perspective [49],[50]. As distinct from national and regional perspectives, a local energy systems perspective provides a unique insight to lead and coordinate efforts towards local and sustainable transition [51]. Such a unique position is related to the social dimension that a local perspective offers on energy transitions [52],[53], by comprehensively illustrating how demand-side behaviors and decision-making powers impact the local energy balance [51]–[55]. Taking a social dimension into account, demands public engagement and benefits from a PA [56].

2.3. Participatory approach

Salter et al. [57] describe a PA as an effective means of engaging stakeholders, emphasizing that research can greatly benefit from incorporating stakeholder experiences, knowledge, and perspectives. Engström [50] presents PA as a key tool to identify different dimensions (i.e., temporal, spatial, and action) associated with local energy systems and corresponding planning. This is in line with Colenbrander et al. [58] who further highlight that a PA fosters a close collaboration between researchers and local authorities, leading to a more nuanced understanding of local energy systems. In the context of energy transitions, a PA integrates bottom-up, local-specific knowledge of techno-economic and socio-geographical aspects by involving various local stakeholders and incorporating their expertise. These insights provide valuable information on the operational dynamics of local communities and services [59]–[61], their commitment to climate issues, and their challenges [62].

Despite the valuable insights a PA can offer, as highlighted by previous studies, it is important to recognize its limitations. A PA is resource-intensive, requiring significant amounts of data and time. Its success relies heavily on the representativeness of the samples, calling for a clear distinction between stated preferences versus revealed preferences, as well as a high degree of heterogeneity among the involved stakeholders [63]. Consequently, not all research benefits from a PA approach, making it essential to carefully evaluate under which research scope its application is justifiable. A PA is particularly beneficial in research where local knowledge is often undervalued, as it treats research as context-specific, avoiding the standardization and generalization of strategies [64]. Accordingly, a PA is defined to be an effective tool for addressing tangible human and social issues, aiming to create practical local solutions [64], such as in energy transition studies. Adopting a PA can improve the social inclusivity of energy transitions [65], thereby bolstering local climate resilience [66]. Therefore, incorporating a PA is a crucial aspect to be considered in local energy transitions [67]–[70].

2.4. Participatory energy systems modeling

Existing literature already extends a PA to the realm of ESM, highlighting the benefits of this synergy, including: (i) effectively bridging theoretical objectives with practically feasible and attainable targets [71]; (ii) improving the credibility and transparency of modeling outcomes [72]; and (iii) promoting legitimate decision-making by considering and weighing both the positive and negative feedback from various potential outcomes according to a holistic and a system approach [73]. The existing studies often apply PA as a tool for stakeholder engagement, employing it not only to design but also to evaluate the feasibility of modeling pathways. Developing and evaluating modeling pathways are widely applied as a key tool to address the intricacies linked to the decarbonization of society [74]–[77]. Particularly, pathways can illustrate numerous potential futures and the interplay between various technical and socio-economic transition elements within a specific context [59]. Consequently, generating and assessing pathways may outline the principal strategies for an energy transition and effective methods of resource allocation within a transitioning system [78]–[84].

2.4.1. Road transport decarbonization

In the context of road transport, some authors have already stated and emphasized the excellence of ESM and PA [85]–[91], as presented in Table 1. These authors assert that discussing but also, developing modeling scenarios in a participatory manner is an effective strategy of incorporating spatial dynamics into ESM exercises. Soria-Lara et al. [85] introduce a regional spatial dimension to conventional backcasting scenarios for road transport decarbonization, proposed by policymakers. The authors develop a “collaborative appraisal framework” involving a Delphi-method that combines a PA with a multi-criteria analysis (MCA) to evaluate the feasibility, acceptability, and potential barriers of backcasting road transport scenarios, in the context of a Spanish region. The study suggests that integrating a PA in ESM, within the energy transition field, facilitates a more effective transition from quantitative research to actionable decisions. Hickman et al. [86] adopt the same approach of combining a PA with a MCA to test and visualize the feasibility of different road transport scenarios, in the context of a British county. The authors argue that incorporating a PA enhances the reliability of ESM results by providing broader modeling outcomes. This approach goes beyond focusing solely on "optimum theoretical" solutions, considering socio-political factors such as political and public acceptance. Varho et al. [87] use a hybrid qualitative and quantitative Delphi-method to identify factors that are expected to shape the future of road transport in the country-context of Finland. Such factors are later ranked and grouped into "themes", resulting in different socio-technical scenarios. The authors conclude that a PA is an effective and inclusive way of identifying such factors, offering a wider range and legitimacy to the process of developing socio-technical ESM scenarios.

Four studies within the field of ESM were found to integrate ESOM with PA to address road transport decarbonization [88]–[91]. McDowall [88] proposes a theoretical framework of combining a PA, as a socio-technical scenario developing tool, with quantitative ESM to test the potential role of hydrogen in different energy sectors (including road transport), in the multi-country context of the United Kingdom. The authors' reasoning suggests that energy transitions can benefit from establishing a "dialogue" between PA and ESM. Accordingly, one should (i) not see ESM as a quantified representation of a PA, but instead as a quantitative tool to analyze the elements considered in socio-technical scenarios; while (ii) understand a PA as a metric to validate and challenge different ESM results. Venturini et al. [89] merged a PA, involving stakeholders' inputs on future driving forces in road transport, with ESOM, at the Danish national level. The authors translated the stakeholders' inputs into quantitative modeling scenarios and assumptions, enriching the ESOM exercise with spatial dynamics. Moreover, the authors noted that while ESOM, when used alone, focuses on long-term techno-economic optimization, it overlooks critical behavioral, socio-political, and economic barriers – issues that can be addressed by adding a PA to the modeling exercise. Fortes et al. [90] compared energy supply portfolios for decarbonizing various economic sectors, including road transport, using either a PA or ESOM, at the Portuguese national level. Although there are some similarities, the authors first concluded that purely qualitative pathways resulting from a PA struggle to capture long-term uncertainties, potentially hindering cost-effectiveness or technical feasibility, particularly in achieving quantitative goals, e.g., emissions mitigation targets. Additionally, ESOM was defined as not accounting for road transport decarbonization strategies that are inconsistent with the prevailing socio-political and economic context. Consequently, the authors advocated for a combined approach that establishes a complementing synergy between PA and ESOM exercises to enhance understanding of energy transitions. Forsberg [91] conducted a thorough analysis of road transport decarbonization by developing an ESOM model, at the Swedish national level. This research was extended to include local spatial dynamics, by modeling different sizes of municipalities. Incorporating local spatial dynamics enabled the testing of global CO_2 mitigation and local air quality goals within the framework of strong national climate policies. The modeling results showed how road transport fleets and thus, fuel consumption, will develop over the transition years. These results were further presented and discussed with municipalities' stakeholders, according to a PA. The PA was applied as serving a validation metric, encouraging discussions on model assumption, results, and implications. By bridging the gap between ESOM and PA, the author advocates for the critical role of local governments in enhancing and implementing national climate policies. Engaging with stakeholders through PA was emphasized as a crucial step of the modeling exercise, underscoring the need for local actions to implement the cost-efficient measures identified in the model analysis.

Table 1. Existing literature review that combines different types of ESM with PA. The colored cells represent studies that, as this thesis, applied (i) ESOM (lighter green); (ii) PA as a modeling scenario development tool (medium green); and (iii) assumed local spatial dynamics (darker green). ESM, Energy Systems Modeling; ESOM, Energy Systems Optimization Model; MCA, Multi-criteria Analysis; TIMES, The Integrated MARKAL-EFOM System, with EFOM, Energy Flow Optimization Model and MARKAL, Market Allocation.

Source	Method Applied	Participatory Approach Purpose	Spatial Dynamics Considerations	Main Conclusions
Soria-Lara at al. [85]	MCA	Evaluation feasibility, social acceptability, and related barriers of backcasting road transport scenarios purposed by national policymakers.	National level (Spain)	A soft link between ESM and PA facilitates the shift from conceptual energy transition strategies to actionable decisions.
Hickman et al. [86]	MCA	Visualization of the visibility of different road transport scenarios.	Regional level (British county)	The reliability of ESM results benefits from a PA, as it adds socio-political factors that are often hidden by "optimum" solutions suggested by ESOM.
Varho et al. [87]	Delphi-method	Development of national socio-technical scenarios towards road transport transition.	National level (Finland)	PA, as an effective and holistic way of identifying factors that shape the future of road transport, offers a broad perspective and legitimacy to the process of developing socio-technical scenarios to be applied in ESM.
McDowall et al. [88]	UK MARKAL	Development of national socio-technical scenario towards road transport decarbonization.	National level (United Kingdom)	Energy transitions can benefit from integrating ESM with PA. ESMs should be viewed not merely as quantified representations of PA, but as tools for analyzing socio-technical scenarios. PAs should be used to validate and challenge ESM results.
Venturi et al. [89]	TIMES-DK	Model formulation, by translating stakeholders' input into modeling scenarios and assumptions on road transport decarbonization.	National level (Denmark)	ESOM, as a standalone exercise focuses on long-term techno-economic optimization, overlooking critical behavioral, socio-political, and economic barriers, which can be addressed by integrating a PA.
Fortes et al. [90]	TIMES-PT	Qualitative discussion on the potential outcome that different scenarios might have on the future energy supply portfolios for different energy sectors, including road transport.	National level (Portugal)	A purely PA may overlook long-term uncertainties crucial for achieving cost-effective and feasible quantitative goals like emissions targets. ESOM, in isolation, might suggest non-carbon transport strategies that may not align with the socio-political context. Combining approaches PA with ESOM enhances understanding of energy transitions.
Forsberg [91]	TIMES-SE	Validation metric and discussion tool on model assumptions, scenarios, results, and implications related to road transport decarbonization.	National level (Sweden), desegregate at the municipal level	A feedback loop between ESOM and PA highlights the crucial role of local governments in strengthening and executing national climate policies. PA becomes an important feature to add to the ESOM, emphasizing that local actions are required to implement ESOM cost-efficient solutions.

2.5.Research gaps and main thesis contribution

Although the existing literature on road transport decarbonization has made significant strides, this thesis seeks to address two primary research gaps identified in the field. As the first, scholarly gap, conventional ESOM applied to road transport decarbonization still overlooks the intricate spatial dynamics at the local level. Dismissing local spatial dynamics hampers the understanding of road transport decarbonization as context-specific. Some scholars propose that incorporating a PA as a tool for socio-technical pathway design could enhance the local spatial dynamics in modeling exercises. However, as the second literature gap, no study was found within the ESOM field that (i) utilizes a PA as a socio-technical pathways development tool to offer insights into road transport systems at the local level, (ii) integrates socio-technical pathways, developed through a participatory manner, as a local spatial dynamics tool; and (iii) investigate the impact of road transport decarbonization across diverse municipalities and their corresponding socio-geographical contexts (i.e., urban versus non-urban settings).

Acknowledging the identified gaps in the literature regarding road transport decarbonization, this thesis offers two different types of contributions to this scholarly, namely (i) method contribution and (ii) application contribution. Both contributions aim to highlight how different socio-geographical contexts can influence the decarbonization of road transport. As a method contribution, this thesis develops an ESOM that assumes a local energy systems perspective, by adding local spatial dynamics. These dynamics are implemented through transcribing socio-technical pathways, that are developed according to a PA, involving, thus municipal officials, in socio-geographical modeling scenarios. As an application contribution, this thesis focuses on understanding the value of considering local spatial dynamics by comparing the evolution of the road transport system at the national level with that at the local level of urban and non-urban municipalities. Figure 5 identifies and summarizes the void that this thesis tries to solve while presenting the two main contributions of its work.

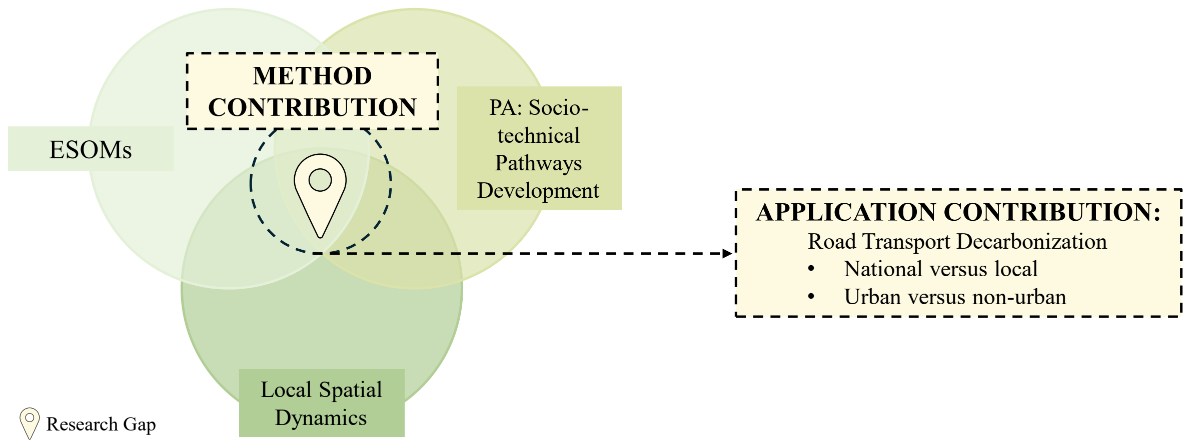


Figure 5. Research gap addressed in this thesis, highlighting in yellow the two main contributions of this thesis. ESOM, Energy Systems Optimization Models; PA, Participatory Approach.

3. Method

In this chapter, the method developed and applied in this thesis, to address the research questions and aims, is presented.

3.1. Case study

This thesis aims to analyze the effect that different socio-geographical contexts can have on the decarbonization of road transport. Moreover, this thesis tests the importance of assuming local spatial dynamics, by comparing the development of the road transport system, at the national level versus municipalities' local level. Four Swedish municipalities were selected as the case study of this thesis, complemented with national results for Sweden.

Existing climate policies, regulations, and directives are likely to shape how road transport decarbonization might develop over time. Therefore, this thesis summarizes different climate policies that directly impact the energy transition regarding road transport, with a special focus on passenger cars.

3.1.1. System definition

Located in the north of Europe, Sweden is worldwide recognized for its leading sustainability spirit. It is second highly ranked according to the Country Sustainability Ranking [92], according to which the 193 United Nations (UN) Member States' sustainability performance is evaluated towards each country's process of achieving the 17 Sustainable Development Goals (SDGs), thus becoming a good case study for this thesis.

As previously mentioned, this thesis aims at understanding the importance of local spatial dynamics when assessing road transport decarbonization. Similarly, this thesis focused on analyzing how road transport decarbonization might change according to different socio-geographical contexts. Within a total of 290 municipalities, the Västra Götaland Region houses different-sized municipalities, experiencing different energy consumption trends, variable renewable energy sources (VRESs) potential, financial context, policy aspirations, and social background. Accordingly, the Västra Götaland Region was elected to be a good case study to evaluate the differences associated with road transport decarbonization when assessed at (i) national (i.e., Sweden) versus local (i.e., Swedish municipalities); and (ii) urban versus non-urban municipalities.

According to the Swedish Association of Local Authorities and Regions (SALAR), the Västra Götaland Region is composed of different types of urban and non-urban municipalities, classified based on the number of municipalities inhabitants and working travel needs [93]. Following SALAR's classification, the Västra Götaland Region is composed of four different types of municipalities; "storstäder" (larger city); "mindre stad/tätort" (small cities); "pendlingskommun nära mindre stad/tätort" (commuting municipalities near a small city); and "pendlingskommun nära större stad" (commuting municipalities near a medium-sized city). For simplification matters, this thesis assumes that only "storstäder" municipalities are urban, while the remaining three types of municipalities are considered to be non-urban.

Capturing socio-geographical diversity was key to understanding the importance of assuming local spatial dynamics. Thus, this thesis considered the real case of four municipalities, each of them representing one of the four different municipalities types: Gothenburg – a larger city (defined as having a population of at least 200,000 inhabitants in the largest urban area); Lidköping – a small city (defined as having a minimum population of 15,000 within the largest urban area); Skara – a commuting municipality near a small city (defined as either >30% of its working population commuting to work from a small city or >30% of the employed during daytime population residing in a different municipality); and Grästorp – a commuting municipality near a medium-sized city (defined as >40% of its working population travel to a medium-sized city for work). The four municipalities assessed in this thesis are depicted in Figure 6.

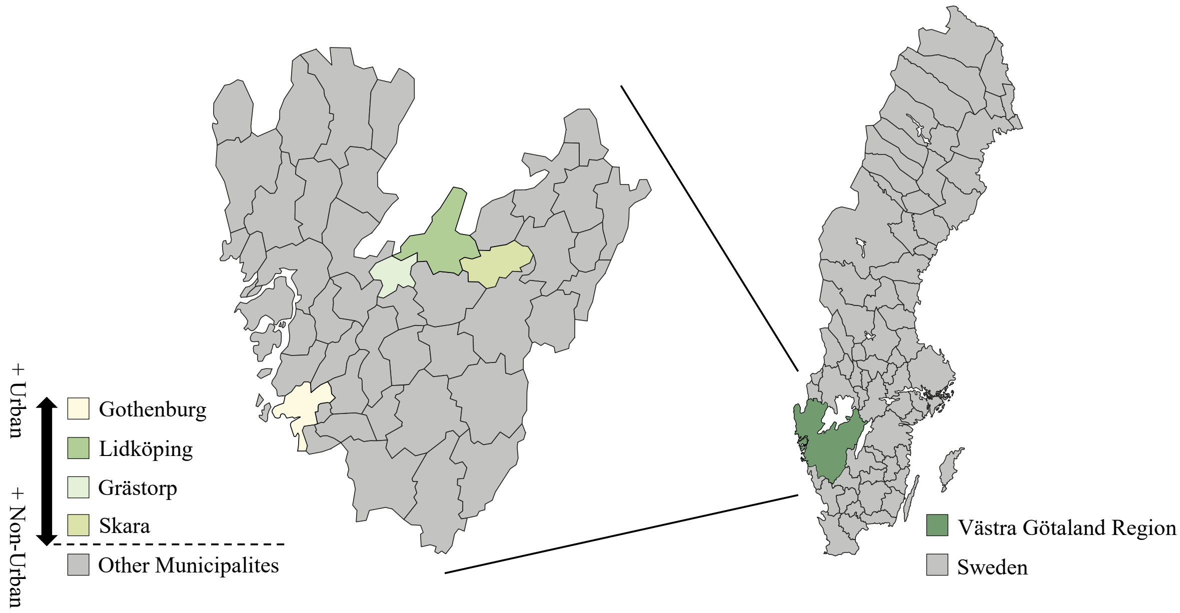


Figure 6. On the right, a map of Sweden is presented, with Västra Götaland marked in dark green. On the left side, the participating municipalities in this thesis are illustrated, according to different shades of light green and yellow.

3.1.2. Climate policies

In the light of the Paris Agreement, the European Union (EU), in 2019, stated its intention to meet a net-zero emissions target by 2050 [2]. This climate goal further motivated the EU to implement related climate policies and regulations to support the required transition. The EU's climate ambition was also extended to several countries, which, accordingly, reinforced and established new national climate targets. Within some of the EU countries, and as a response to their national climate targets, different regions and municipalities have also shown their commitment to contributing towards these goals.

Different climate policies and regulations were considered in the modeling exercise conducted in this thesis. Figure 7 summarizes which and how (i.e., see "*Policy Modeling Assumptions*" column) policies and regulations were included in The Integrated MARKAL-EFOM System

(TIMES) model. One might note that the modeling assumptions of the policies colored in green are specified in Section "*Step 2: Energy systems optimization model – TIMES*"

The policies and regulations included range from the EU to the Swedish national level. Moreover, the Swedish Västra Götaland regional and municipal climate commitments, that the participating municipalities agreed on, were also considered. It is also worth mentioning that road transport is the main focus of this thesis, especially passenger cars, treating it as a standalone system. Accordingly, only climate and transport policies, regulations, and directives directly impacting this transport sector's segment were considered, as described in the next-coming sections and summarized in Figure 7.

European Union climate policies

As a response to the Paris Agreement, in 2019, the EU presented the ***European Green Deal*** that sets the goal of achieving climate neutrality (i.e., net-zero GHG emissions), by 2050 [2]. Achieving such a goal motivated the EU to establish different climate policies, regulations, and directives that set clear milestones towards the required transition. Within the different climate policies and regulations as well as road transport directives in place, this study considered the following:

- In 2021, the EU presented ***"Fit for 55"*** [94] as a climate policy package that collects different regulations needed to meet a reduction of 55% in GHG emissions, by 2030, compared to 1990. Within this package, two specific regulations are of special interest in road transport:

  (i) ***Effort Sharing Regulation*** (ESR) was adopted in 2021 and set a specific national GHG emission reduction goal for each of the 27 Member States. This goal was set individually for each of the Member States. Personalizing this goal to each country guaranteed that every country would experience the same proportion between the cost of emission reduction and its Gross Domestic Product (GDP). Until 2030, and according to ESR, all Member States are required to collectively lower the total EU GHG emissions by 30%, compared to 2005 [95]. In the specific case of Sweden, ESR imposes a GHG emissions reduction of 50% to be met by 2030, compared to 2005 [96]. In this thesis, ESR was not directly included in the modeling exercise, as more ambitious goals in regard to GHG emission reduction by 2030 were set at the Swedish national level, according to the Swedish Climate Act (see more in Section "*Swedish National Climate Policies*").

  (ii) ***Emissions Trading System II*** (EU-ETS II) will be in place as extending the EU emission trading scheme to cover, from 2027, CO_2 emissions resulting from fuel combustion in road transport, buildings (resulting from heating systems), and small industries [97]. Currently, it is still not clear how the EU-ETS II scheme will be implemented. Hence, in this thesis, EU-ETS II was assumed in the modeling exercise to increase the total fuel cost of all types of fuels compatible with being used in internal combustion engine vehicles (ICEVs). The increase in fuel cost was assumed to be proportional to the existing Swedish Energy Tax (see more in Section "*Fuel cost and vehicle tax*").

- In 2023, the ***Renewable Energy Directives III*** (RED III) was presented as a target of achieving a renewable share of 42.5% in the overall energy mix, by 2030. Achieving this renewable share requires the total fuel consumption of road and rail transport to either achieve a renewable share of at least 29% (through blending alternative fuels) or decrease its related emissions by 14.5%, by 2030 [98]. In this thesis, RED III was not directly considered in the modeling exercise, as more ambitious goals were set at the Swedish national level, according to the Reduction Obligation (see more in Section "*Swedish National Climate Policies*").

- In 2023, the EU adopted a ***ban on new ICEVs sales***, to be applied from 2035 [99]. From a model perspective, ICEVs are not included as possible investment options after 2035 in all modeling scenarios tested, except in *Climate target* scenario (see more in Section "*Modeling scenarios*").

Swedish National Climate Policies

In 1924, Sweden introduced an ***Energy Tax*** on gasoline and, later, on diesel, when used as transport fuels [100]. In 1991, a ***Carbon Tax*** was also added to the carbon content of all transport fuels [101]. From early on, these taxes were imposed as an incentive to reduce energy consumption through improved energy efficiency, but also increase the renewable share in the total energy use. Thus, these taxes are levied on low-efficient fuels, such as fossil fuels and biogas (only energy tax is applied to biogas) [102]. Liquid biofuels, such as ethanol and Hydrotreated Vegetable Oil (HVO, in this thesis assumed to be HVO 100), are exempt from both these taxes until, at least, 2026 [103]. As part of the modeling exercise, the fuel cost of gasoline, diesel, and biogas adds the corresponding energy and carbon taxes. As no clear directives exist on ethanol and HVO taxation beyond 2026, this thesis assumed that these fuels, from a national perspective, remain exempt from these taxes during the whole modeled period (i.e., 2019-2050).

Some years after the implementation of Energy and Carbon taxes, in 2018, as an EU Member State, Sweden promised to contribute towards the Paris Agreement by presenting and adopting the ***Swedish Climate Act***. This national act states the national climate goal of meeting net-zero emissions, by 2045 [104]. The Swedish Climate Act not only sets the long-term 2045 net-zero emissions target, but also clarifies the emission reduction milestones expected to be met in 2030 and 2040. Regarding transport, this act states that domestic transport-related emissions must (i) register a decrease of 70% by 2030, compared to 1990; and then (ii) become net-zero by 2045. In this thesis, the Swedish Climate Act was included in the modeling exercise by constraining the total domestic transport-related emissions to be reduced (i) by 70% compared to 1990, by 2030; and (ii) to net-zero by 2045. It is important to note, that CO_2 is the only GHG considered in this thesis, meaning that GHG emissions reduction targets were translated into CO_2 reduction targets (see more in Section "*Emission mitigation targets and timeframe*").

Meeting the national climate target motivated the implementation of different climate policies and regulations, especially targeting road transport. In this thesis, the following national directives were considered:

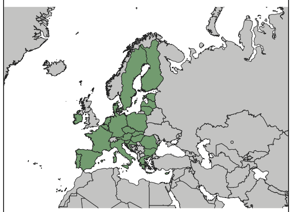
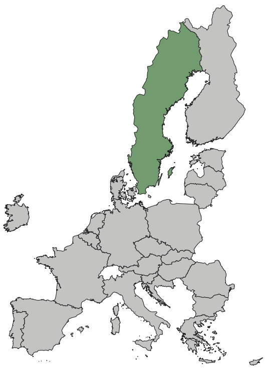
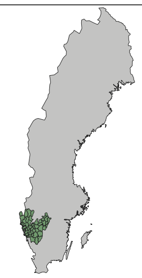
- In 2018, Sweden signed the ***Reduction Obligation*** that covers a reduction of GHG emissions from fossil fuels by blending biofuels in gasoline and diesel. Fossil fuel suppliers must reduce the GHG emission of their sold products according to a specific percentage every year, by gradually increasing the share of biofuels [105]. In this thesis, the Reduction Obligation was modeled by annually increasing the biofuel share in both gasoline and diesel, according to the values suggested by the Swedish Government, in 2018. As there is no recommendation on the biofuel share in gasoline and diesel content after 2030, this thesis assumes that the share achieved in 2030 remains until 2050. It is worth mentioning that by the time of writing this thesis (i.e., after January 2024 [106]), the Reduction Obligation registers lower requirements than the ones first presented in 2018. Still, the work presented in this thesis (i.e., **Paper I** and **Paper II**) was developed before the easing of the biofuel blending requirements and thus, this thesis assumed the values presented in 2018.

- In 2018, Sweden also adopted a "***Bonus-Malus"*** scheme, that as a "feebate system" introduces a "green tax shift", which motivates the renewing of the passenger car fleet towards lower tailpipe CO_2 emission vehicles by taxing higher emitting ICEVs. Accordingly, ICEVs running on gasoline, diesel, and biodiesel registered after the 1st of July, 2018, are taxed higher during the first three years after their registration [107]. In this thesis, the "Bonus-Malus" system was implemented by modeling a higher annual vehicle tax for gasoline, diesel, and biodiesel-powered ICEVs registered after 2019 (i.e., from the base year of the model), during the first three years after their registration (see more in Section "*Fuel cost and vehicle tax*").

Västra Götaland region and municipalities climate policies

Securing the Swedish contribution towards the Paris Agreement establishes a collective obligation, under which every region and municipality is required to contribute towards meeting the goal of climate neutrality. As a result of their climate commitment, the participating municipalities of the Västra Götaland region signed the ***"Klimat 2030"*** agreement, in 2017 [108]. With respect to this agreement, the signing municipalities agreed to achieve municipal domestic independence from fossil fuels and climate neutrality by 2030. From a domestic transport-related emission perspective, a reduction of 80% compared to the values registered in 1990 is expected to be met by 2030. Such an expectation was modeled by constraining the total domestic transport-related GHG emission (i.e., CO_2 emissions, in the case of this thesis) to experience a decrease of 80% by 2030, comparatively to 1990 (see more in Section "*Emission mitigation targets and timeframe*").

Overall, the considered EU, Swedish national, and municipal climate policies, and ambitions, were implemented in the model through model parameters and constraints that are thoroughly illustrated in Figure 7 and later presented in Section "Step 2: Energy systems optimization model – TIMES"

Geographical Application	Policy Name ("In Force" Year)	Policy Description	Policy Modeling Assumptions
 European Union	***European Green Deal (2019)***	The European Green Deal set the ambitious goal of achieving European climate neutrality, characterized by net zero GHG emissions, by 2050.	By **2050**, the total **CO_2 emissions** are constrained to be **zero**.
	"Fit for 55" (2021) — ***Effort Sharing Regulation (2021)***	Within the "Fit for 55" framework, ESR sets a national GHG emission reduction goal for each of the 27 EU countries. Collectively, ESR expects a reduction in GHG emissions of 30% by 2030, compared to 2005.	By **2030**, the **CO_2 emissions** are set to be **50% lower** than 2005's values (for Sweden).
	Emission Trading System II (2027)	Within the "Fit for 55", EU-ETS II covers the CO_2 emissions originated by fuel combustion in road transport, buildings (heating), and small industries.	From **2027**, an **increase in fuel cost, proportional to the existing energy tax,** is levied on all **fuels used in ICEVs**.
	Renewable Energy Directives III (2023)	EU expects to meet a total share of 42.5% renewables by 2030. For road transport, RED set a minimum renewable share to be blended in road and rail transport fossil fuels.	By **2030**, **renewable fuels** are required to represent at least **29% of transport energy consumption** OR **GHG emissions** from the use of fossil fuel in transport need to be **reduced by 14.5%**.
	Ban on new ICEV Sales (2035)	EU set a ban on sales of new ICEVs running on fossil fuels, to be applied from the year 2035.	From **2035**, there is **no option for investing in new ICEVs.**
 Sweden	***Energy Tax (1924) & Carbon Tax (1991)***	Both energy and carbon taxes are levied on low-efficient fuels, such as fossil fuels.	The total **gasoline and diesel fuel cost is increased** by adding the corresponding **energy and carbon tax.**
	Swedish Climate Act (2018)	National Climate Act that set: (i) long-term net zero GHG emissions target to be met by 2045; (ii) milestone targets that define GHG reduction objectives for Years 2020, 2030, and 2040.	By **2030**, the total **domestic transport CO_2 emissions** are constrained to be **70% lower** compared to 2010. By **2045**, the total **domestic transport CO_2 emissions** are constrained to be **zero**.
	Reduction Obligation (2018)	National regulation that acts on reducing the GHG emissions from fossil fuels by blending biofuels in gasoline and diesel. Fossil fuel suppliers must reduce the GHG emissions of their sold products according to a specific percentage every year, by gradually increasing the share of biofuels.	Gasoline and diesel composition **annually increases the biofuel share**.
	"Bonus-Malus" (2018)	"Feebate-system" that, as a "green tax shift", motivates the renewing of the passenger car fleet towards lower tailpipe CO_2 emission vehicles by taxing higher ICEVs registered after 1/July/2018.	Gasoline, diesel, and biodiesel (HVO) **ICEVs purchased after 1/July/2018 pay higher vehicle tax** for the first three years of utilization.
 Västra Götaland Municipalities	***"Klimat 2030" (2017)***	Regional and municipal climate target set a domestic GHG emission of 80% to be reached by 2030, compared to 1990.	**Municipalities' domestic transport CO_2 emissions** are constrained as being **80% lower** than the values registered in 1990.

Policies directly included in the modeling exercise. The non-marked policies are "overtaken" by more ambitious goals covered in the policies marked

Figure 7. Matrix of existing and future road transport-related policies. Policies implemented in this thesis are marked green. CO_2, Carbon Dioxide; GHG, Greenhouse gas; ESR, Effort Sharing Regulation; ETS, Emission Trading System; HVO, Hydrotreated Vegetable Oil (biodiesel); ICEVs, Internal Combustion Engine Vehicles; RED, Renewables Energy Directives.

3.2. Participatory energy systems modeling approach

To better assess the potential impact that different socio-geographical contexts can have on road transport decarbonization, this thesis developed and applied a participatory energy systems modeling approach, as depicted in Figure 8. This approach consists of two main steps, both included in this thesis, each being a direct outcome of **Paper I** and **Paper II**.

As a first step (**Paper I**), different socio-technical pathways for road transport decarbonization were identified in different socio-geographical contexts, resulting from developing and applying a context-specific iterative method. As a context-specific method, the pathways were identified according to a local energy systems perspective and thus, including real case municipalities and their socio-geographical specifications. Moreover, as an iterative process, the pathways were identified through a complementing loop, by combining different phases of both literature review on road transport decarbonization and municipal officials' PA. The first step here presented is thoroughly described in Section "*Step 1: Participatory approach – Local Pathways*".

The pathways identified in the first step were exclusively qualitative, missing, thus, to be quantitatively evaluated, a process added in the second step of this thesis (**Paper II**). The identified socio-technical pathways were integrated into a bottom-up cost-optimization model, TIMES, as modeling scenarios (in this thesis, "pathways" refer to various strategies – e.g., fleet electrification – that can be employed to achieve a well-defined end goal – e.g., road transport decarbonization; "scenarios" are typically used in modeling context as adding a transition perspective of the different pathways, providing how the systems will evolve from the current situation to the desired target point). Adding these pathways to the model framework allowed for integrating a local spatial dynamic perspective, typically dismissed in existing techno-economic studies. As a result of incorporating municipality and local specifications as well as road transport-related existing policy into the TIMES model, the socio-technical pathways, previously identified in the first step, were quantitatively evaluated as modeling scenarios. Thus, the model results allowed for interpreting the dynamic of the passenger car fleet towards decarbonization when comparing (i) short-term (i.e. transition) versus long-term perspective; and (ii) urban versus non-urban socio-geographical contexts. The second step of this thesis is thoroughly presented in Section "*Step 2: Energy systems optimization model – TIMES*".

Combining these two steps was motivated as adding a holistic understanding of road transport decarbonization, by merging the gap between a socio-geographical (**Paper I**) and techno-economic (**Paper II**) perspective. By doing so, this thesis treated road transport decarbonization as context-specific, testing the importance of tailoring strategies to specific local contexts, avoiding thus standardized solutions.

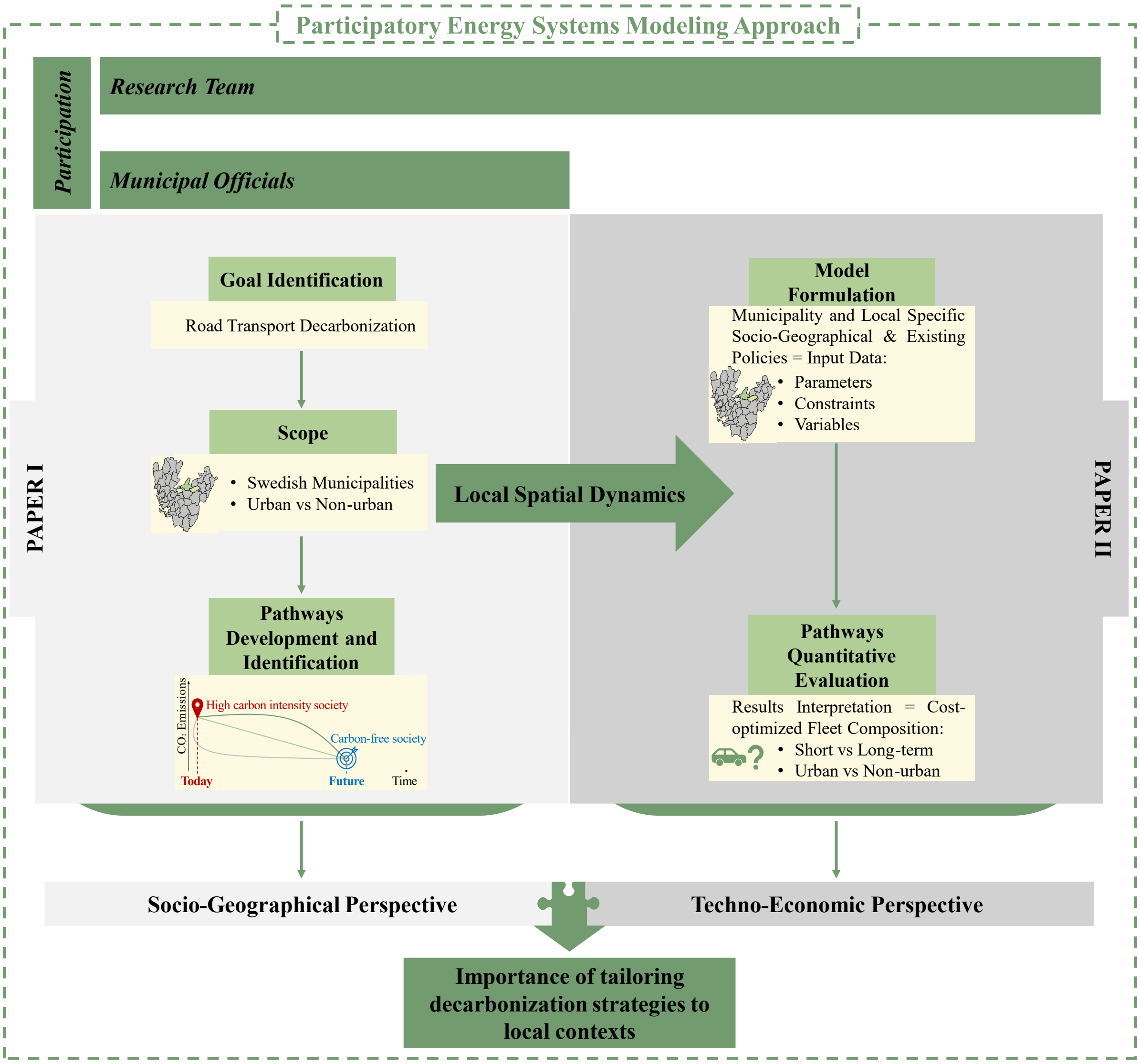


Figure 8. Framework integrated in this thesis, based on the method developed and applied in Paper I (left side, light-gray-shaded rectangle) and Paper II (right side, dark-gray rectangle). The development of this framework included the involvement of both a research team and municipal officials, as presented in the "Participation" green bars.

3.2.1. Step 1: Participatory approach – Local Pathways

As previously introduced, this thesis developed and applied a participatory energy systems modeling approach, composed of two main steps, as illustrated in Figure 8. The first step (**Paper I**) was dedicated to developing a context-specific iterative method of generating road transport decarbonization pathways, as depicted in Figure 9. As a context-specific method, the generation of pathways was tailored according to a local energy systems perspective, as a way to capture the real case of different types of municipalities and their local specifications. The iterative dimension of the developed method was explained by the complementary loop established between two phases of literature review and municipal officials' engagement (i.e., PA).

Phase 1 was initiated with a literature review on different fuels and mobility solutions towards road transport decarbonization, regardless of the level of applicability (i.e., the literature review was not exclusive to how road transport decarbonization might fall out locally). This literature review resulted in identifying the most common road transport decarbonization strategies suggested by the existing literature, strategies that this thesis defined as conceptual pathways. Due to the aim of this thesis, a local energy systems perspective was added through municipal officials' engagement, according to a PA. The municipal officials were invited to participate in semi-structured interviews as a participatory interaction. During these interviews, the municipal officials were not only presented with the conceptual pathways and their suggested fuel and mobility decarbonization strategies, but also asked for their opinions regarding the potential and possible impact of the implementation of the identified pathways. The municipal officials' perspectives were also complemented by the analysis of municipal documents. Accordingly, the opportunities and challenges associated with the implementation of each conceptual pathway were evaluated. Just the conceptual pathways classified as their implementation opportunities exceeding the associated implementation gaps were further considered feasible.

Municipal officials may sometimes have difficulty fully grasping long-term uncertainties. Hence limiting the identification of pathways to only the pathways that municipal officials deemed feasible, could lead to a biased representation of the local energy systems under study. Thus, **Phase 2**, through a second literature review and PA stages, investigated the implications that the implementation of each of the identified feasible pathways could inject into the considered local energy systems. Phase 2 was initiated with a second literature review to identify cross-sectoral linkages. These cross-sectoral linkages were depicted in a qualitative Reference Energy System (RES), allowing for the identification of which local resources act as system integrators. Locating the existing system integrators results in higher awareness regarding possible cross-sectoral synergies and competition for both local development and financing. Adding a cross-sectoral understanding of the local implementation of the feasible pathways resulted in identifying the systemic pathways. Systemic pathways are the same as the feasible pathways, with an additional and thorough understanding of their implementation-responsive impacts on local energy systems. The systemic pathways were then presented in a second round of meetings with the municipal officials. During those meetings, the municipal officials were encouraged to validate the local feasibility of systemic pathways. Such an assessment resulted in the generation of road transport decarbonization, the so-called identified pathways. As the last step, the performance of identified pathways was qualitatively evaluated according to different assessment criteria. For each of the selected criteria, each pathway's performance was labeled according to a "traffic light" scheme (i.e., labeled with one of the three typical traffic light colors: red for poor performance, yellow for neutral performance, and green for good performance). This qualitative performance assessment enabled the identification of pathways with the highest and lowest performances according to a specific criterion, see **Paper I**.

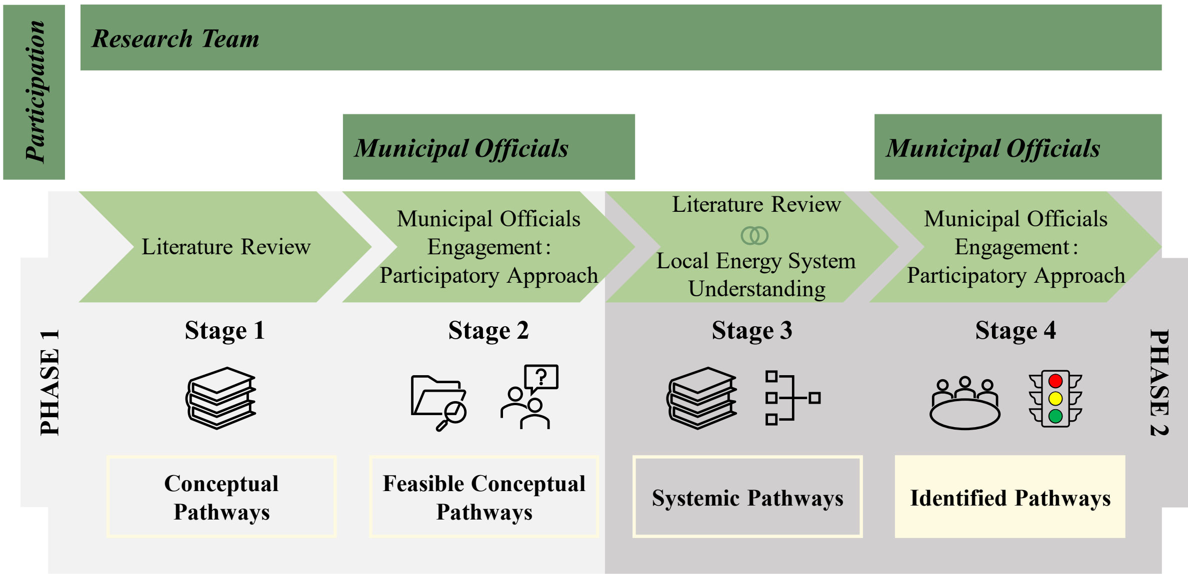


Figure 9. Framework of Step 1 developed and applied in this thesis. The framework is based on an iterative process composed of two phases – Phase 1 (light-gray-shaded rectangle) and Phase 2 (dark-gray-shaded rectangle). Each phase is composed of two stages (lighter green arrows) that are associated with the generation of different pathways (yellow outline boxes) used as an identification tool of road transport pathways ("Identified Pathways" – yellow-shaded box). Green dark bars indicate the type of participation – i.e., research team and municipal officials – associated with each stage.

3.2.2. Step 2: Energy systems optimization model – TIMES

In this thesis, a cost-optimization model was developed according to the TIMES modeling framework (**Paper II**) [33]. TIMES modeling framework development and continuous updates are the responsibility of the Energy Technology Systems Analysis Program (ETSAP), at the International Energy Agency (IEA) [109].

According to the TIMES modeling framework, the model developed and presented in this thesis is a deterministic Linear Programming model that combines flexible temporal modeling (i.e., the TIMES modeling framework compromises both short-term – daily, seasonal, single year – and long-term – many years – modeling scales) with both a detailed sectoral representation and a spatial dynamic approach (i.e., the TIMES modeling framework allows for considering spatially desegregated modeling regions [91],[110]). Thus, it can capture the heterogeneity in, and between, supply-side and demand-side factors, as well as other socio-economic and political differences within the modeling regions of e.g., a single country – Sweden, in the case of this thesis – and different municipalities – the four Västra Götaland participating municipalities, in the case of this thesis. Such a modeling approach depicts the development of the energy systems over time, showing how decisions made in a specific time period will impact future time periods. TIMES modeling framework is acknowledged by its broad and multi-geographical scope, becoming a good fit to model energy transition from various geographical scales (from a local to a global perspective) [111].

While part of the Energy, Economy, Environment, and Engineering (E4) models, the TIMES modeling framework is also defined as a bottom-up model. As such, TIMES is a technology-explicit model, allowing for a detailed techno-economic representation of the energy systems under study. This representation is complemented by the partial-equilibrium nature of TIMES models, which captures the energy carriers and energy end-use technologies composing the energy sector under study as well as the techno-economic interactions between them. Nonetheless, as a partial-equilibrium model, TIMES does not capture the interactions with the rest of the economy, challenging a broader analysis of the potential impacts that a given policy might inflict on the whole society [35]. It is also important to note that while the TIMES' structure fits the representation of all energy sectors, in this thesis, the road transport sector is treated as a standalone system (i.e., the only energy sector modeled in this thesis, see more in Section "*Road transport sector* ").

According to the scope of this thesis, the objective of the TIMES model is to identify the lowest-cost configuration that satisfies future transport demands, under different modeling constraints and assumptions, over the entire modeled time horizon. The total system cost, expressed in net present values (NPV), as the objective function, is calculated as follows in Equation (1) [33]:

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

The NPV represents the minimized total systems cost over the chosen modeled time horizon. The term *ANNCOST (r,y)* is composed of the annual cost for a specific modeling region (*r*) in a given year (*y*). In the context of this thesis, the term *ANNCOST (r,y)* is a sum of (i) annual investments in new vehicles as well as refueling and charging infrastructure; (ii) fixed (e.g., annual vehicle tax) and variable (e.g., repair costs) operation and maintenance (O&M) costs; and (iii) fuel cost. Over the whole modeled time horizon, all the aforementioned costs are discounted for each modeled time period relative to the reference year (*REFYEAR*) (i.e., base year), 2019. This thesis used a discount rate ($d_{r,y}$) of 4%, applied to all technologies and modeling regions (*r*). Worth mentioning that the modeling exercise conducted in this thesis examined a total of six modeling regions: the country Sweden, the Västra Götaland region, and the four municipalities presented in Section "*System definition*".

Considering to be technology-explicit, different techno-economic specific data (e.g., investment, O&M, and fuel costs but also vehicles' lifetimes, efficiency, and fuel economy) were implemented in this TIMES model, as parameters. Apart from the objective variable, the model was designed to consider two more decision variables: (i) vehicle available capacity (*CAP (p,r,y)*), representing the sum between the initially modeled capacity (if the lifetime is not yet reached) and the investments (both made in past and current modeled time period) in a specific vehicle (*p*), in a given modeling region (*r*), during a specific modeled time period (y); (ii) *GEN (p,r,t)*, representing the transport activity (i.e., demand) produced by a specific vehicle (*p*) in a modeling region (*r*), at the modeled time period (*y*). Both decision variables are interlinked according to the conversion factor between units of capacity (i.e., number of vehicles) and activity [i.e., passenger-kilometers (pkm)], as follows in Equation (2) and (3):

$$CAP\ (p, r, t) * CF\ \left(\frac{number\ person*km}{vehicle}\right) \geq GEN\ (p, r, t), \text{ with} \tag{2}$$

$$CF\ \left(\frac{number\ person*km}{vehicle}\right) = Occupancy\ Rate \left(\frac{number\ person*km}{vehicle}\right) * Annual\ Mileage\ (km) \tag{3}$$

The load balance is an intrinsic constraint applied in the TIMES model. According to such a constraint, the total road transport demand (*D (r,t)*), as a parameter exogenously defined, is required to be met under the whole modeled time horizon, according to the following Equation (4):

$$\sum_{p} GEN\ (p,r,t) \geq D\ (r,t) \tag{4}$$

The TIMES model operates according to perfect foresight, therefore holding a complete knowledge of the exact demands and costs for all the modeled time horizon. Within the scope of this thesis and according to the lowest systems cost, such a feature enables the model to optimize the decision between utilizing the existing vehicle fleet or investing in new vehicles. The model also accommodates a residual value of the investments that did not yet reach the end of their lifetime at the end of the modeled time horizon, the so-called salvage value. As representing the expected resale value of goods, the salvage value, in the context of this thesis, ensures that investments in vehicles with remaining lifetimes continue to be economically viable at the end of the modeled time horizon.

The specific input data, assumptions, and modeling scenarios considered in the TIMES model developed and implemented in this study are a comprehensive part of **Paper II** and will be presented in the following sections.

Road transport sector representation

As previously mentioned, road transport was the only energy sector explicitly modeled in this thesis. Within road transport, passenger cars were the core of the modeling exercise. Figure 10 outlines the structure according to which passenger cars were implemented in this thesis.

Considering the aim of this thesis, the model was run at the local level of the four participating Swedish municipalities, and complemented by runs at the Swedish national level, capturing how road transport decarbonization might unfold according to different socio-geographical contexts and spatial scales. Albeit not being the central focus of this thesis, public transport (buses) and trucks were partly included in the modeling exercise, at the Västra Götaland region level. Expanding the modeling scope to these transport modes was a key discussion in evaluating potential cross-sectoral fuel competition under some of the local modeling scenarios.

Various parameters were included in the model to represent existing national and municipal passenger car fleets, as well as investments in new vehicle options: (i) current total transport demand as well as future expectations; (ii) existing fleet composition; (iii) occupancy rate; (iv) vehicle’s fuel economy; (v) fuel and electricity costs; (vi) annual mileage; (vii) existing vehicle’s retirement; (viii) new vehicle’s lifetime; and (ix) hurdle rates. Similarly, new investment options were fed into the model as variables.

In this thesis, not only input data specific to the modeling level were implemented [in Figure 10, the square symbol represents input data specific to the modeling level (i.e., national, regional, and local), while the triangle symbol represents input data that is not specific to the modeling level, yet applied (e.g., at the modeled local level, when modeling the participating municipalities Swedish, climate targets are applied, despite being decided at the national level)]. External policies (i.e., policies represented by the triangle symbol in Figure 10) were also added to the modeling exercise as both parameters, but also constraints, namely (i) international climate agreements (see Section "*Paris Agreement in European Union climate policies*"); (ii) international policy measures (see EU-ETS II and a ban on new ICEV sales in Section "*European Union climate policies*"); (iii) national climate goals (see Swedish Climate Act in Section "*Swedish National Climate Policies*"); (iv) national policy measures (see the energy and carbon tax, as well as reduction obligation and "Bonus-Malus" scheme in Section "*Swedish National Climate Policies*"); and (v) regional and municipal climate commitments (see Klimat 2030 in Section "*Västra Götaland region and municipalities climate policies*").

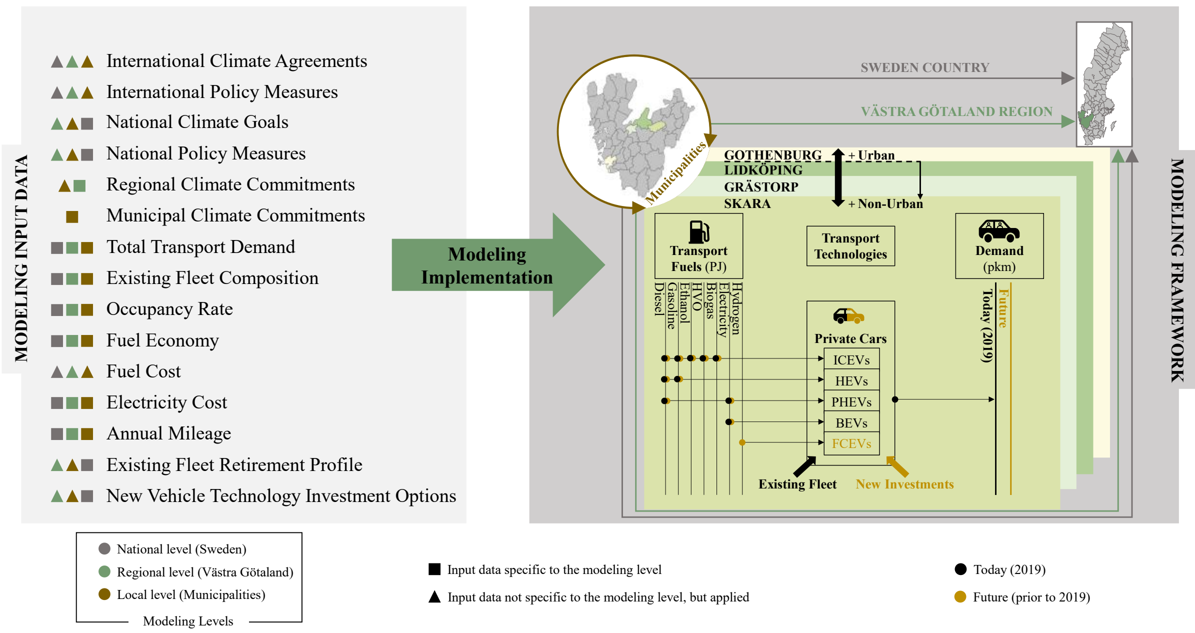


Figure 10. The TIMES model framework was developed and applied in this thesis. The modeling-specific input data is marked on the left side in the light-grey-shaded rectangle. The input data varies according to the three considered modeling levels – national, regional, and local. The square symbol represents input data specific to the modeling level, while the triangle symbol represents input data that is not specific to the level, yet applied in the modeling exercise. The modeling rationale is presented on the right side in the dark-grey-shaded rectangle. BEVs, Battery Electric Vehicles; FCEV, Fuel Cells Electric Vehicles; HEVs, Hybrid Electric Vehicles; HVO; Hydrotreated Vegetable Oil (biodiesel); ICEVs; Internal Combustion Engine Vehicles; PHEVs, Plug-in Electric Vehicles; pkm, Passenger-kilometers.

Input data and modeling assumptions

Typically, a TIMES model is developed according to different input data and modeling assumptions, both exogenously implemented into the model. The main input data and modeling assumption implemented in this thesis will be presented below. Specific input data and modeling assumptions that were added to this thesis, and not presented in **Paper II,** are thoroughly presented in the Appendix.

Emission mitigation targets and timeframe

As previously mentioned in Section "*Swedish National Climate Policies*", Sweden, in response to the Paris Agreement committed to a national climate goal of meeting net-zero domestic GHG emissions by 2045 [104]. Achieving this national climate goal also implies a reduction of total domestic transport GHG domestic emissions by 70%, compared to the 2010 level [108]. Aligning with other Swedish municipalities, the Västra Götaland region is committed to a climate intermediate goal that expects each Västra Götaland municipality to become "fossil fuel independent" by 2030 (i.e., according to "*Klimat 2030*" municipal agreement, fossil fuel independence is defined at the municipal level as "the emissions of GHGs must be reduced by 80 % from the 1990 level by the year 2030" [108]). These three climate targets were considered in the model developed and applied in this thesis, as both intermediate and long-term goals. The national 2030 milestone was constrained as an intermediate emission mitigation target, at the national level, while the *"Klimat 2030"* target was defined as the intermediate target imposed at the modeling level of the participating municipalities. Regardless of the modeling level, the 2045 net-zero GHG emission (i.e., Swedish national target) was set as the long-term target. As previously stated, only CO_2 emissions were considered, meaning that these emission mitigation targets were applied to CO_2 emissions. Moreover, this thesis only considered the CO_2 emissions directly generated from the combustion of fossil fuels. For biogenic fuel options and energy carriers like electricity and hydrogen, upstream emissions have been disregarded and, thus, treated as carbon neutral.

Considering the aforementioned emission mitigation targets, the TIMES model was developed from the base year, 2019, until 2050, making its final year. Embracing the dynamic perspective of the TIMES model, the timeframe from 2019 to 2030 was modeled in one-year time steps. This granular temporal scale enables a comprehensive understanding of the transition path from the base year to achieving the intermediate emission mitigation target, set to be met in 2030. Post-2030, the model becomes a system monitoring tool, aimed at comprehending long-term implications (i.e., to understand how the studied systems, after meeting a given goal, will appear in the long-term). Hence the model applied five-year time steps between 2030-2050.

Table 2 summarizes the emissions reduction targets and corresponding timeframe, according to which the TIMES model was developed.

Table 2. CO_2 emission reduction targets – intermediate and long-term targets - and related modeling assumptions, varying according to a national (i.e., Sweden) and local (i.e., participating municipalities) level. CO_2, Carbon Dioxide; NA, Non-applicable.

Target (Year)	**Municipality Fossil Fuel Independence**	**CO_2 Emissions Reduction**	**Modeling Assumption**
Base Year (2019)	No	0	CO_2 emissions mitigation targets are implemented relatively to the total modeled emissions in 2019.
Intermediate National Climate Target (2030)	NA	70%	**Intermediate Target**: At the national modeling level, the total CO_2 emissions are constrained to be reduced by 70%, compared to the 1990 level.
Municipal Climate Target (2030)	Yes	80%	**Intermediate Target**: At the municipal modeling level, the total CO_2 emissions are constrained to be reduced by 80%, compared to the 2010 level.
National Climate Target (2045)	NA	100%	**Long-term Target:** The total CO_2 emissions are constrained to be zero by 2045.

Transport demand and technology database

Transport demand is expressed in pkm for both present values and future estimations. Future transport demand is modeled in regard to an annual increase. Such an annual increase reflects the expected growth of GDP. Accordingly, private car transport demand increases 1.1%

annually from the base year until 2040, followed by a 0.6% increase, as suggested by Trafikverket [112].

The transport technology database implemented in the TIMES model accounts for both the existing fleet and the new investments made in different vehicle options. As the existing fleet, five different vehicle technology options were considered: ICEVs, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). For the case of BEVs, two types of battery sizes were considered, a small-size BEV housing a 20-kWh battery and an average-size BEV housing a 40-kWh battery. The five types of registered vehicles were assumed to run on seven fuel options (in this thesis fuel is used as a simplified term for energy carriers): gasoline, diesel, biogas ethanol, HVO, electricity, and hydrogen. For future fleets, the model included the same vehicle options as those already registered in the existing fleet, with the addition of fuel cell electric vehicles (FCEVs) as an investment option starting in 2030. New investment vehicle options were modeled considering a fixed lifetime (i.e., contrary to the existing fleet that was modeled according to a retirement profile).

Fuel cost and vehicle tax

Seven fuel options were added to the TIMES model as an exogenous (i.e., imported) commodity used to fulfill a specific transport demand. These fuels were modeled with a cost associated. The cost assumed for each of the available fuels sums up the costs linked to three stages of the entire fuel supply chain. Accordingly, production, transmission and distribution, as well as infrastructure costs were considered. For gasoline and diesel fuels, the Swedish energy and carbon taxes were added. The energy tax was also added to biogas and from 2027, this tax was extended to all fuels compatible with being used in ICEVs, according to EU-ETS II (see more in Section "*European Union climate policies*").

Each vehicle option was modeled according to specific fixed and variable O&M costs. In case of new investment in ICEVs running on diesel, gasoline, and HVO, an extra vehicle tax was added, as a fixed O&M cost, following the "*Bonus-Malus*" scheme (see more in Section "*Swedish National Climate Policies*").

Socio-geographical factors

According to the aim of this thesis, different socio-geographical factors were considered in the development of the TIMES model. Specifically, (i) occupancy rate, (ii) fuel economy, (iii) electricity cost, and (iv) annual mileage were added as socio-geographical specific modeling parameters, differing between the five modeling regions (i.e., Sweden and the four participating municipalities).

Calibration

The calibration of the model's base year is defined as a crucial step in the TIMES model development [33]). Such a need can be explained according to two main reasons: (i) the base year corresponds to a past timeframe, introducing constraints on the model's flexibility and adaptability due to the reliance on user-defined variables, constraints, and parameters rooted in statistical and historical data; and (ii) developing a TIMES model entails a complex data-intensive process, involving the aggregation of diverse and independent data sources, which can compromise the representation of the studied energy system. Appropriately, developing a robust model seeks to be calibrated, which can be done, by setting all model variables as fixed based on a historical year (not the base year) and corresponding official energy statistics.

In the context of this thesis, the year 2022 was used as a calibration metric, meaning that the existing stock and transport demand within the model were calibrated relative to the official national statistics.

Modeling scenarios

As highlighted by Krook Riekkola [111], the future road transport path, like any energy system, is dependent on different underlying key drivers and how those may unfold over time. Examples of road transport key drivers can be climate policy (e.g., the Paris Agreement), market investment preferences (e.g., currently high upfront BEVs investment cost, relative to ICEVs), and user behavior (e.g., vehicle choice, route selection, and trip scheduling). Assessing and understanding future road transport development can benefit from having "images of alternative futures", defined as scenarios by Nakicenovic et al. [113].

As documented by Loulou et al. [33], the TIMES modeling process applies a scenario rationale that tests a set of coherent assumptions about the logic of a given energy system, answering, thus, "if-then" questions. Such scenarios can be framed according to quantitative assumptions (e.g., modeling assumptions), qualitative storytelling (e.g., stakeholders' PA), or combine both, as suggested by the Intergovernmental Panel on Climate Change (IPCC) [114]. Yet, as Skea et al. [115] and Morgan et al. [116] explain, merging both approaches can be challenging and often results in a disrupted representation of the energy systems under transition. As suggested in **Paper I**, such a risk can be mitigated by developing scenarios according to an iterative and co-development framework. By doing so, scenarios will merge by combining different modeling quantitative literature review assumptions and stakeholders' semi-structured interviews, becoming key for implementing local spatial dynamics and thus, a great local energy systems assessment tool.

In the context of this thesis, different modeling scenarios explored the potential impact that different socio-geographical contexts and local spatial dynamics bring to road transport fuel choices. The scenarios were drawn to test different CO_2 mitigation metrics, in response to the intermediate and long-term targets of this thesis.

Climate scenarios were modeled to reflect both the actual and yet-to-be-implemented international commitments and national policy measures that are anticipated to influence the transition path of road transport. To provide a comprehensive local energy systems perspective, this thesis modeled local road transport scenarios, developed in collaboration with municipal officials, as a direct outcome of **Paper I**. Modeling these local scenarios allows for implementing local spatial dynamics in the model framework. Figure 11 illustrates the different scenarios evaluated in this thesis, detailing their main modeling assumptions.

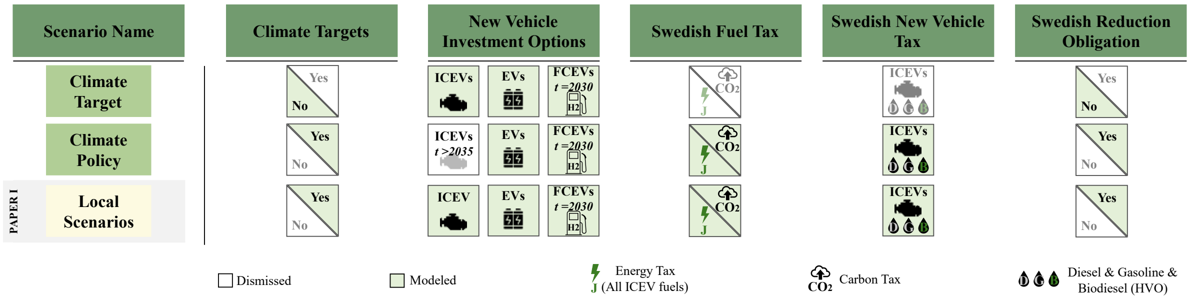


Figure 11. Scenario matrix. CO_2, Carbon Dioxide; EV, Electric Vehicles (including plug-ins, hybrids, and battery electric vehicles); FCEVs, Fuel Cell Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles.

The *Climate target* scenario is based on the current road transport, fuel composition, and fuel costs of the five modeled regions (i.e., the four Västra Götaland participating municipalities, complemented with the level Sweden). Under this scenario, only climate targets are considered, meaning that related climate mitigation policies are disregarded. At the national modeling level, the model is constrained to meet an emission reduction of 70%, compared to 2010, by 2030. At the local level, the model constrains emissions of the participating municipalities to be reduced by 80% compared to 1990, by 2030. The net-zero emissions target needs to be met by 2045, regardless of the modeling level. Swedish energy and carbon tax, “*Bonus-Malus*” vehicle tax, and reduction obligation are added in this scenario at both national and municipal levels. Accordingly, compared to the other scenarios, this scenario will highlight the importance of climate policies from a cost-optimization perspective.

The *Climate policy* scenario is considered to be an extension of the climate target scenario, as it also applies the climate policies, both those already in place today and future ones.

Local spatial dynamics were implemented in the modeling exercise by modeling different *Local* scenarios, allowing for a socio-geographical understanding of road transport decarbonization. Such scenarios were developed by picturing the local pathways identified in **Paper I**. The local scenarios were also evaluated through sensitivity analysis. Sensitivity analysis is a commonly used metric to test how a model and its outcome react to changes in input data and modeling assumptions [117],[118]. By doing so, the tested parameters can be evaluated as binding or not. In this thesis, the specific parameters used for modeling local scenarios were subjected to sensitivity analysis. Both the local scenarios and related sensitivity analysis will be thoroughly discussed in Section “*Results*”.

4. Results

This chapter presents the selected results of the method developed and applied in this thesis, including thus the main results of **Paper I** and **Paper II**. To facilitate the understanding of the results, this chapter is divided into three sections:

- Identification of local pathways, as a direct outcome of **Paper I**.
- Transcription of socio-technical pathways into local socio-geographical modeling scenarios.
- Fleet composition and fuel consumption cost optimization according to two case studies:

  (i) National (i.e., Sweden) versus local (i.e., participating municipalities) level.

  (ii) Urban versus non-urban municipalities, as a direct outcome of **Paper II**.

4.1. Step 1 results: Identification of local pathways

In Step 1 of this thesis, some local pathways were identified by combining different phases of literature review findings and municipal officials' PA. Figure 12 presents the whole process of identifying local pathways, describing it as an iterative loop between different stages and related outcomes (i.e., intermediate pathways: conceptual; feasible conceptual; and systemic pathways).

As a first step, an initial literature review highlighted which road transport technologies and strategies are often presented as potential solutions for passenger car decarbonization, namely (i) fleet electrification; (ii) public transport; (iii) biofuels; (iv) hydrogen; (v) micromobility; (vi) mobility as a service (MaaS); and (vii) autonomous vehicles. These seven most likely non-fossil fuel solutions were translated into seven conceptual pathways.

The conceptual pathways were presented and evaluated according to the local energy systems context and the specifications of the participating municipalities. Municipal officials' PA guaranteed such a local perspective through email communication, questionnaires, semi-structured interviews, and official documents' analysis. Under this stage, each conceptual pathway's local implementation potential (i.e., local feasibility) was evaluated. Only the pathways assessed as having a positive local implementation potential (i.e., implementation enablers greater than challenges) were considered feasible. Due to the need for short-term solutions (i.e., "*Klimat 2030*"), municipal officials favored pathways associated with mature technologies, voting positively for (i) fleet electrification; (ii) public transport; and (iii) biofuels. These three pathways were defined as feasible conceptual pathways.

The three feasible conceptual pathways still devalued potential cross-sectoral implications that their implementation could have on other parts of the local energy system. Hence a new literature review stage was added to the process of local pathways identification. This literature review targeted the identification of cross-sectoral linkages, adding thus a local-regional spatial dimension to the whole process. This dimension was represented by identifying systems integrators, which are local resources that find applicability in different local energy systems sites. In the context of this thesis, biomass, biogas, and VRESs, as local resources, were defined as systems integrators. Identifying the systems integrators better illustrated which technical and socio-economic factors may influence the implementation of a given pathway and, thus, municipalities' progress towards decarbonization. Appropriately, integrating a local-regional spatial dimension, as depicted in a local RES, clarified a descriptive cross-sectoral representation of each feasible conceptual pathway. Adding such a cross-sectoral representation to the three presented feasible conceptual pathways resulted in identifying three systemic pathways.

The three systems pathways and their "beyond road" cross-sectoral implications were described, and their local feasibility was evaluated by a second PA stage. Based on the description of each pathway, the municipal officials provided a final feasibility assessment, resulting in the identification of four road transport decarbonization pathways – "Identified Pathways":

- *Reference* pathway was identified according to today's context (as year 2019), meaning that historical and current (i) trends (e.g., transport demand and fuel prices); and (ii) climate policies are extrapolated over the timeframe given by "*Klimat 2030*". This pathway addresses concerns involving what might occur to road transport decarbonization if historical and current factors are extrapolated into the future.

- *Local self-sufficiency electricity* pathway highlights the ambition of municipalities, by solely depending on VRESs becoming self-sufficient in terms of electricity generation. This pathway limits local electricity demand, including the expected increase resulting from fleet electrification, which is to be met, on an average annual perspective, through local production. This pathway explores how local, and specifically non-urban, road transport decarbonization can leverage the local availability of VRESs.

- *Regional bio-locked* pathway dismisses the possibility of trade with bioenergy sources (in and out of a municipality), meaning that municipalities can only use what is available locally, in terms of biogas and liquid biofuels (i.e., ethanol and biodiesel – HVO). This pathway underscores the importance of local bioenergy sources by examining the implications of their availability constraints. It further aims to explore the boundaries of sector coupling at the local and regional levels.

- *Local flexible public transport* pathway benefits from the typical inter-municipal demand of the considered municipalities. This pathway highlights the role that a structured, integrated, and on-demand, public transport service plays in minimizing the downside of individual transport modes.

The performance of identified pathways was qualitatively evaluated according to different criteria, enabling the ranking of their relative performance. This assessment highlighted that: (i) the *Local self-sufficiency electricity* pathway can significantly reduce local emissions; (ii) the *Regional bio-locked* pathway provides benefits to car owners by accommodating continually ICEVs driving and giving them the freedom of planning their trips; and (iii) the

Local flexible public transport pathway reduces the need for private car travel, thereby lowering car usage and fuel demand, and consequently reducing local emissions. Such an assessment raises the awareness that the most attractive pathway varies depending on the municipalities' priorities. Nevertheless, all pathways might have the potential to contribute to the decarbonization of their road transport systems, as long as they adopt a local energy systems perspective. A local energy systems perspective, within the context of identifying pathways, allows for all municipalities within the region to follow a consistent pathway, aligning their short-term accessibility and mobility needs with long-term climate goals. This alignment is particularly significant in this study, as the interviewed officials at the three municipalities were identified as commuting hubs, with inter-municipal travel demands playing a dominant role.

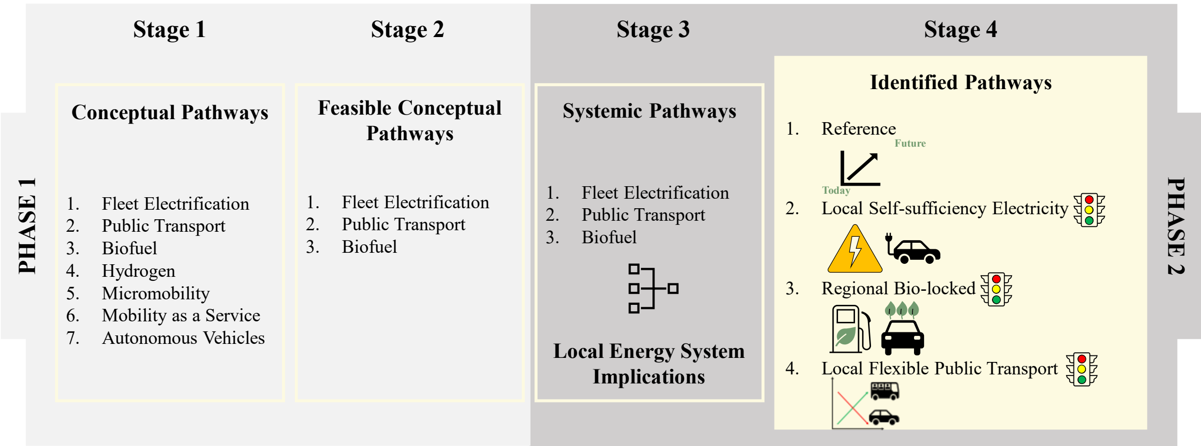


Figure 12. The outcomes of each stage of Step 1 of this thesis, resulting in four identified road transport decarbonization pathways, as presented in the yellow rectangle.

4.2.From local pathways to modeling scenarios

Local spatial dynamics were added to the modeling exercise by including the identified pathways, above presented as **Paper I** outcomes, as modeling scenarios. Transcribing the local pathways, as purely qualitative descriptive, into modeling quantitative assumptions involved rationale attribution of different model assumptions in the format of model parameters, decision variables, and constraints, as portrayed in Figure 13. Accordingly, three local modeling scenarios were considered:

- *Local self-sufficiency electricity* scenario limits the municipality's passenger car electricity demand to be met locally, on an annual average basis. Being met locally means that this demand cannot exceed the local VRESs (i.e., wind and solar) electricity production. If BEVs' electricity demand reaches this limit, the model is given the option to invest in new renewable capacity. From a model perspective, this scenario tests a potential fuel shift, by assessing what happens in case the local electricity supply is constrained, i.e., does the model prefer to either (i) invest in new local VRESs capacity; or (ii) shift the passenger car electricity demand to another fuel? As part of the assessment, this modeling scenario considers techno-economic input data – e.g., (i) current and future projection of annual electrification generation; (ii) investment and operations costs; (iii) power plant lifetime; and (iv) annual capacity factor. It is also important to note that hydrogen, although assumed to be produced utilizing electricity, is added to the municipalities as an imported commodity, meaning that hydrogen can be used with no constraint, in this scenario.

- *Regional bio-locked* scenario restricts the whole regional road transport biofuel demand to what is regionally produced within the Västra Götaland region. Such a scenario calls for evaluating the use of biofuels for cars in a potential competition for biofuels among other transport segments. Thus, under this scenario, both public transport (i.e., buses) and trucks were added to the modeling exercise. Moreover, only biogas and biodiesel (HVO) are currently being produced regionally, meaning that these two biofuel options are the only biofuels considered possible, to use in this scenario (i.e., ethanol was excluded, since it is produced outside the Västra Götaland region). Both biogas and biodiesel are available in the model and can be consumed within the regional production capacity at their base case fuel costs. This scenario tests the regional allocation of these biofuels, across road transport segments. This allocation aims to highlight the monetary willingness and thus, capturing the varying levels of acceptance among different road transport segments, regarding the use of these biofuels. The total annual average regional production of both biogas and biodiesel, as well as techno-economic buses and trucks-related input data were added to this scenario. It should be noted that the export of biofuels from the Västra Götaland region is assumed negligible, and it is further assumed that the fuel production levels remain at current levels.

- *Flexible public transport* scenario exogenously envisages a modal shift from passenger cars to public transport. This shift is represented by reducing the demand for passenger cars proportionally to the increase in bus transport demand. Thus, both the municipalities' passenger cars, but also regional public transport systems, were modeled under this scenario. Modeling this modal shift is expected to increase flexibility in managing the existing vehicle stock. By reducing demand for passenger car transport, there is potential to extend the lifespan of current private cars, as meeting the CO_2 emissions reduction targets can still be possible with the current fleet.

Pathway ➡ Scenario (PAPER I / PAPER II)	PAPER I: Qualitative Local Road Transport Pathways	PAPER II: Modeling Quantitative Local Road Transport Scenarios — Model Formulation: Parameters	Decision Variable	Constraints	Extra Outputs
Local Self-sufficiency Electricity	*"In this pathway, from the average annual perspective, a given municipality is fully supplied by local energy resources regarding the stationary energy sector (...) This pathway evaluates how rural road transport decarbonization can benefit from the local availability of VRESs."*	NA	• Investments in new VRESs	• Municipal passenger cars electricity demand ≤ local existing VRESs • Local existing electricity consumed at base case fuel cost	• Fuel shift assessment: electricity versus other alternative fuels • New electricity cost when investing in new local electricity production sites
Regional Bio-locked	*"This pathway emphasizes the role of local bio-energy sources by understanding what happens if the availability of these sources is constrained (...) tests the local/regional sector-coupling boundaries."*	NA	NA	• Regional road transport biogas, and biodiesel demand ≤ regional existing biogas and biodiesel • Regional existing biogas and biodiesel consumed at base case fuel cost	• Cross-road transport segment biogas and biodiesel allocation assessment • Monotary willingness of the different road transport segments to pay for consuming biogas and biodiesel
Local Flexible Public Transport	*"This pathway looks at how public transport can reduce the travel demand of cars and, thereby, lower the environmental impact of individual transport modes."*	• Proportional bus passenger transport demand increase and passenger car transport demand decrease	NA	NA	• Flexibility of the existing stock development

Figure 13. Transcription of qualitative road transport pathways into modeling local scenarios and related modeling assumptions. NA, Non-applicable; VRESs, Variable Renewable Energy Sources.

4.3. Step 2 results: Participatory energy systems modeling outcome

This section outlines the findings from the TIMES model tailored to the socio-geographical contexts of Sweden as a country, and four Swedish municipalities. The results presented mainly focus on the fleet composition and the fuel consumption of passenger cars. It is worth noting that while the results varied between urban and non-urban municipalities, similar trends emerged across the three different non-urban municipalities. Therefore, the results on local differences between different types of socio-geographical municipalities are presented to illustrate the most significant disparities between the urban municipality under consideration and the average outcomes of the three non-urban municipalities.

4.3.1. National versus local level

The fleet composition for both the national level (Sweden) and local level (two types of municipalities – the urban and the average over the three non-urban municipalities) was evaluated according to two different scenarios, *Climate target* and *Climate policy*, as presented in Figure 14.

At the national level (Figure 14 a left graph), under the *Climate target* scenario (i.e., the model is only constrained to meet a net-zero 2045 emission goal) the passenger car fleet composition experienced a gradual increase towards diesel ICEVs dominance. Such dominance is understood by two main factors. First, biodiesel (HVO) was modeled as a 100% biogenic fuel and thus treated as carbon neutral, meaning that it can be used with no constraints, still under CO_2 emission reduction targets. Similarly, as a result of a pure cost-optimization modeling exercise, the optimal solution tends to be reflected over the passenger car associated with the lowest investment cost and fuel cost, which under this scenario and thus emissions constraints, was, for a major part of the model horizon, ICEVs running on biodiesel. This trend started to shift post-2045, where BEVs achieve a cost-parity with diesel ICEVs, becoming thus the cost-effective choice. Both the urban (Figure 14 b left graph) and the non-urban (Figure 14 c left graph) municipalities maintained the same trend as the national case, with ICEVs running on biodiesel prevailing until later years and BEVs starting to change the fleet dynamics post-2045.

Testing the impact that existing and future climate policies can have on passenger cars' fleet dynamics, as done in the *Climate policy* scenario, revealed an acceleration in the whole fleet electrification. In the case of national (Figure 14 a right graph) and urban municipality (Figure 14 b right graph) levels, more than 50% of the whole fleet was characterized as electric already in 2030. In the non-urban municipalities (Figure 14 c right graph) case, fleet electrification became dominant after 2035.

Comparing the national case with two different socio-geographical municipalities might initially seem odd, as in all cases electrification is gradual and increasingly taking over the fleet. Yet, when looking at how the fleet dynamics change according to different spatial dimensions, it becomes worth noting that while fleet electrification was dominated by small BEVs at the national level as well as at the urban municipality level, the average BEVs were preferred in the non-urban municipalities, although their relative upfront purchase cost. This difference is explained by different socio-geographical factors that characterize the travel needs in these three case studies. In the national and the urban municipality cases, both low average milage (Figure 14 d) and trip distances (Figure 14 f) favored a lower upfront purchase cost, meaning that the gradual model choice shifting towards small BEVs only happened when these vehicles were gauged as the cheapest model option to invest in. On the other hand, the model favored a lower overall driving cost for average BEVs in non-urban municipalities. Due to their good fuel economy (Figure 14 e), average BEVs require less frequent fast charging, reducing total fuel costs over longer trip distances (a typical characteristic of non-urban municipalities, as seen in Figure 14 f). Therefore, the average BEVs emerged as the most economical solution for non-urban municipalities, at a cost parity of 9%, compared to diesel ICEVs.

Overall, the shift in fleet dynamics aligns with the model's cost optimization, prioritizing either low upfront purchase costs or more efficient technologies based on different travel patterns, defined as varying according to different spatial and socio-geographical contexts. Analyzing fleet dynamics at the national level and in two distinct socio-geographical municipalities reveals that while a national perspective can capture the broader picture, it may not fully account for local specifications. Although a national approach, based on weighted average values, might accurately represent an urban perspective, it falls short in capturing the nuanced socio-geographical factors that influence road transport decarbonization. Therefore, a local spatial dimension is essential for understanding and planning a comprehensive and inclusive road transport decarbonization, treating it as a context-dependent process.

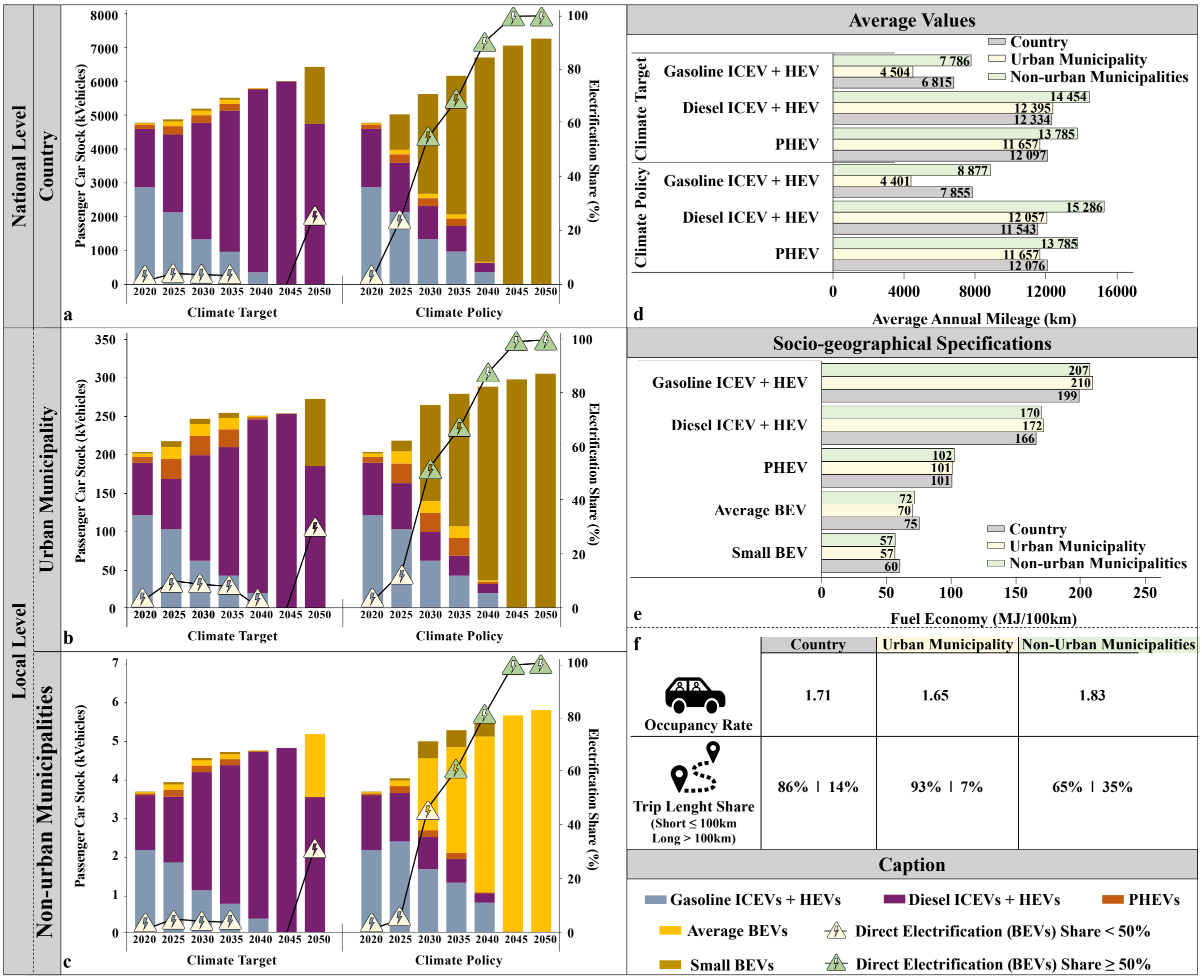


Figure 14. Fleet mix in the *Climate target and Climate policy* scenarios, presented in stock of thousand (k) vehicles (left axes). The black curves show the electrification share (right axes) (a-c). For electrification shares above or equal to 50%, the symbol of electricity is green color. Socio-geographical average values – annual mileage - and related factors – fuel economy, occupancy rate, and trip length share – are also represented (d-f). Only the annual mileage of vehicles that changed between national and local perspectives are presented in graph d. BEVs, Battery Electric Vehicles; FCEVs, Fuel Cell Electric Vehicles; HEVs, Hybrid Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

4.3.2. Urban versus non-urban municipalities

Comparing how the fleet composition is projected to evolve over meeting the set climate targets at the national level and according to two different socio-geographical municipalities motivates road transport decarbonization to be treated as a context-dependent process. As a context-dependent process, it calls for being addressed at the local level, which in this thesis was done by modeling local scenarios, developed in a participatory manner.

Fleet composition

Results for the *Local self-sufficiency electricity* scenario (Figure 15 a and d) showed a shift in fleet dynamics when compared to the *Climate policy* scenario (Figure 14 b and c right graphs). For the urban municipality (Figure 15 a), meeting the fleet electrification suggested in the *Climate policy* scenario (Figure 14 b right graph) exceeded the local VRESs capacity. This resulted in the model showing diesel ICEVs to be the cost-effective choice up to 2030. From 2030, FCEVs became available as an investment option and due to the vehicle taxes associated with ICEVs, were perceived as the most cost-effective choice, when compared to biofuels. From 2045, FCEVs represented more than 50% of the whole urban fleet. In non-urban municipalities (Figure 15 d), the existing local VRESs could not self-sustain the fleet electrification as projected in the *Climate policy* scenario (Figure 14 c right graph). Thus, diesel ICEVs were deliberated as the cost-optimal choice in the early years. Post-2035, motivated by the ban on the sales of new ICEVs, the model opted for a shift towards average BEVs, which came hand in hand with an investment in new local VRESs capacity. The difference in fleet composition between urban and non-urban municipalities stems from differences in land availability for VRESs capacity. Compared to non-urban municipalities, the urban municipality faced strict land constraints to invest in new local VRESs. Consequently, urban passenger car fleet electrification must rely heavily on the transmission grid to supply electricity, as their local generation capacity is insufficient. For the urban municipality, the model identified, in the early years, importing fuels, first biofuels and, later, hydrogen as the most cost-effective solution. For the non-urban municipalities, biofuels also played an important transition role, yet BEVs emerged as the least-cost solution, post-2035. Post-2035, the model prioritized engines with the lowest fuel costs (i.e., electricity), due to the longer travel distances in these regions. Despite delayed electrification due to the high investment cost associated with new VRESs capacity, the non-urban municipalities held the potential to meet the increased electricity demand from BEVs with locally produced electricity on an annual basis, at a marginal cost 31% lower than the base cost.

Evaluating the *Regional bio-locked* scenario (Figure 15 b and e) indicated that limiting the supply of biofuel accelerates the electrification of the passenger car fleet in both types of municipalities. The model preferred to allocate biofuels to transport sectors with longer driving distances and thus from a weight and volumetric perspective would benefit from using liquid fuels with high energy density, such as road freight transport. Despite widespread electrification in both municipality types, the fleet composition shifted compared to the *Climate policy* scenario (Figure 14 b and c right graphs). Starting in 2030, the biofuel constraint hastened the adoption of BEVs, with these vehicles making up more than 50% of the total fleet in both socio-geographical contexts. In this scenario, in non-urban municipalities, small BEVs replace ICEVs running on biodiesel, as a transition technology. Yet, post-2030 average BEVs achieve, in the non-urban municipalities, a cost-parity of 5%, compared to small BEVs.

Local flexible public transport scenario (Figure 15 c and f) indicated that a modal shift from passenger cars to public transport reduces the overall passenger car transport demand, allowing the existing fleet to operate over longer distances and extended periods throughout its lifespan. Initially, the model showed a dominance of conventional diesel ICEVs in both urban and non-urban areas. However, post-2035, this trend shifted to small BEVs in the urban municipality and to average BEVs in the non-urban municipalities. These results aligned with those of the *Climate policy* scenario (Figure 14 b and c right graphs) but on a smaller scale due to the decreased demand for passenger car transport in this scenario.

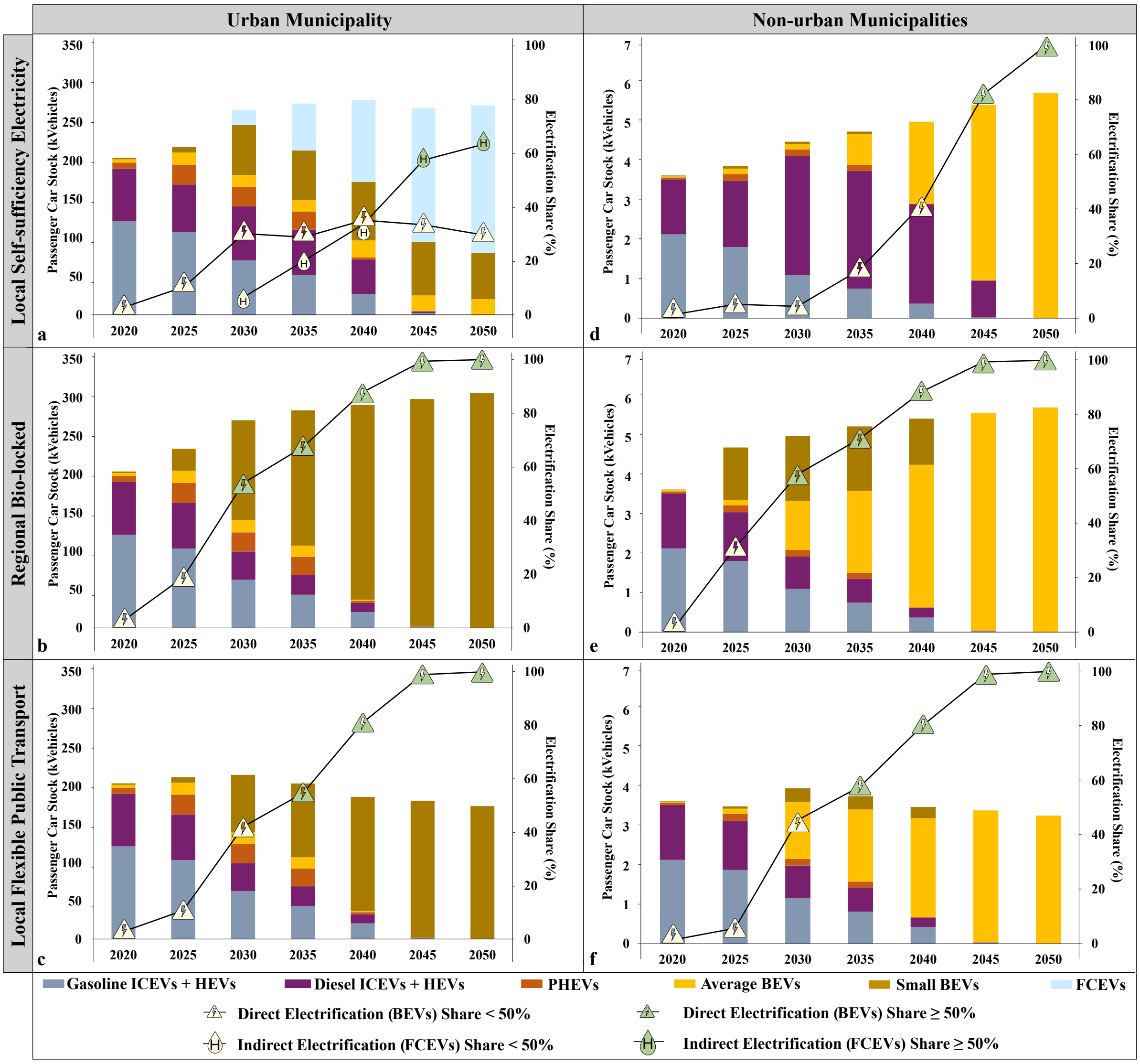


Figure 15. Fleet mix when applying the three local scenarios, for urban (a-c) and non-urban (d-f) municipalities, presented in stock of thousand (k) vehicles (left axes). The black curve shows the electrification share (right axes), including both direct (BEVs share) and indirect (FCEVs share) electrification. For electrification shares above or equal to 50% the symbol of both electricity and hydrogen is green color. BEVs, Battery Electric Vehicles; FCEVs, Fuel Cell Electric Vehicles; HEVs, Hybrid Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

Fuel consumption and total systems cost

Testing different local scenarios resulted in differences in total fuel consumption and total systems cost for both urban (Figure 16 a) and non-urban (Figure 16 b) municipalities, comparatively to the *Climate policy* scenario.

In the urban municipality, limiting the passenger cars resulting electricity demand being met locally, as tested in the *Local self-sufficiency electricity* scenario, resulted in a total electricity consumption decrease, which was balanced by, first, an increase in biofuel import and consumption and, later, replaced by hydrogen import and consumption. In non-urban municipalities, while ICEVs were allowed as an investment option (i.e., pre-2035), these vehicles were gauged to be the cost-effective choice, increasing the total biofuel consumption, with a strong dependency on biodiesel. Post-2035, the model shifted towards electrifications which was accompanied by local VRESs capacity investments.

Setting a regional limit on biofuel supply, as tested in the *Regional bio-locked* scenario increased the total electricity consumption in both types of municipalities. This trend was further accentuated in the non-urban municipalities, where according to the *Climate policy* scenario, biofuel was defined as playing a transition role.

As a modal-shift direct effect, the *Local flexible public transport* scenario resulted in an overall decrease in fuel consumption, motivated by a total reduction in passenger car transport demand.

When looking at the total systems cost (i.e., the objective value for each municipality tested), it becomes worth noting how the economic impact of local scenarios differed according to the two different socio-geographical types of municipalities. In the urban areas, the *Local self-sufficiency electricity* scenario resulted in an increase of 17% in total systems cost compared to the *Climate policy* scenario. This increase can be understood by the model being constrained to invest in small BEVs, which were defined as having the lowest upfront purchase cost over the whole modeling horizon. As a replacement, the model was forced to invest in diesel ICEVs and FCEVs that were described as holding a high upfront purchase cost, compared to small BEVs. Relying on diesel ICEVs also increased the driving cost, due to carbon and energy fuel associated taxes, as well as the vehicle tax. Contrarily, in the non-urban municipalities, despite the required investments in VRESs capacity, the *Local self-sufficiency electricity* scenario reduced the total system cost by 7%, compared to the *Climate policy* scenario. Adding a limit on the regional biofuel supply, as tested in the *Regional bio-locked* scenario, did not bring significant changes to the system, as regardless of this constraint, the model already avoided, in the long-term, the use of these fuels considering their relatively high running costs. Decreasing the total passenger car demand, as modeled in the *Local flexible public transport* scenario, as expected, decreased the total systems cost by 28% and 30%, compared to the *Climate policy* scenario, in the urban municipality and non-urban municipalities, respectively.

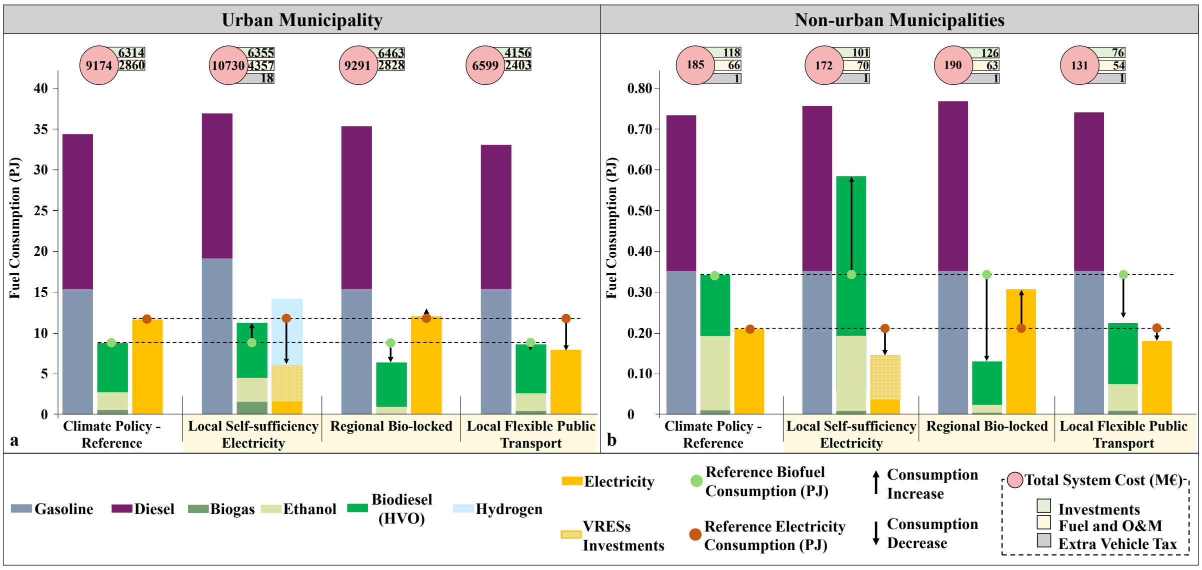


Figure 16. Sum of the total fuel consumption and total system cost for each local scenario for all modeled years, representing the urban municipality on the right (a) and the non-urban municipalities on the left (b). HVO, Hydrotreated Vegetable Oil; O&M, Operation and Maintenance; VRESs, Variable Renewable Energy Sources.

4.3.3. Sensitivity analysis

The assumptions associated with the modeled local scenarios were evaluated as being binding or not, through sensitivity analysis. In specific, the model parameters for each of the local scenarios, such as (i) future local VRESs electricity production; (ii) current biofuel regional production; and (iii) decrease in passenger car transport demand; were reduced in half and increased in double. Conducting a sensitivity analysis allowed for testing the impact that the selected model parameters have on the total electrification share of the resulting fleet composition of passenger cars and the total system cost of passenger cars.

Not all local modeling assumptions, according to the carried sensitivity analysis, were selected as being binding. Accordingly, only the binding assumptions are further presented, specifically, the future local VRESs electricity production, tested in the urban municipality.

Reducing in half as well as increasing by double the projected future VRESs capacity (compared to the *Local self-sufficiency electricity* scenario) resulted in different electrification shares, as depicted in Figure 17. Limiting even further the use of electricity, motivated a consequent increase in indirect electrification, characterized by a higher number of FCEVs. Contrarily, doubling the VRESs capacity increased the number of BEVs in the total fleet, further decreasing the need for investments in FCEVs. Despite the consequential shift between direct and indirect electrification, no major changes were experienced in the total system cost. Performing this sensitivity analysis further underscores the model’s preference for direct electrification. In the long term, FCEVs are identified as the most cost-efficient replacement for

BEVs according to urban settings, but only when the use of BEVs, due to local electricity supply constraints, is limited.

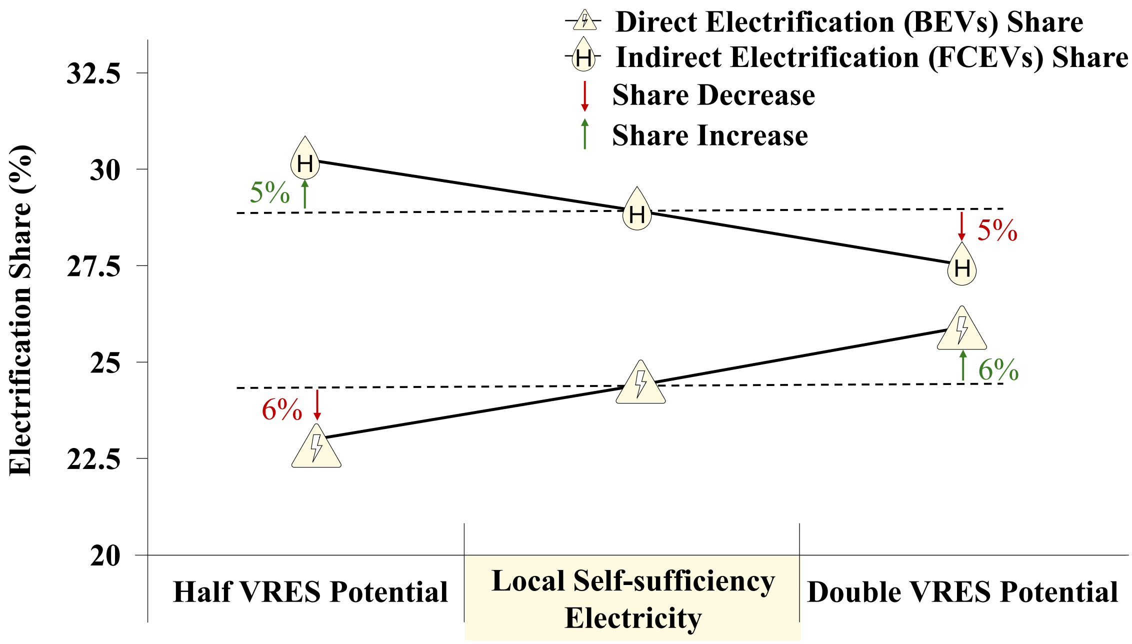


Figure 17. Sensitivity analysis on VRESs potential and the impact on electrification share. The values represent the case of the urban municipality. BEVs, Battery Electric Vehicles; FCEV, Fuel Cell Electric Vehicles; VRESs, Variable Renewable Electricity Sources.

5. Discussion & conclusions

In this chapter, the specific contributions of this thesis will be thoroughly discussed. The discussion here presented is twofold. First, the research questions will be answered, allowing for a discussion of the developed framework and outcomes from applying it. This chapter will conclude with a summary and reflections on the learning outcomes of this thesis.

5.1.RQ1: Participatory energy systems modeling framework

RQ1 intends to understand (i) how a local perspective on road transport can be implemented in the ESOM framework; and (ii) which modeling features are needed when assessing the decarbonization of this sector at the local level.

Answering this question calls for understanding that road transport depends on travel patterns that are shaped by diverse socio-economic and socio-technical factors. Such factors are specific to a given socio-geographical context (see Figure 14 d-f), highlighting the need to treat road transport decarbonization as a context-dependent process. The effectiveness of such a transition is thus dependent on the capability of aligning low-carbon solutions with local behaviors, as an outcome of different socio-geographical specifications.

Acknowledging road transport as a context-dependent process, this thesis developed a new modeling framework capable of assessing road transport decarbonization at the local level. The developed framework contributes to the existing scholarly by integrating local spatial dynamics as the key modeling feature. Integrating local spatial dynamics can be guaranteed by establishing an iterative and complementing loop between PA and ESOM. Such a loop allows for transcribing socio-technical pathways into modeling local scenarios (see Figure 13). The socio-technical pathways can, firstly, be identified through a PA, by involving municipal officials (see Figure 12). This involvement further ensures that the identified pathways are aligned with the local travel patterns, preferences, and needs. Implementing the resulting socio-technical pathways into the modeling exercise can provide an often-missing local spatial dynamics dimension, allowing road transport decarbonization to be treated as a context-dependent process. Specifically, by incorporating socio-technical pathways as modeling scenarios, the model-based analysis becomes more comprehensive, by capturing a broader range of knowledge and real-world perspective. These aspects are often overlooked in standalone techno-economic modeling exercises but are essential for fully understanding any type of energy transition at the local level.

Overall, this thesis addressed RQ1 by developing a participatory energy systems modeling framework that integrates local spatial dynamics (see Figure 8). Road transport decarbonization pathways, identified in a participatory manner in collaboration with municipal officials, can be transcribed into modeling scenarios and then applied in a techno-economic model. The modeling scenarios will thus be drawn on assumptions that depict the local specifications of the participating municipalities, allowing for assessing road transport decarbonization in a context-dependent manner.

5.2. RQ2: Local road transport decarbonization pathways

RQ2 focuses on understanding how to generate pathways as a context-dependent process to better support road transport decarbonization at the local level.

As a response to RQ2 intention, this thesis developed a new method of generating pathways that iteratively combines and complements different stages of conceptual literature review with qualitative municipal officials' storylines derived from a participatory approach (see Figure 9). This loop enhances the credibility of the method of generating and the identified pathways, addressing limitations in the literature, particularly recognizing that some non-carbon transport solutions may not fit the current social, political, and economic contexts of different socio-geographical environments. Similarly, this iterative approach aids in managing municipal stakeholders' participation and navigating challenges associated with long-term uncertainties.

In summary, addressing RQ2 concerns involves generating pathways that can shed light on road transport decarbonization, particularly when these pathways are tailored to the context under transition (see how fleet mix and fuel consumption change according to the different modeling scenarios in Figure 15 and Figure 16). Generating pathways, when developed as a context-dependent method, are recognized as providing a personalized understanding of not only the local road transport system in transition but also of its broader environment. Thus, generating pathways can provide a holistic perspective on the transitioning context. A holistic dimension fairly captures key parts of the considered local energy systems, therefore considering both local targets and local priorities, while identifying which local resources play a systems integrator role. Tailored to the local specification of the socio-geographical context under transition, generating and identifying pathways can effectively support road transport decarbonization at the local level (see Section "*Urban versus non-urban municipalities*").

5.3. RQ3: Spatial dynamics' impact on road transport decarbonization

RQ3 relates to the value of spatial dynamics when testing the evolution of road transport decarbonization, by comparing how the outcome differs between national (i.e., Sweden) and local (i.e., participating municipalities) levels.

This thesis contributes to the scholarly of RQ3 by applying the participatory energy systems modeling framework (see Figure 8), previously developed according to RQ1, to three different case studies, i.e., the national level (i.e., Sweden) and the local level (i.e., one urban municipality and three non-urban municipalities). As a direct outcome of the techno-economic modeling exercise, the fleet composition and the fuel composition were evaluated for the three case studies.

This thesis delves into RQ3 concerns by reflecting on how the dynamics of fleet composition and related fuel consumption change according to travel patterns, i.e., (i) annual average mileage; (ii) occupancy rate; (iii) trip length; (iv) charging patterns; and (v) fuel economy, specific to socio-geographical contexts. National travel patterns, represented by weighted average values, effectively characterize urban contexts but tend to overlook the unique characteristics of non-urban municipalities. This mismatch underlies two main conclusions (see

Figure 14): (i) identical optimal choices identified for both national and urban contexts, and (ii) a disparity in optimal choices between the national level (similar to urban contexts) and non-urban contexts.

At the national level and within urban contexts, where annual average mileages and trip distances are typically low, the model tends to favor vehicles with lower upfront costs. Conversely, in non-urban contexts with longer trip distances, the emphasis shifts towards vehicles that enhance fuel economy and low fuel cost, despite their higher upfront purchase costs. Furthermore, this thesis explored the significance of spatial dynamics by analyzing local socio-geographical modeling scenarios. These scenarios, derived from the pathways identified in response to RQ2 and incorporating real-world local assumptions, examine the challenges and opportunities that local communities may encounter in achieving climate targets. Overall, the analysis of these local scenarios emphasized the importance of fleet electrification. However, it also highlighted the necessity of integrating fleet electrification with developing a resilient electric grid capable of accommodating the growing demand for electricity from VRESs. While non-urban municipalities show potential in managing increased electricity demand through renewable production, urban areas struggle to meet their local needs solely through VRESs. Under strict local electricity production constraints, urban areas will thus increase their dependency on the imports of fuels such as biofuels and hydrogen.

In brief, addressing RQ3 reveals that road transport electrification stands out as the most predominant and cost-effective decarbonization strategy across the three cases studied. While a national perspective can adequately prescribe long-term solutions for this transition, it tends to underestimate the importance of local specifications in road transport decarbonization (see Section "*National versus local level*"). Therefore, incorporating local spatial dynamics as a key feature in ESOM becomes essential to (i) comprehensively describe the road transport transition; and (ii) shape inclusive and resilient decarbonized road transport systems.

5.4. RQ4: Road transport decarbonization – A context-dependent process

RQ4 concludes this thesis work by reflecting on the value of the developed participatory energy modeling systems framework, specifically adding local spatial dynamics to the modeling exercise.

Results from this thesis showed local spatial dynamics as being an essential dimension in enhancing the understanding of road transport decarbonization. Perceiving this transition through the lens of local spatial dynamics reveals it as a context-dependent process, where the decarbonization potential of different strategies varies according to different socio-geographical characteristics (see Figure 14 and Figure 15). Integrating local spatial dynamics into the modeling exercise underscores that standardized strategies proposed by techno-economic models may not be replicable to every type of socio-geographical context. Achieving socially inclusive road transport decarbonization requires addressing these transitions at the local level, which can be effectively facilitated by integrating PA and ESOM exercises.

In summary, assessing socio-geographical modeling scenarios, in a cost-optimization framework, emphasizes the necessity of tailoring road transport decarbonization strategies to fit the specificities of local contexts in transition. Therefore, integrating local spatial dynamics, resulting from participatory interaction with local stakeholders, is essential to complement ESOM's purely techno-economic outcomes. This approach underscores how assuming a local perspective can not only improve the effectiveness of decarbonization efforts but also foster more socially inclusive climate policies.

5.5. Learning outcomes

This thesis examines road transport decarbonization according to a local perspective, emphasizing it as a process influenced by socio-geographical factors.

5.5.1. Comparison with previous studies

Consistent with earlier existing literature [88]–[91], this thesis also asserts that developing modeling scenarios through a PA allows for effectively integrating spatial dynamics into ESOM exercises. This thesis expands on previous literature by providing a method and application contribution to the field of road transport. As a method contribution, this thesis develops an ESOM that incorporates local spatial dynamics, demonstrated through the evaluation of participatory-developed local socio-geographical modeling scenarios. Additionally, this thesis highlights that road transport decarbonization, like any energy transition, varies between the national level (i.e., Sweden) and local level (i.e., participating municipalities – one urban and three non-urban municipalities), underscoring the importance of integrating local spatial dynamics in understanding and facilitating such a transition.

5.5.2. General reflections

The aim of this thesis was primarily to understand the influence that different socio-geographical contexts offer to road transport decarbonization. As the main method contribution to the overarching aim of this thesis, a new framework was developed to investigate road transport decarbonization at the local level. Such a framework is defined by an iterative loop established between PA and ESOM exercises. Moreover, this thesis offered an application contribution to the discussed scholarly, by bridging the gap between the two aforementioned methods and applying them to enhance the understanding of local spatial dynamics role. Specifically, this thesis used the developed framework to compare the evolution of the road transport systems' decarbonization at the national level with its development at the local level of urban and non-urban municipalities.

This thesis fosters a dialogue on how incorporating a local perspective, by involving local stakeholders, can mitigate the complexities associated with road transport decarbonization and broader energy transitions. While the work of this thesis provides an in-depth analysis of a Swedish case, its principles are universally applicable, offering valuable insights on how policy-making can advance towards more sustainable and inclusive road transport systems. This thesis' findings critique existing practices that adopt "one-size-fits-all" decarbonization strategies, advocating instead for a tailored approach that considers local contexts. Such a rationale aligns with the European Commission's recent recommendations [21], emphasizing the importance of engaging local authorities in the transition. Local authorities can more accurately represent socio-geographical factors, e.g., behavioral and consumption trends, climate actions, and the availability of local resources; all of which influence the decarbonization potential of different strategies. Hence this thesis underscores the pivotal role of municipalities and local authorities in shaping sustainable and inclusive transitions, not only in road transport but across society as a whole.

Overall, road transport decarbonization is about balancing resilience with efficiency, placing people at the "heart" of this transition. Therefore, it is crucial to adopt local and bottom-up approaches to navigate the complexities involved. Municipalities should be recognized as playing a vital and positive role in this process, as they are the places where policy directly impacts people's lives. Consequently, municipalities become the ideal settings to demonstrate how climate targets, in general, and transport goals, in particular, can benefit from various policies. Moreover, achieving climate goals on time often feels like a "race against the clock", necessitating creative and innovative solutions that can be effectively tested and implemented at the local level. Municipalities and their unique contexts offer a promising foundation for society's broader climate ambitions, providing a source of hope and tangible progress towards sustainability.

6. Reflection on limitations and future work

This thesis delved into various aspects and challenges of decarbonizing road transport, particularly when focusing on the impact of different socio-geographical contexts on this transition. While the main contribution of this work highlights the importance of integrating local spatial dynamics into the decarbonization process, several uncertainties remain. These uncertainties warrant further investigation and therefore motivate future work.

The method framework developed in this thesis was initiated with a literature review on road transport decarbonization, where the findings were limited to the search commands applied. Complementary phases of literature reviews were conducted to ensure fair coverage of the literature found. Also, it is important to mention that literature review findings are not static in time, meaning that there is a need to actively keep updating these findings with new research that is actively published in the field. In general, each time a new literature review is conducted, using the same search commands, one can gain insights into recent developments in the field, but also compare how trends (e.g., the most often presented fuel and mobility strategies for road transport decarbonization) evolve over time.

PA is presented as one of the two main key tools utilized in this thesis. Albeit the great perspective (i.e., social inclusivity, climate resilience, and decision legitimacy), as discussed in this thesis, that PA can offer to energy systems studies, such an approach is tied with different limitations, that one might be aware of. The applied PA involved the interaction of different municipal officials whose stated preferences and revealed preferences can be mismatched. In addition, not only the involving municipal officials, but stakeholders in general tend to express their vision in different ways but also have difficulties expressing value-free opinions. Accordingly, stakeholders' thinking tends to be a "black box", where responses might be biased, prioritizing specific needs and goals, rather than a holistic perspective, failing to capture long-term interactions and uncertainties. Stakeholders' PA typically evolves around narrow "subjects", challenging the representativeness of their outcomes. Similarly, transcribing participating stakeholders' stated preferences into fairly representative conceptual and quantitative data can be challenging and, mainly, resource demanding (i.e., data and time-intense exercise). Tackling the aforementioned issues, this thesis carried out semi-structured interviews, which allowed for a continuous discussion between the researcher and municipal officials. Moreover, semi-structured interviews were revealed to provide the room to ask clarification questions, guaranteeing a thorough comprehension of the participant's responses, whereas providing the room to delve in-depth into specific details. In future work, when carrying out a PA, one can expand the heterogeneity of the involved stakeholders, ensuring that different perspectives are brought to the table, providing thus a fair representation of the topic under discussion.

This thesis was carried out in a Swedish context, assessing how road transport decarbonization changes according to an urban and non-urban context. While being recognized for its sustainability action-oriented spirit, Sweden is also placed in the top 10 of the European countries holding the highest GDP per capita. Such circumstances might be argued as advantageous when meeting climate goals. Yet, this might not be the case in lower GDP countries, where urban and non-urban definitions might differ from the ones applied in this thesis. In future work, the same study could be replicated by considering other countries with lower GDP and higher rurality share. In the specific case of road transport, poorer countries will hold higher hurdle rates per capita, which will influence the purchasing power of people to invest in more efficient and cleaner vehicles, which at the moment still hold a high upfront purchase cost.

ESOMs, aligned with PA, are at the core of the method developed in this thesis. Despite the great insights that ESOMs offer on understanding how a given system might evolve in the future towards different stimuli, one might use this tool with some care. In general, ESOMs tend to describe energy systems in a simplified way, considering (i) a price-inelastic demand; (ii) an optimal selection being cost-based, neglecting intangible costs that might affect investment options (i.e., people are not necessarily economically rational); (iii) assuming a perfect foresight, adding an uncertain aspect on future trends (e.g., fuel cost, energy demand, and climate targets); and (iv) redundancy about energy security. Accordingly, every ESOMs is an evolving and dynamic tool, seeking thus for continuous updates regarding the integration of new technologies as well as the refinement of techno-economic data and related assumptions.

Reflecting on the specific case of the TIMES model developed in this thesis, one might be aware of the main factors that potentially limited the modeling analysis carried out in this thesis, as follows:

- Future assumptions were adopted both on the upfront cost of emerging vehicles, such as BEVs and FCEVs, and fuel cost. Similarly, neither the fleet second-hand market was considered an investment option, nor technology readiness for alternative vehicle options and market dynamics. Also, vehicle efficiency improvements were disregarded in both existing and future fleets.

- Travel patterns were modeled according to annual average values, neglecting daily (i.e., day and night), weekly (i.e., work week and weekend), and seasonal variations. Moreover, the charging profiles' representation was simplified, not fully reflecting how charging behaviors might evolve in the future, where the opportunity cost might differ from what is typically observed in ICEVs. For future work, research can delve into this issue by increasing the model timestep resolution. Higher temporal resolution further provides an ancillary benefit to any research promoting electrification, due to the intermittency associated with renewable electricity production, gradually increasing in the coming years.

- The road transport sector was treated as a standalone system, failing to capture cross-interactions between other transport segments but also other energy sectors. This simplification potentially overlooked the complex interdependencies between the transition of road transport and other sectors undergoing similar changes. Disregarding cross-sectoral interactions dismisses potential synergies and competition for the same primary energy source. Similarly, this thesis does not focus on fuel feedstock and production, dismissing that other fuels than electricity and biofuels can, in the future, also be produced locally, such as hydrogen. This is something that can be tackled in future work, by adding other energy sectors to the already modeled road transport sector, allowing for a better understanding of cross-sectoral resource allocation and fuel production.

- Biofuels were, in this thesis, subjected to the Swedish Reduction Obligation, as presented first in 2018 [105]. However, at the time of writing this thesis, biofuel blending registers lower requirements than the ones tested in this work [106]. In future work, testing less restrictive requirements on biofuel blending can motivate quicker fleet electrification, resulting thus in a higher total system cost (i.e., there will be a need for a faster replacement of the existing fleet, before reaching its lifetime). Moreover, comparing the two contexts (i.e., strict and flexible biofuel blending share) will further highlight the role that regulatory policies might have in limiting the use of fossil fuel and thus, on road transport decarbonization.

- CO_2 emissions resulting from the combustion of fossil fuels were considered in this thesis. In future work, the emission target can be expanded to include local air quality but also the whole fuel chain (i.e., emissions related to (i) fuel feedstock; as well as (ii) fuel extraction, conversion, and distribution) and infrastructure (i.e., emissions from vehicle manufacturing and road and fuel supply infrastructure building).

Overall, it is worth noting that developing models is not necessarily a value-free process, but rather built upon different assumptions that reflect the modeler's judgment, which at times, can be biased towards own beliefs. Accordingly, developed models always come with the risk that some parts of energy systems representations are misjudged or simply missing, leading to gaps when assessing and understanding a given sector and its intricacies. To avoid such biased outcomes, this thesis kept a close and collaborative discussion with different modeling experts, improving the likelihood that all assumptions made were representative and a good fit for the scope of this research. In general, "all models are wrong, but some are useful" [119] and, in the specific case of this thesis, the developed model proves to be a valuable tool for understanding the behavior of road transport, while effectively capturing the different links among socio-geographical factors, vehicle technologies, and the transition to a carbon-free system.

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Appendix

National modeling input data and related assumptions

Table A 1. Existing Swedish stock for passenger cars for the base year, 2019, and the calibrated year, 2022. Data retrieved from [37],[120]– [123]. BEVs, Battery Electric Vehicles; HEVs, Hybrid Electric Vehicles; HVO; Hydrotreated Vegetable Oil (biodiesel); ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

Passenger Cars Types	**Existing Stock (Number of Vehicles) – Sweden**	
	2019	**2022 – Calibration Year**
Gasoline ICEVs	2,694,251	2,485,975
Diesel ICEVs	1,735,589	1,167,023
HVO ICEVs	1,214,912	500,153
Ethanol ICEVs	201,714	178,316
Biogas ICEVs	41,633	38,086
Small BEVs	9,406	61,290
Average BEVs	20,936	136,419
Gasoline HEVs	58,756	86,738
Diesel HEVs	58,756	86,738
Gasoline PHEVs	66,609	239,531

Table A 2. Transport demand input data for private cars in Sweden, given in billion (B = 10^9) pkm. The input data is calibrated for the year 2022. Data retrieved from [124]. Bpkm, Billion Passenger-kilometers.

Passenger Car Transport Demand - Sweden	**Units**	**2019**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	Bpkm	96.89	95.85	101.24	106.93	112.94	116.37	119.90

Table A 3. Economic input data used for passenger cars[36],[37],[107]. BEVs, Battery Electric Vehicles; FCEVs, Fuel Cell Electric Vehicles; HEVs, Hybrid Electric Vehicles; HVO; Hydrotreated Vegetable Oil (biodiesel); ICEVs, Internal Combustion Engine Vehicles; NA, Non-applicable; PHEVs, Plug-in Hybrid Electric Vehicles.

Passenger Cars Types	**Lifetime (Years)**	**Investment Cost (€)**			**Operation & Maintenance Cost (€/km)**	**Vehicle Tax (€)**	
		2019	**2030**	**2050**		**First 3 years**	**After the first 3 years**
Gasoline ICEVs	17	21,400			0.027	1216.59	154.22
Diesel ICEVs		21,900			0.032	6527	326.50
HVO ICEVs		21,900			0.032	6527	326.50
Ethanol ICEVs		21,400			0.027	NA	
Biogas ICEVs		23,112			0.027		
Small BEVs		28,900	26,416	21,900	0.021		
Average BEVs		31,042	27,581	22,968	0.021		
Gasoline HEVs		26,535	26,164	25,420	0.027		
Diesel HEVs		27,156	26,784	26,288	0.032		
PHEVs		30,125	26,829	25,371	0.027		
FCEVs		NA	30,414	22,968	0.025		

Table A 4. Fuel taxes (i.e., energy and carbon taxes) associated with the different fuels used in ICEVs. Data retrieved from [100]–[103]. HVO; Hydrotreated Vegetable Oil (biodiesel); NA, Non-applicable

Fuel Type	**Fuel Taxes (M€/PJ)**			
	Year < 2027		**Year ≥ 2027**	
	Energy	**Carbon**	**Energy**	**Carbon**
Diesel	3.93	7.29	3.93	7.29
Gasoline	7.41	9.06	7.41	9.06
Ethanol	NA		4.80	NA
HVO			3.78	
Biogas	13.71	NA	13.71	NA

BEVs charging profiles were considered in this thesis by implementing two different electricity costs (ECost), corresponding to standard public charging (SP) and fast charging (FC). The resulting electricity cost was calculated as follows in Equations (A1) and (A2), by considering the average share of charging events happening at work (CW), home (CH), as well as extra and unforeseen fast charging needs. The shares used for these calculations were retrieved from [125], according to the authors define that BEVs charge (i) 75% at work; (ii) 90% at work and home, in case of home charging; and (iii) 10% of the charging events correspond to unforeseen needs for fast charging.

$$Small\ BEVs\ ECost = Share\ of\ CW\ (\%) * SP\ ECost + (Share\ of\ FC + Long\ Trips)\ (\%) * FC\ ECost \tag{A1}$$

$$Average\ BEVs\ ECost = Share\ of\ CHW\ (\%) * SP\ ECost + Share\ FC\ (\%) * FC\ ECost \tag{A2}$$

Table A 5. Fuel economy for passenger cars for the whole model horizon. Data retrieved from [126]–[128]. BEVs, Battery Electric Vehicles; FCEVs, Fuel Cell Electric Vehicles; HEVs, Hybrid Electric Vehicles; HVO; Hydrotreated Vegetable Oil (biodiesel); ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

Passenger Cars Types	**Fuel Economy (Mkm/PJ) – Sweden**
Gasoline ICEVs	467.81
Diesel ICEVs	548,49
HVO ICEVs	548.49
Ethanol ICEVs	463.14
Biogas ICEVs	430.98
Small BEVs	1758.91
Average BEVs	1393.53
Gasoline HEVs	568.57
Diesel HEVs	670.60
Gasoline PHEVs	976.18
FCEVs	830.01

Additional modeling results

The focus of the modeled local scenarios was the passenger car fleet. Yet, for both *Regional bio-locked* and *Local flexible public transport* scenarios, both buses as well as medium and heavy-duty trucks were further included in the modeling exercise.

Figure A 1 depicts the stock for these vehicles under the two abovementioned local scenarios, while Figure A 2, for the same vehicles and local scenarios, illustrates the fuel mix.

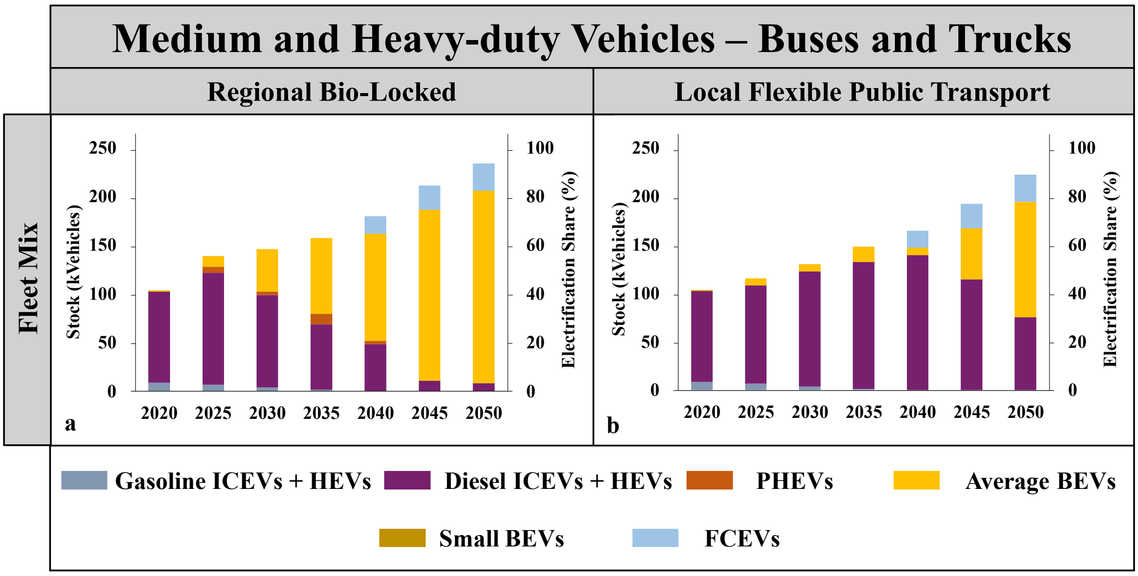

Figure A 1. Fleet mix presented in stock of thousand (k) vehicles (left axes). The black and blue curves show the electrification share (right axes). BEVs, Battery Electric Vehicles; FCEVs, Fuel Cell Electric Vehicles; HEVs, Hybrid Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

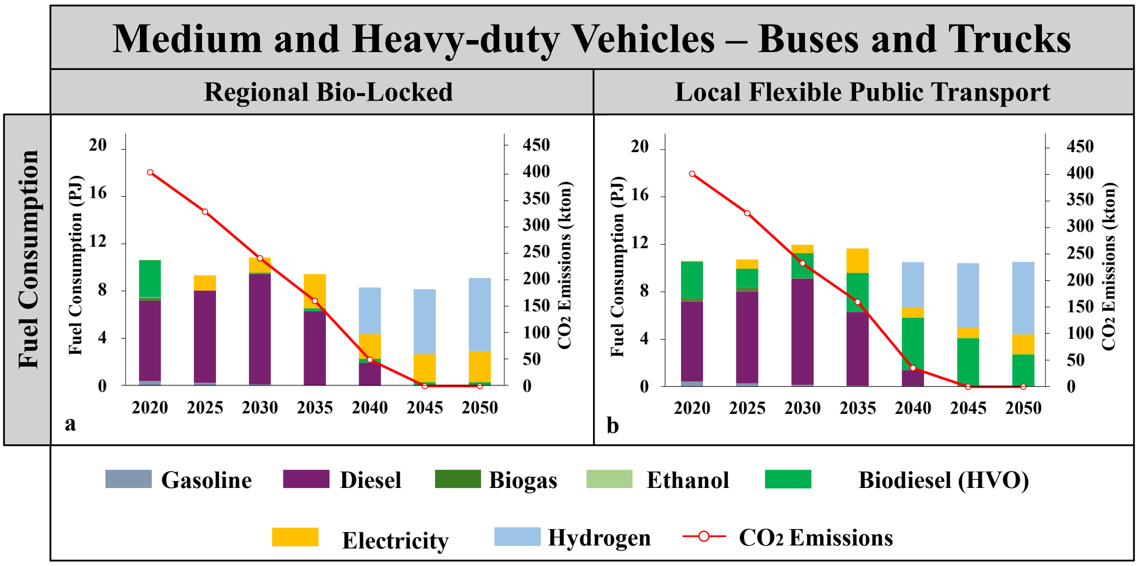

Figure A 2. Fuel consumption (left axes) and resulting CO_2 emissions (right axes). CO_2, Carbon Dioxide; HVO; Hydrotreated Vegetable Oil (biodiesel).