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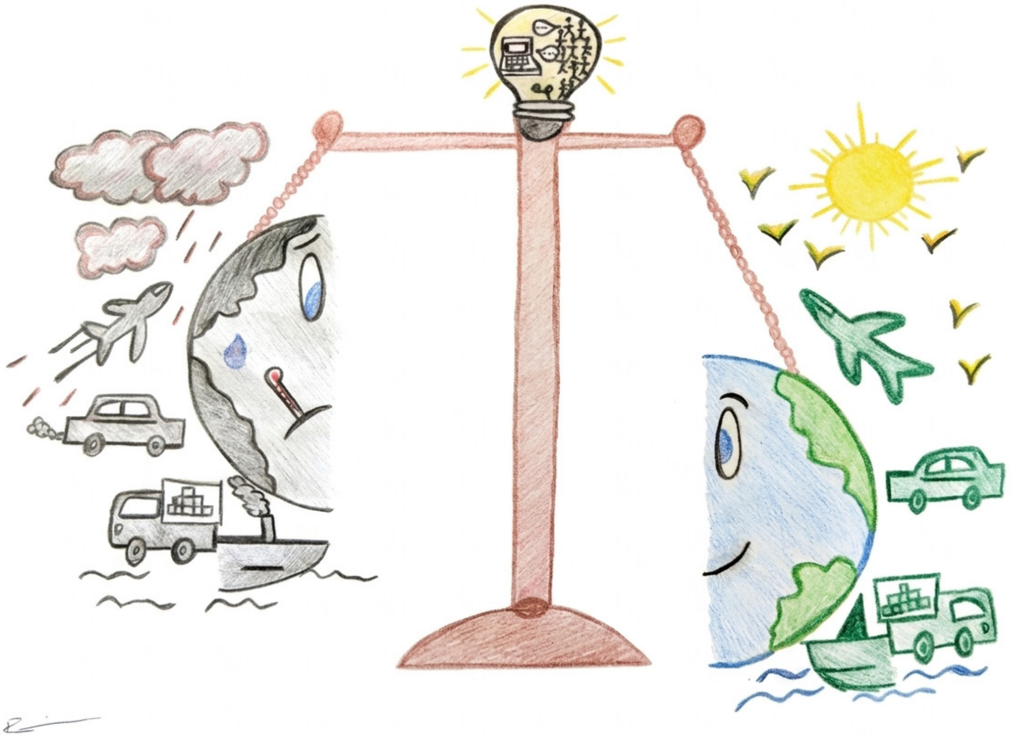

Insights from Energy Systems Optimization Models and Stakeholders Engagement

– A Multi-Scale and Cross-Sectoral Perspective on Low-Carbon Transport

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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Cover: An illustrative summary of my thesis, created to help me tell “my story” to my nephews, who are not yet able to read. The cover was inspired by drawings from nine- to ten-year-old students from Class 4B at Agrupamento de Escolas Martim de Freitas in Coimbra, Portugal, who were invited to draw what they thought of when hearing my thesis title. Further details about the story behind the cover can be found in the Appendix.
Illustration by Maria de Oliveira Laurin

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"Struggling means successfully not giving up"
Bennett

"Valeu a pena? Tudo vale a pena
Se a alma não é pequena"
Fernando Pessoa

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Abstract

While energy transition literature often describes such a transition as a context-specific process, this perspective is frequently overlooked in studies of low-carbon transport systems. This thesis addresses this research gap, by developing a single analytical framework that considers (i) a multi-scale perspective; (ii) cross-sectoral interactions; and (iii) a continuous soft-link between energy systems optimization models (ESOMs) and stakeholders engagement. The framework considers local (urban and non-urban), national, and global scales, and examines low-carbon transport transition under both exogenous and endogenous cross-sectoral perspectives.

The results show that low-carbon transport pathways are context-dependent, varying not only across spatial scales, but also socio-geographical contexts. For passenger cars, all scenarios converge toward increased electrification in the long term; however, the pace and cost-optimal technology pathways are influenced by travel behavior, infrastructure availability, and policy constraints. A multi-scale perspective further reveals that aggregated national results tend to reflect urban dynamics, potentially overlooking non-urban transport systems' dynamics.

Adopting a cross-sectoral perspective demonstrates that transport transitions are shaped by systems-wide interactions rather than transport-specific dynamics alone. Results from the global and endogenous modeling framework highlight how system-integrators (e.g., electricity, biomass, carbon capture technologies, and co-products availability) govern the allocation of resources and the timing of transition across sectors. Sectors with higher mitigation flexibility, often associated with greater electrification potential (e.g., heat and road transport), tend to transition earlier, thereby relaxing systems-wide constraints and allowing hard-to-abate sectors, particularly aviation, to transition more gradually. The findings further show that the role of liquid fuels as sustainable aviation fuels is strongly dependent on carbon budgets, biomass availability, and carbon storage capacity, reflecting cross-sectoral trade-offs and synergies.

Soft-linking stakeholders engagement with ESOMs enhances the contextual relevance and legitimacy of modeling formulation. By incorporating a socio-technical dimension, this analytical link strengthens the representation of modeling assumptions, supports scenario development, facilitates mutual learning between modelers and decision-making stakeholders as well as technical experts. Accordingly, this thesis demonstrates that such a continuous interaction might provide a more robust and realistic understanding of low-carbon transport systems. Hence this thesis contributes to ESOMs scholarly by moving beyond "one-size-fits-all" approaches into more transparent, context-sensitive, and decision-relevant analyses applicable not only to transport systems but to broader energy transitions.

Keywords: Cost-Optimization Models; Cross-Sectoral Perspective; Low-Carbon Transport; Multi-Scale Perspective; Stakeholders Engagement; Socio-Geographical Contexts; Socio-Technical Systems.

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Jim Rohn once said, “You are the average of the five people you spend the most time with” I would like to gently challenge that number, as Jim clearly did not meet all the people who, over the past years, have crossed paths with me and, in one way or another, shaped this thesis.

I have to admit that writing the acknowledgments was something I had always eagerly looked forward to when thinking about my thesis. Not because it might be the only part that most people will actually read of my thesis. Nor because it is the only part my supervisors will not shorten for being “too long”. But because, in the rush of the last days before printing, it allows me to pause, reflect, and express my gratitude to those who have been part of this journey.

First, I would like to thank my supervisors, Maria Grahn and Selma Brynolf. Maria, thank you for believing in second chances and for making them truly worth it. Thank you for your positivity, wisdom (i.e., teaching me that words like “which” and “bridging” are best avoided), and above all, for always reminding me of the first law of thermodynamics and how it applies to almost everything in life. Thank you for showing me that with determination, almost anything is achievable, and for all other incredible things you have brought into my life. Among those, I am especially grateful that you made my path cross with Selma. Selma, thank you for your encouraging “it is fantastic” in every meeting, while still immediately challenging me to look closely at every detail. Thank you for teaching me to be my own first critic, and that critique is not something to fear, but something that helps us grow. To both of you, thank you for showing me what it truly means to be part of a team. I could describe you both as one being an ESOM and the other a group of stakeholders, the perfect and complementary match to tackle any challenge. And this is exactly what makes closing this chapter so difficult. I will truly miss you.

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Göteborg, 23rd of June 2026

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. (2025). Exploring the applicability of "One-Size-Fits-All" road transport decarbonization strategies: a participatory energy systems modeling comparison of urban and non-urban municipalities. *Scientific Reports*, 15: 10747. https://doi.org/10.1038/s41598-025-94579-w

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

Paper III

de Oliveira Laurin, M., Parsmo, R., Johansson, O., Grahn, M., Hansson, J., Kanchiralla, F.M., Lehtveer, M., Brynolf, S. (2026). Is there a role for liquid fuels in future low-carbon energy systems? – A continuous interaction between global energy systems modeling and local energy port cluster participation. *Applied Energy*, 412: 127640. https://doi.org/10.1016/j.apenergy.2026.127640

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

Paper IV

de Oliveira Laurin, M., Rådberg, H., Grahn, M., Tiwari, S., Brynolf, S. (202X). Cost-Effective Fuel Pathways for Aviation under Varying Carbon Reduction Targets: The Cross-Sectoral Role of Biomass Availability in Global Energy Systems (*Manuscript in preparation*)

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

List of Additional Publications

A. Kanchiralla, F. M., de Oliveira Laurin, M., Brynolf, S., & Grahn, M. (2026). Battery-Electric vs. Hydrogen: Modeling the Decarbonization Pathways and Environmental Trade-offs of Global Road Freight. *Advances in Applied Energy 22, 100278*. https://doi.org/10.1016/j.adapen.2026.100278

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D. de Oliveira Laurin, M., Ott Cruz, G. (2025). Navigating the Green Transition: Evaluating the Cost-Effectiveness of EU Shipping Decarbonization Under Different Policies, *presented at International Energy Workshop, Nara, Japan, June 10-13*. https://www.diva-portal.org/smash/get/diva2:1959184/ATTACHMENT01.pdf

E. de Oliveira Laurin, M., Grahn, M. (2025). How 'Local' is 'National'? The Importance of Local Spatial Dynamics in Passenger Car Decarbonization, *presented at Transport Research Board (TRB) Annual Meeting, Washington DC, United States of America, January 5-9*.

F. de Oliveira Laurin M. (2024). A Participatory Energy Systems Modeling Approach – Insights on the Local Dynamics of Passenger Car Decarbonization. *Thesis for the degree of Licentiate – Department of Mechanics and Maritime Science: 2024:05.* https://research.chalmers.se/publication/542030/file/542030_Fulltext.pdf

G. de Oliveira Laurin, M., Farabi-Asl, H., Grahn, M., Taljegard, M. (2024). 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*.

H. de Oliveira Laurin, M., Taljegard, M., Ahlgren, E.O. (2023). 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.*

Contents

Abbreviations, Acronyms, and Terminology

Abbreviations and Acronyms

ABM	Agent-based Modeling
AtJ-kerosene	Alcohol-to-Jet Kerosene
BEVs	Battery Electric Vehicles
CC	Carbon Capture
CCU	Carbon Capture and Utilization
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
ESMs	Energy Systems Models
ESOMs	Energy Systems Optimization Models
ESR	Effort Sharing Regulation
ETSAP	Energy Technology Analysis Program
EU	European Union
ETS	Emission Trading System
FCEVs	Fuel Cells Electric Vehicles
FT-diesel	Fischer-Tropsch Diesel
FT-kerosene	Fischer-Tropsch Kerosene
GDP	Gross Domestic Product
GET	Global Energy Transition
GHG	Greenhouse Gas
H_2	Hydrogen
HEVs	Hybrid Electric Vehicles
HEFA	Hydroprocessed Esters and Fatty Acids
HVO	Hydrotreated Vegetable Oil (Biodiesel)
IAMs	Integrated Assessment Models
ICAO	International Civil Aviation Organization
ICEVs	Internal Combustion Engine Vehicles
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LH_2	Liquefied Hydrogen
LCH_4	Liquefied Methane
MARKAL	MARKet ALlocation
MeOH	Methanol
MSW	Municipal Solid Waste
MW	Municipal Waste
NDCs	National Determined Contributions
NO_X	Nitrogen Oxides
O&M	Operation and Maintenance
PHEVs	Plug-in Hybrid Vehicles
pkm	Passenger-kilometers
RCPs	Representative Concentration Pathways
REMIND	REgional Model of Investments and Development
RED	Renewable Energy Directives
RES	Reference Energy System
RFNBOs	Renewable Fuels of Non-Biological Origin
RQs	Research Questions
SAF	Sustainable Aviation Fuels
SALAR	Swedish Association of Local Authorities and Regions
SDGs	Sustainable Development Goals
SSPs	Shared Socioeconomic Pathways
TIMES	The Integrated MARKAL-EFOM System
UK	United Kingdom
tkm	Tonne-kilometers
VRESs	Variable Renewable Energy Sources

Description of Concepts Used in this Thesis

Bottom-Up Approach is typically applied to 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) and Global Energy Transition (GET) models 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.

Carbon Budget represents the total amount of carbon dioxide (CO_2) that can be emitted over time while keeping global warming below a specific limit.

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

Decision-Making Stakeholders are defined, in this thesis, as actors primarily involved in policymaking and consumer behavior, encompassing expertise across the dimensions of industry, technology, infrastructure, policy, culture, and markets.

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.

Electrofuels defined in this thesis as fuels based on hydrogen from water electrolysis combined with carbon atoms.

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”.

Multi-Scale Perspective describes the interaction between energy and society, as well as the evolution of energy patterns, as a context-dependent process shaped by techno-economic factors, infrastructure availability, climate concerns, and policy frameworks, which vary across different socio-geographical contexts. In this thesis, the multi-scale perspective encompasses local (both urban and non-urban), national, and global levels.

Radiative Forcing is the balance between incoming shortwave solar radiation and outgoing longwave terrestrial radiation, which determines the Earth’s temperature.

Residual Emissions refer to emissions that cannot be fully eliminated due to technical, economic, or practical limitations, even after applying all available mitigation measures.

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).

Synthetic Fuels are, in this thesis, regarded as all fuels not originating from the refining of crude oil or natural gas. Depending on their production pathway (i.e., carbon atom origin), synthetic fuels can be regarded as fossil-based or non-fossil-based. The latter can be either biofuels (i.e., depending on biogenic carbon) or electrofuels.

Systems-Integrators are defined as energy carriers and technologies that find applications in different parts of energy systems, and their identification provides an understanding of both potential cross-sectoral synergies and conflicts, i.e resources that can be allocated to substitute fossil fuels in different parts of the energy system.

Technical Stakeholders are defined, in this thesis, as actors primarily holding technical scientific expertise.

Declaration of Generative AI-Assisted Technologies

During the preparation of this thesis and the appended work, AI tools such as Microsoft 365 Copilot were used to assist with language editing, including improving grammatical correctness, refining structure, and enhancing clarity. All content was thoroughly reviewed and edited by the author, who takes full responsibility for the final work.

1. Introduction

In light of the Paris Agreement, European Union (EU), together with other 194 states, committed collectively to limiting the increase in global average temperature to well below 2 °C above pre-industrial levels, while pursuing efforts to limit warming to 1.5 °C [1]. In response, countries were encouraged to communicate their long-term climate strategies through Nationally Determined Contributions (NDCs), outlining national commitments to reduce greenhouse gas (GHG) emissions and thereby contribute to achieving the goals of the Paris Agreement. In addition, NDCs emphasize the importance of strengthening national resilience and adaptive capacity to address the impacts of climate change [2].

In 2022, available data indicate that crude oil and oil-based products accounted for the largest share of total energy supply, approximately 30%, and were responsible for a comparable share of global GHG emissions (30%) [3]. Consequently, addressing climate change is closely linked to the ability to substantially reduce oil consumption. Such a reduction requires contributions from the entire energy sector. However, particular attention must be given to the transport sector, as it is the largest consumer of oil. As illustrated in Figure 1, the global oil consumption reached 188 EJ in 2022, of which the transport sector accounted for 64% [4,5].

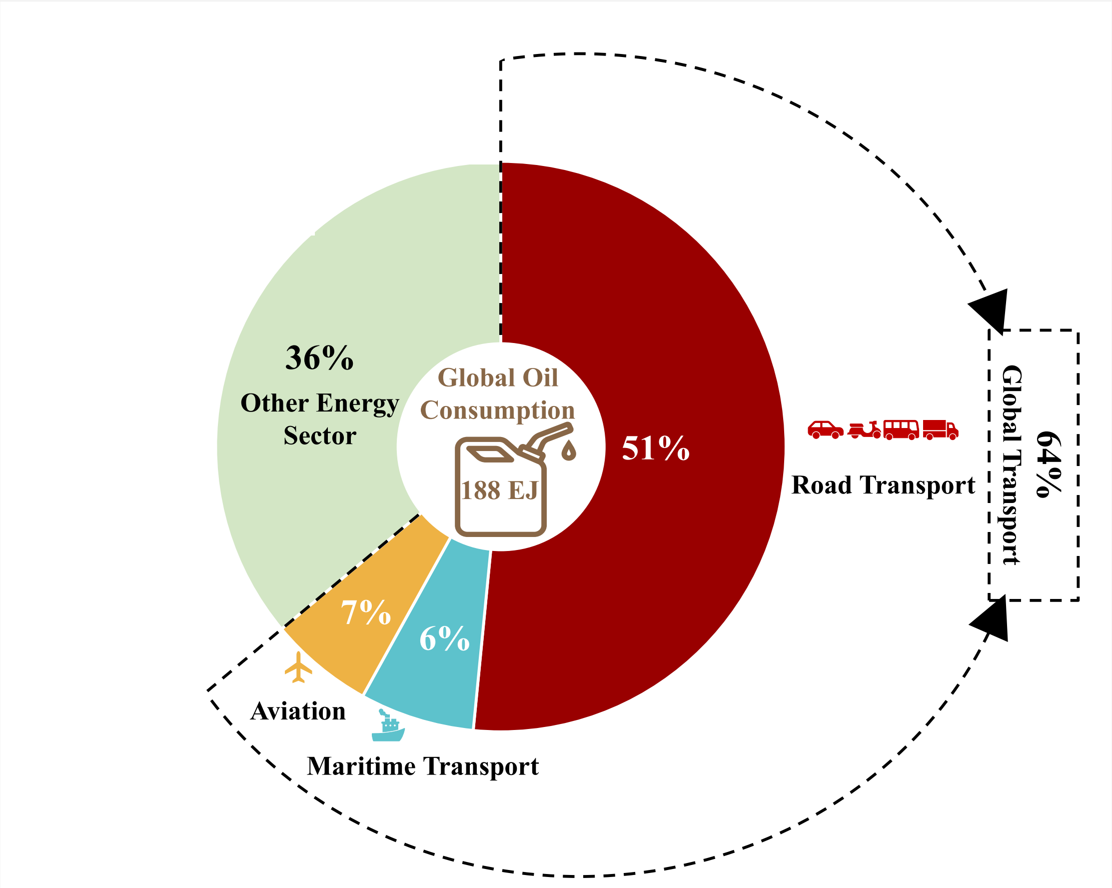


Figure 1 – Global oil consumption, 2022, divided per energy sector. Date retrieved from [4,5]. Other energy sectors include electricity and heating sector, at both residential, commercial, and industrial sites, as well as non-energy feedstock (i.e., agricultural and industrial feedstock).

Despite the clear need to reduce oil consumption, absolute global oil use has continued to gradually increase. This trend is particularly evident in the transport sector, which, as shown in Figure 2, experienced an increase in oil consumption of 47% between 2000 and 2022 [6]. Given the evident oil-dependency of transport sector, this sector accounted for a share of 22% of the global carbon dioxide (CO_2) emissions in 2022 [7]. Limiting climate warming to 1.5 °C by 2050, requires, thus, transport-related CO_2 emissions to be reduced by approximately 60%, compared to 2020 values [8].

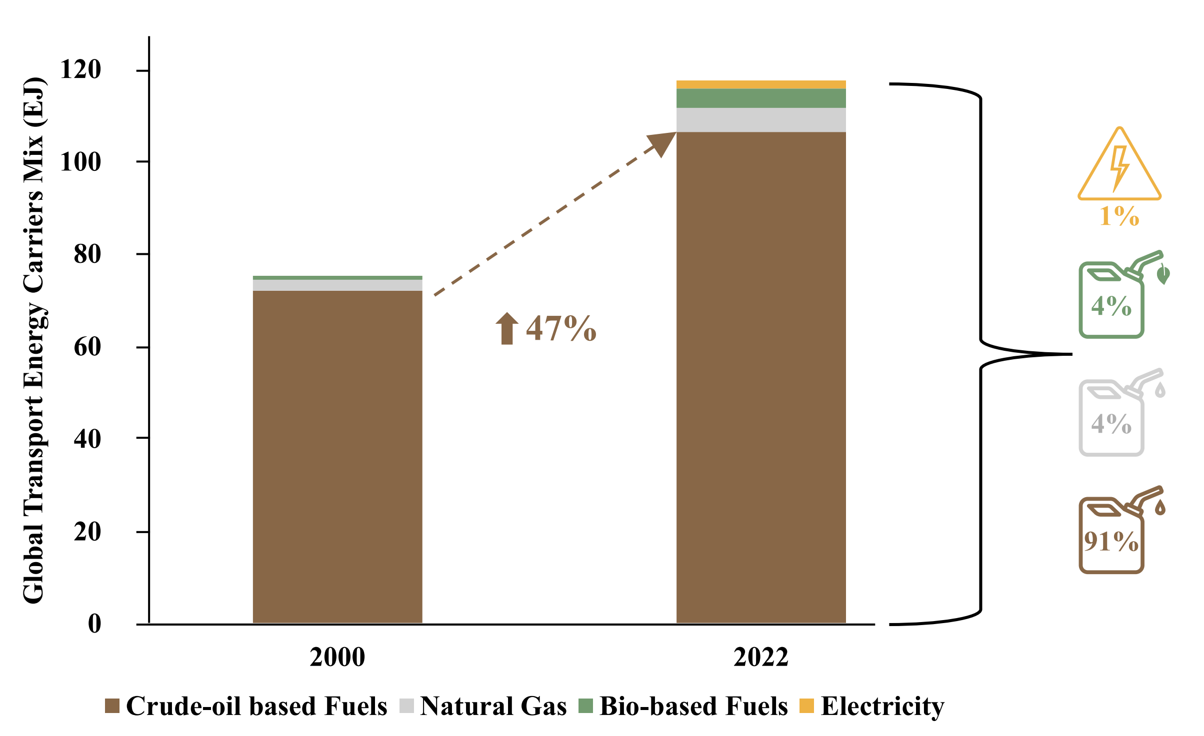


Figure 2 – The change in the consumption and type of energy carriers for transport globally, between 2000 and 2022. Natural gas includes both compressed and liquified forms. Data retrieved from [6].

A globally distributed low-carbon transport transition requires an examination of each transport segment and an assessment of its individual contribution to overall emissions. Based on current data, particular attention must be given to the road transport sector, as it represents the dominant transport-based oil consumer (see Figure 1) and thus, the major source of emissions, accounting for 74% of total transport-related CO_2 emissions [9]. Accordingly, it can be argued that meeting the 2050 climate targets requires a rapid low-carbon transition of the road transport sector. In response, road transport has become the focus of extensive research examining the challenges, potential bottlenecks, and opportunities associated with achieving a low-carbon transition in this transport segment, see e.g., [10,11].

Existing studies on low-carbon road transport transition (see e.g., [8,12,13]), typically suggest strategies centered on technical, behavioral, and systemics measures. The literature consistently highlights a set of complementary solutions for achieving a low-carbon transition in road transport. These include (i) vehicle electrification, benefiting from the gradual decarbonization of the electricity sector through increased renewable energy uptake; (ii) fuel switching towards low-carbon energy carriers in first and foremost segments that are harder to electrify, such as the use of sustainable biofuels, hydrogen (H_2), and other synthetic fuels; (iii) fleet turnover towards more energy-efficient vehicles; (iv) transport demand reduction through a modal shift to transport modes with lower emissions per passenger or unit of freight; (v) urban planning measures, including passenger and freight re-routing as well as digitalization; and (vi) the expansion of enabling infrastructure and the implementation of strong policy frameworks. Together, these approaches reflect the broad consensus that deep emissions reductions in road transport require an integrated portfolio of solutions rather than reliance on a single technological fix.

From a road transport perspective, although the existing literature provides substantial technical insights into the low-carbon transition, its scope is often limited to aggregated national-level analyses, overlooking the fact that road transport demand is predominantly shaped at the local level. Such an approach fails to capture the strong dependence of road transport on local spatial and socio-geographical conditions. Examples of these conditions identified in previous studies [14–21] include (i) travel patterns; (ii) vehicle fleet composition; (iii) fuel consumption trends; and (iv) traffic regulations. Effectively addressing the road transport's low-carbon transition therefore requires moving beyond purely theoretical and technical considerations. Similar to other energy transitions, road transport's low-carbon transition must be understood as a context-dependent process and thus insights stemming from assessments made on a national or global level benefit from being complemented from a local perspective [22].

A comprehensive understanding on low-carbon transport transition requires considering other transport modes beyond road transport, such as aviation and shipping, which together represent about 20% of total global transport-related CO_2 emissions [23]. While emissions from road transport are expected to decline more rapidly, primarily due to the scalability of vehicle electrification and, consequently, the potential for fuel economy improvements [24], aviation and shipping are projected to increase their emissions in future [25]. This divergence reflects the structural challenges that are often discussed. According to literature [8], both aviation and shipping, face challenges that include (i) limited electrification potential due to high energy-density requirements; (ii) long asset lifetimes that delay fleet turnover; (iii) complex engineering leaning towards reliance on scarce low-carbon fuels; and (iv) complex international governance frameworks that complicate regulation and accountability. Such challenges are inherent to the hard-to-abate nature of these transport segments [26].

Beyond their low-carbon challenges, aviation and shipping play a critical and growing role in the global economy and society. Maritime shipping delivers over 90% of globally traded goods by volume [27], while aviation carries more than 4.27 billion passengers annually [28]. These activities are expected to expand further in line with projected growth in global population and gross domestic product (GDP), amplifying their climate relevance if emissions are not effectively addressed [29,30]. Moreover, these transport modes contribute to climate change through non-CO_2 effects that can significantly enhance their warming impact. In aviation, emissions of nitrogen oxides (NO_x) at cruise altitude and the formation of contrail-cirrus clouds can exert a warming effect comparable to or greater than that of aviation CO_2 emissions [31]. In shipping, the combustion of heavy fuels leads to the emission of black carbon, affecting the Earth's radiative energy balance and contributes to accelerated cryosphere melting and regional warming [32].

Taken together, the abovementioned factors have led some studies (see e.g., [33–35]) to conclude that failing to adequately address emissions from aviation and shipping could place disproportionate mitigation pressure on other sectors, thereby potentially jeopardizing the achievement of economy-wide climate targets. Accordingly, despite the strong focus of current literature on road transport, a robust and resilient low-carbon energy system does not only depend on the rapid decarbonization of road transport. It further requires a well-structured and explicitly accounted transition of these hard-to-abate transport sectors as an integral part of comprehensive climate mitigation strategies.

This thesis acknowledges the need to examine the low-carbon transition of the transport sector in broader terms and therefore goes beyond a sole focus on road transport. While road transport indeed plays a central role, its low-carbon transition is already well advanced, particularly due to recent and rapid technological developments driven by electrification [36]. Hence this thesis expands the scope to reflect on the low-carbon transition of the transport system as a whole, explicitly considering all transport segments, including hard-to-abate transport modes such as aviation and shipping. At the same time, transport differs from other energy sectors, as electricity and industry sectors, in that it is particularly closely connected to society's daily lives, behaviors, and mobility choices [37]. As a result, understanding the low-carbon transport transition requires an explicit representation of the existing links between transport systems and society and how their dynamics vary across scales [37]. Accordingly, these dynamics manifest differently depending on the transport segment considered. In specific, road transport is largely shaped by local and national contexts, whereas aviation and shipping operate predominantly at the global scale due to their inherently international nature. Capturing these multi-scale perspectives (i.e., local, national, and global) is therefore essential for adequately representing transport demand, system interactions, and the social dimensions of the low-carbon transition.

Furthermore, taking a closer look at the wider transport sector requires recognizing that electrification cannot be replicated across all transport modes, particularly in hard-to-abate sectors. Instead, these sectors are likely to rely on drop-in low-carbon liquid fuels, offering chemical properties similar to those of conventional fossil fuel-based products. Such low-carbon liquid fuels depend on energy carriers that behave as systems-integrators (i.e., resources that can be allocated to substitute fossil fuels in different parts of the energy system). As finite energy carriers, the applicability of systems-integrators (e.g., biomass and electricity) in transport may therefore be subject to cross-sectoral competition or synergies with other energy demanding sectors. This highlights the need to assess the low-carbon transition of transport not only from a broader transport system perspective, but also within the context of the wider energy sector. Accordingly, a system perspective is required to identify potential synergies and bottlenecks that a low-carbon transition may impose across different parts of the energy system, as well as to understand how transitions occurring in other parts of the system in parallel may influence and constrain the transport transition.

Acknowledging these intricacies related to transport systems, this thesis develops a framework that investigates the low-carbon transport transition from a multi-scale perspective, thereby offering insights at the local, national, and global levels. The framework applies to a rationale based on the interaction between Energy Systems Optimization Models (ESOMs) and stakeholders engagement. Stakeholders engagement represents a central contribution to this thesis, as it enables the involvement of experts from different parts of the wider energy sector, giving voice to the particularities of a given energy system. This interaction allows stakeholder inputs to be translated into modeling assumptions and to support a continuous discussion of model outputs. Moreover, the approach presented in this thesis enables an improved understanding of system's inertia towards transition by exploring what-if questions through modeling scenario exercises.

1.1. Motivation, Aim, and Research Questions

Existing literature already emphasizes the importance of adopting a systems energy perspective at multi-scale levels when examining energy transitions (see e.g., [38]). Existing studies consistently frame energy transitions as context-dependent processes that emerge from the unique socio-geographical, economic, and infrastructural characteristics of the systems under transition [39–42]. However, the current state-of-the-art still falls short in capturing low-carbon transport transition across a thorough multi-scale perspective, as analyses are often confined to either national or regional levels, thereby overlooking the relevance of both local and global dimensions. The omission of these perspectives limits a comprehensive understanding of low-carbon transport transitions, especially given the interconnections among the three major transport segments. Road transport, for instance, is strongly shaped by local conditions and therefore requires a local perspective that accounts for variations in socio-geographical attributes, highlighting the importance of assessing the low-carbon potential of fuels and mobility technologies within a context-specific local framework [22]. In contrast, aviation and shipping function as international backbones of passenger and freight mobility and therefore their low-carbon transition demands a global perspective [43]. Understanding their transition requires capturing how mobility and trade flows evolve across world regions, shaped by heterogeneous socio-geographical contexts that are reflected in differing trajectories of population growth, urbanization, and GDP development (see e.g., [44,45]).

Accordingly, the overarching aim of this thesis is to develop a framework that establishes a soft-link between ESOMs and stakeholders engagement to assess low-carbon transport transitions from a systems-oriented rationale and multi-scale perspective. Specifically, the proposed approach integrates multi-scale perspective to capture how low-carbon transport transitions unfold across local, national, global (disaggregated in different world regions) levels, while explicitly accounting for the influence of local socio-geographical conditions that not only shape transport demand but also suitable transition pathways. At the same time, and given a systems-oriented rationale, the developed framework embeds a cross-sectoral perspective, allowing the analysis of interactions between transport and parallel transitions in other energy sectors, with a particular focus on synergies and trade-offs arising from competition over limited energy carriers, i.e., systems-integrators. To bridge the gap between model-based analysis, that often focus solely on a techno-economic perspective, and real-world decision-making, the framework further incorporates continuous stakeholders engagement through a soft-linking approach based on modeling scenarios exercise. Such an approach further enables qualitative insights to inform modeling assumptions, scenario design, and result discussion. In doing so, this thesis demonstrates how a continuous and interactive dialogue between ESOMs and stakeholders is mutually beneficial, as it can enhance the representation of context-dependent transition dynamics, improve the relevance of model outcomes, and support more robust and informed assessments of low-carbon transport transitions within the wider energy system.

Accordingly, the research questions (RQs) formulated in this thesis follow three research objectives:

- **Develop a multi-scale modeling framework to assess low-carbon transport transitions as context-dependent processes**. This objective focuses on representing low-carbon transport transition across multiple spatial scales (i.e., local, national, and global), while acknowledging that transition pathways and outcomes depend strongly on specific socio-geographical aspects.

  RQ1: How can a multi-scale modeling framework be designed to represent low-carbon transport transitions as context-dependent processes across municipal, national, and global scales?

- **Analyze how low-carbon transport transitions may evolve applying a systems-integrated, i.e., a cross-sectoral, perspective**. This objective addresses how low-carbon transport transition interacts with parallel transitions in other sectors, highlighting both synergies and competition for limited energy resources (i.e., in this thesis defined as systems-integrators). Furthermore, this objective is extended to analyze the cross-sectoral effects of co-products when producing energy carriers, and how the availability and allocation of energy carriers may constrain or enable low-carbon transport transitions, and to assess the systems-wide impacts of these dynamics.

  RQ2: How can a cross-sectoral perspective influence cost-effective pathways for low-carbon transport transitions, and what synergies and trade-offs emerge between transport and other energy demand sectors?

- **Establish and integrate a continuous interaction between ESOMs and stakeholders through a soft-linking approach.** This objective explores how qualitative stakeholders input can be systematically incorporated into modeling assumptions, scenario development, and validation to better capture specific spatial dynamics and context-specific transition narratives. It further develops an analytical framework demonstrating how a dialogue between energy modelers and stakeholders can be mutually beneficial, as modeling insights can facilitate guidance towards low-carbon and long-term transition strategies.

  RQ3: What insights can emerge from soft-linking stakeholders engagement with ESOMs, and how can this integration generate mutual benefits for the modeling process and stakeholders decision-making in analyses of low-carbon transport transitions and the wider energy system?

1.2. Scope and Delimitations

This thesis presents, as illustrated in Figure 3, an introductory essay based on four appended papers that collectively examine low-carbon transport systems from a multi-scale perspective, ranging from local to global level. The appended papers further explore different forms of interaction between ESOMs and stakeholders involvement, highlighting stakeholders engagement as a key modeling feature for (i) the integration of context-specific dynamics; (ii) validation of assumptions; and (iii) the interpretation of results. Similarly, the thesis reflects on how these interactions are mutually beneficial, as they enhance the relevance of modeling outcomes as key support for stakeholders decision-making processes related not only to low-carbon transport transitions, but also to transitions in the wider energy sector.

Paper I presents a context-specific method that considers a local energy systems perspective when generating non-urban road transport pathways. **Paper II** develops a techno-economic energy systems model to test road transport decarbonization according to a cost-effective perspective, through modeling scenarios that mirror the local pathways developed in a participatory manner. **Paper III** broadens the analysis of a low-carbon transport transition beyond road transport by explicitly including hard-to-abate transport systems, such as aviation and shipping, while situating transport transitions within the wider energy system. Accordingly, the paper examines the role of these energy carriers from a cross-sectoral perspective. To this end, it develops a single analytical framework that integrates a global ESOM with multi-phase stakeholders engagement. **Paper IV** develops a global, integrated, cross-sectoral analytical framework based on an ESOM to better represent the dynamics of low-carbon aviation transition. The analysis includes a detailed representation of the full range of Sustainable Aviation Fuels (SAF) production pathways and explicitly captures competition for shared energy carriers that act as systems-integrators, such as biomass and electricity, across multiple energy-using sectors.

It should be noted that in the Licentiate thesis (halfway to this PhD thesis), some assessments were made that are not published elsewhere, i.e. model runs on a national (Swedish) level. Thus, to complement the multi-scale perspective also these energy systems model results, on road transport transition, has been added, see Figure 3.

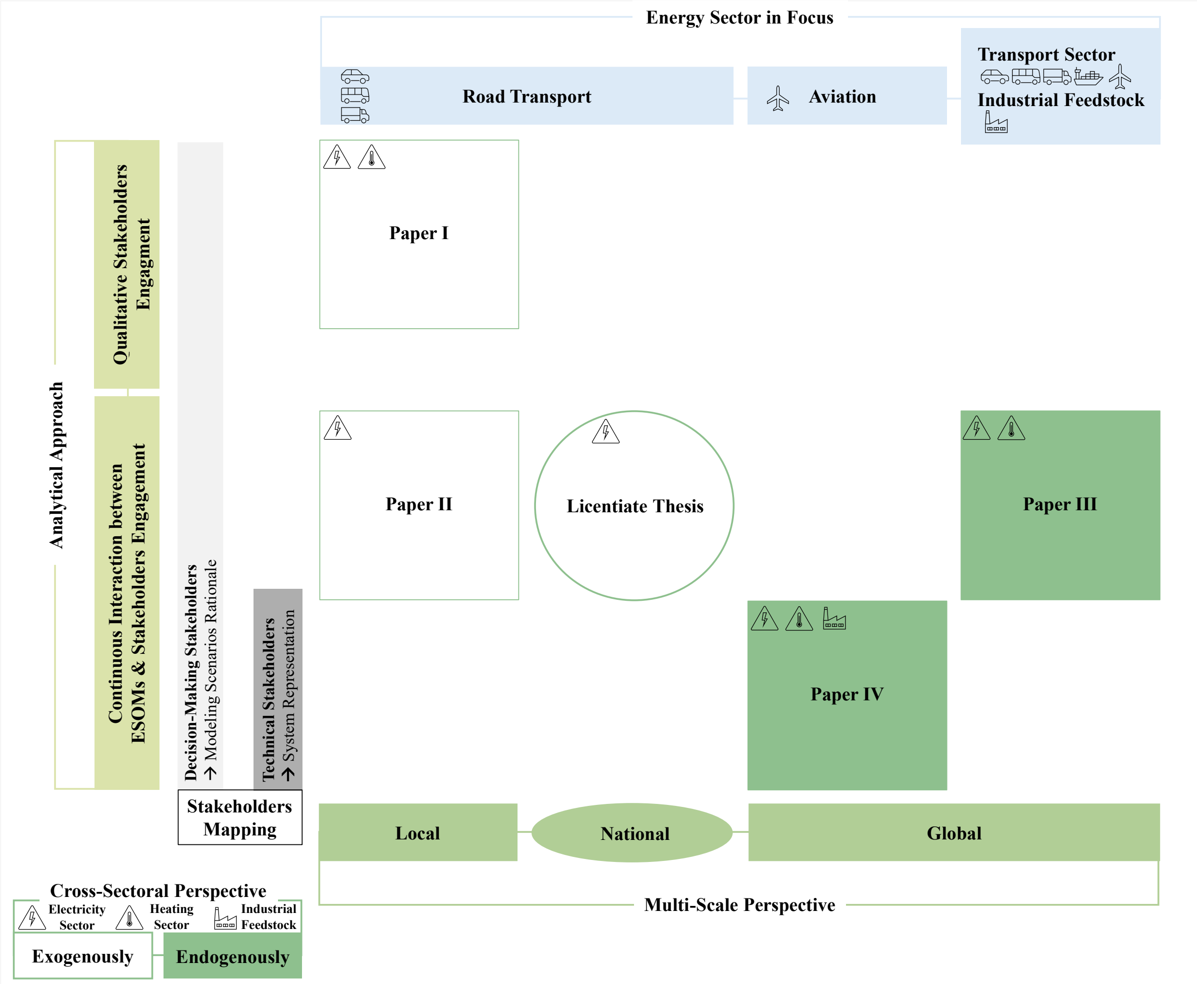


Figure 3 – Overview of the overall scope of this thesis, as well as of the appended papers. The appended work ranges according to (i) energy sector in focus; (ii) analytical approach; (iii) multi-scale perspective; and (iv) cross-sectoral perspective. A cross-sectoral perspective is adopted across all appended work, with applications varying between exogenous and endogenous approaches. In an exogenous approach (i.e., white colored elements with green contours), the cross-sectoral perspective assumes system wide energy trends through modeling assumptions and constraints. In contrast, in an endogenous approach (i.e., green colored elements), the modeling rationale considers the energy sector in focus and includes parts of, or the entire, energy system. The energy sectors considered in each paper, beyond the energy sector in focus, are indicated by the sector symbols, defined in the legend. The model runs made and assessed in the Licentiate thesis, of Swedish national level road transport, has been included in this thesis, as a complement to the discussions presented in the appended papers, offering a national perspective to low-carbon road transport transition.

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, which, through municipal officials engagement, resulted in the identification of different local pathways. The primary contribution of **Paper I** 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 an urban context. By advocating for a tailored approach that considers the specific context of each transition, **Paper I** underscores the importance of aligning low-carbon solutions with local behaviors and socio-geographical characteristics. Overall, **Paper I** 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 test road transport low-carbon strategies, 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 **Paper II** is the understanding of how road transport dynamics fit within cost-optimization models. The 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.

Paper III reflects on the role that liquid fuels might play in a low-carbon transition, based on evidence from current statistics and the medium-term road transport results presented in **Paper II** and in the Licentiate thesis, which together indicate that liquid fuels might constitute the major energy carrier in the future transport sector. Thus, **Paper III** expands the scope of **Papers I-II** by moving beyond an understanding of transport as a standalone system where an exogenously cross-sectoral perspective is assumed. Instead, **Paper III** considers the transport sector, as an integral part of the wider energy system and thus, it models endogenously a cross-sectoral perspective. This approach makes it possible to examine how the role of liquid fuels evolves by cross-sectoral competition of energy carriers that function as systems-integrators. **Paper III** develops a single analytical framework defined through continuous interaction between a global cost-optimization ESOM and stakeholders engagement representing a local energy port cluster. The application of this framework clarifies that the role of liquid fuels is mainly influenced by socio-economic factors, while also being constrained by inherent energy systems parameters such as the carbon budget, carbon storage capacity, and the availability of energy carriers, particularly those that act as systems-integrators across sectors. One main contribution of **Paper III** is the reflection on the mutual benefits of a continuous dialogue between techno-economic modeling and stakeholders engagement. Local and national actors contribute contextual knowledge that helps refine modeling uncertainties, while model results provide guidance for local actors in identifying and navigating pathways towards low-carbon transitions.

Paper IV acknowledges that among the different hard-to-abate sectors included in **Paper III**, aviation emerges as the main driver of a continued demand for liquid fuels in the future. In response to this finding, **Paper IV** updates a global ESOM by expanding on the dynamics of a low-carbon transition in aviation. These dynamics include a detailed representation of a range of SAF production pathways and an explicit characterization of competition for shared energy carriers that act as systems-integrators across multiple end-users' sectors. Furthermore, **Paper IV** examines how heterogeneity across different range-haul aviation categories may give rise to different cost-effective alternative low-carbon fuel choices. To ensure complexities associated with biomass supply potential, bioenergy conversions, SAF options and aircraft technologies, have been captured, and not oversimplified, **Paper IV** establishes a continuous exchange of knowledge with experts in bioenergy and aviation. These expert discussions helped ensuring a reasonable representation of techno-economic constraints and potential bottlenecks along the diverse fuel supply chains, from primary energy extraction through fuel production pathways to final energy conversion and end use. This approach enables a discussion that challenges the view of aviation solely as a barrier to a low-carbon transition due to its hard-to-abate nature. Instead, the results suggest that aviation may contribute positively to broader systems flexibility by enabling the deployment of low-carbon co-produced liquid fuels that would be economically unattractive in other sectors.

Merging together the insights of each appended paper, this thesis advances multi-scale modeling framework to assess low-carbon transport transitions as context-dependent processes, adding mainly two complementary contributions: (i) a method contribution; and (ii) an application-oriented contribution. Together, these contributions demonstrate how a multi-scale perspective, and thus socio-geographical contexts, influence not only transport transitions, but also interactions within the wider energy system. Figure 4 synthesizes the identified research gaps and illustrates how the methodological and application-based contributions of this thesis address them.

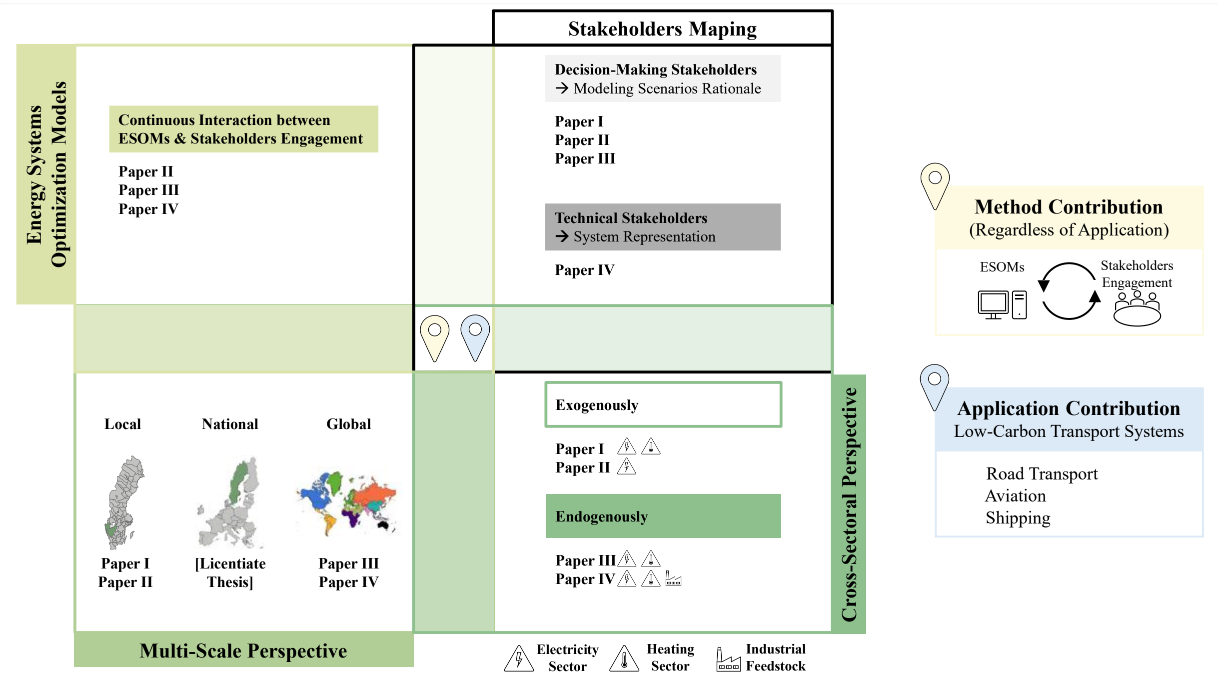


Figure 4 – Research gap addressed in this thesis, highlighting in yellow and blue the two main contributions of this thesis. i.e., method and application contribution, respectively.

While this thesis provides an in-depth analysis of the transport sector, its framework offers a universal message on creating more sustainable and inclusive energy systems. This message is relevant for an international audience and a wide range of stakeholders, as it promotes a global dialogue on the importance of adopting multi-scale and cross-sectoral perspectives as key elements for accurately representing behavioral and consumption trends, climate action strategies, and the availability of local resources, acting as systems-integrators, across diverse socio-geographical contexts. Furthermore, this thesis strengthens the understanding that ESOMs should not be applied as standalone tools. Instead, it argues for a more holistic and equitable representation of energy systems through the establishment of soft-links between ESOMs and stakeholders that represent different parts of the system. In this way, the thesis contributes both to the energy systems modeling community and to qualitative decision-making processes by explicitly describing the complementary role between these two perspectives. By demonstrating how dialogue between energy modelers and local actors can be mutually beneficial, this thesis shows that stakeholders can help refine modeling uncertainties through contextual and experiential knowledge, while model results can guide actors in identifying and pursuing cost-effective, low-carbon, long-term transition pathways.

1.4. Structure of the Thesis

This thesis is structured in six different chapters. Chapter 2 presents an overview of the background and theoretical framework this thesis was built upon. Chapter 3 presents the method developed and applied in the appended papers. Chapter 4 presents selected outcomes of the developed framework. Discussion on the presented results and conclusions, as providing specific answers to the research questions of this thesis, can be found in Chapter 5. This thesis concludes with Chapter 6, outlining the research limitations and presenting broader reflections on the work.

2. Background and Theoretical Framework

This chapter presents the key background and theoretical foundations necessary for understanding the scope of the thesis as well as the method developed and applied in this thesis.

2.1. Climate and Transport Policy

Despite the challenges identified with a low-carbon transport transition, no overarching global transport policy yet exists that is applied uniformly across countries to regulate road transport, aviation, and shipping. This is primarily because transport policy remains largely a national responsibility, shaped by domestic institutions, national policy priorities, and socio-economic conditions [46].

2.1.1. Global

Not only transport-related policies but also climate policies are predominantly governed at the national level, meaning that no single, binding global climate obligation exists. Nevertheless, the European Union, together with 194 other states, has acceded to the Paris Agreement [1]. Although not all countries have ratified the Agreement, the participating Parties collectively account for more than 99% of global GHG emissions [47]. Each party communicates its climate ambitions through NDCs, which often include targets related to achieving climate neutrality (i.e., net-zero GHG emissions) around mid-century, calling for a cross-sectoral effort, including national transport systems [48].

Consistently tracking and representing all individual NDCs is recognized to be a complex and resource-intensive task [49]. At the global scale, a scenario-based modeling approach is typically used by exploring different carbon budgets derived from Representative Concentration Pathways (RCPs). RCPs describe alternative greenhouse-gas concentration trajectories, defined by the level of radiative forcing (i.e., balance between incoming solar energy and outgoing heat in the Earth system, see e.g., [50]) reached by the year 2100 [51]. These pathways were adopted and used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, published in 2014 [52].

Given the international nature of shipping and aviation, several global governance frameworks have been developed to address emissions from these hard-to-abate sectors. Prominent examples include the International Maritime Organization (IMO) Net-Zero Framework [53], which is still under development, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [54], established by the United Nations' International Civil Aviation Organization (ICAO). While CORSIA has already entered its pilot phase (i.e., initiated in 2021and extended to 2026) and is expected to become mandatory for most participating states from 2027, the IMO framework, is still being negotiated.

The IMO Net-Zero Framework is intended as a mandatory global regulatory approach aimed at enabling the low-carbon transition of the maritime sector through increasingly stringent fuel-intensity standards and potential economic measures, such as carbon pricing. In contrast, CORSIA operates as a global market-based mechanism designed to address emissions from international aviation. Rather than directly reducing emissions at source, CORSIA allows airlines to offset emissions growth above baseline levels primarily through the purchase of verified carbon credits. Furthermore, the CORSIA framework allows the airlines to reduce their offsetting obligations by using eligible fuels with low lifecycle emissions [55]. Currently, three eligible SAF are certified, including Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch kerosene (FT-kerosene), and Alcohol-to-Jet kerosene (AtJ-kerosene) [55].

Despite ongoing efforts to strengthen and operationalize these frameworks, their effectiveness is uncertain. Their inherently international nature requires broad and global consensus, potential limiting ambition and make policy design and implementation susceptible to political negotiation and stakeholder influence (see e.g., [56,57]).

2.1.2. European Union

As a response to the Paris Agreement, in 2019, the EU presented the "European Green Deal" that sets the goal of achieving climate neutrality, by 2050 [58]. Achieving such a goal motivated the EU to establish different climate policies, regulations, and directives that set clear milestones towards the required transition, as follows:

- In 2021, the EU presented "Fit for 55" [59] 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, four specific regulations are of special interest in transport:

  (i) "Effort Sharing Regulation" (ESR) was adopted in 2021 and set a specific national GHG emission reduction goal individually for each of the 27 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 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 [60]. In the specific case of Sweden, ESR imposes a GHG emissions reduction of 50% to be met by 2030, compared to 2005 [61].

  (ii) "Emissions Trading System II" (EU-ETS II) will extends the EU emission trading scheme to cover, from 2027, the CO_2 emissions resulting from fuel combustion in road transport, buildings (resulting from heating systems), and small industries [62]. Currently, there is still a lack of guidance on how the EU-ETS II scheme will be implemented.

  (iii) In 2024, "ReFuelEU Aviation" regulation was implemented, establishing progressively increasing annual mandates for the use of SAF, including both bio-based fuels and electrofuels. The regulation requires SAF to account for 70% of the total energy consumption of commercial flights departing from EU airports by 2050, with at least half of this share to be met by electrofuels [63].

  (iv) In 2025, "FuelEU Maritime" went into effect, introducing limits on the GHG intensity of the energy used onboard ships. The regulation sets an initial reduction target of 2% in 2025, which will progressively tighten to an 80%

reduction by 2050. It applies to all eligible vessels, regardless of flag, provided they are cargo or passenger ships of more than 5,000 gross tonnage [64]).

- In 2023, the "Renewable Energy Directive III" (RED III) was presented as a target of achieving a renewable share of 42.5% in the overall energy sector, 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 [65].

- In 2023, EU announced an ambition towards a "ban on new Internal Combustion Engine Vehicles (ICEVs) sales", to be applied from 2035 [66]. Yet, by the time of writing this thesis, EU revoked the ambition of ICEVs ban, last quarter of 2025 [67].

2.1.3. National and Local: A Swedish Perspective

As mentioned previously, climate and transport policies are often governed at a national level. Sweden is widely acknowledged for its strong commitment to sustainability and is sometimes used as a good example on how different climate and related policies can be structured.

In 1924, Sweden introduced an "Energy Tax" on gasoline, and, later, on diesel, when used as transport fuel [68]. In 1991, a "Carbon Tax" was also added to the carbon content of all transport fuels [69]. From early on, these taxes were imposed as an incentive to reduce energy use through improved energy efficiency but also for increasing the renewable share in the total energy system. These taxes are levied on fossil fuels and biogas (only energy tax is applied to biogas) [70]. Biofuels, such as ethanol and Hydrotreated Vegetable Oil (HVO, in this thesis simplified as biodiesel), have been exempted from both these taxes until, first until 2026 [71] then until 2032 [72].

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-emission, by 2045 [73]. 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.

Meeting the national climate target motivated the implementation of different climate policies and regulations, some major national policies targeting transport are:

- 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 emissions of their products sold according to a specific percentage every year, by gradually increasing the share of biofuels [74]. In 2025, the reduction obligation was expanded to also allow for renewable fuels of non-biological origin (RFNBOs), for Swedish law to align with a revised version of RED III [75].

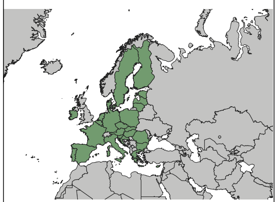
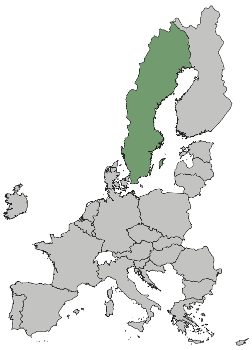
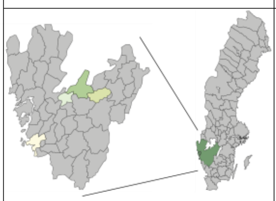
- In 2018, Sweden adopted a "Bonus-Malus" scheme, a feebate system that introduces a "green tax shift", which motivates the renewing of the passenger car fleet towards lower tailpipe CO_2 emission vehicles by taxing higher emitting ICEVs. Accordingly, ICEVs running on gasoline, diesel, and biodiesel registered after 1st of July, 2018, are taxed higher during the first three years after their registration whereas low-emitting vehicles were given a financial bonus [76]. Currently, only the Malus system is in force.

- In 2021, Sweden expanded its "Reduction Obligation" to include nationally supplied aviation kerosene, introducing progressively increasing GHG reduction targets relative to fossil-based kerosene [77]. However, by the time of writing this thesis, this policy has been repealed [78].

Västra Götaland Region and Municipalities

As previously presented, this thesis further considers a local perspective, by collaborating with different Swedish municipalities. A local perspective is especially important when assessing policies, as 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 [79]. 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.

According to the specific research scope of the appended papers, some of the abovementioned Global, EU, Swedish national, regional, and municipal climate and transport policies, as well as ambitions have been included in this thesis. The targeted legislation was further considered through the different modeling rationales developed and applied in the appended papers. Figure 5 summarizes the specific policies included in this thesis, and how they were considered in the modeling framework. The respective paper, as identified through different colors, includes a detailed description of how a certain policy has been included.

Spatial Scale	Policy Name ("In Force" Year)	Policy Description	Policy Modeling Assumptions
 Global	***Paris Agreement (2018)***	Collectively agreement to limiting the increase in global average temperature to well below 2 °C above pre-industrial levels, while pursuing efforts to limit warming to 1.5 °C.	From **2010 to 2100** carbon budgets, representing different RCPs, are applied.
	Carbon Offsetting and Reduction Scheme for International Aviation	Global aviation climate scheme that requires airlines to offset emissions growth above a baseline mainly by buying carbon credits, while allowing the optional use of lower-carbon fuels to reduce those offsetting requirements.	Currently **eligible SAF routes**, i.e., HEFA, FT-kerosene, and AtJ-kerosene, are considered in the modeling exercise.
 Continental ***European Union***	***European Green Deal (2019)***		
	Fit for 55 (2021)		
	Emission Trading System II (2027)	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**.
	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.**
 National ***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 **ICEVs purchased after 1/July/2018 pay higher vehicle tax** for the first three years of utilization.
 Regional ***Västra Götaland***	***"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.

Paper I   **Paper II (∈ Licentiate Thesis)**   **Paper III**   **Paper IV**

Figure 5 – Existing and announced climate and transport polices considered in this thesis, varying among different spatial scales, i.e., world, EU, Sweden, and Västra Götaland Swedish region. Considered policies are illustrated by different colors in "Policy Modeling Assumptions" column. Some EU regulations (e.g., the European Green Deal, the Effort Sharing Regulation, and the Renewable Energy Directive III) were indirectly included in the modeling exercise, as the considered policies set more ambitious targets than those implied by these regulations. Atj-kerosene, Alcholol-to-Jet; CO_2, Carbon Dioxide; FT-kerosene, Fischer-Tropsch Kerosene; GHG, Greenhouse Gas; HEFA, Hydroprocessed Esters and Fatty Acids; ICEVs, Internal Combustion Engine Vehicles; RCPs, Representative Concentration Pathways; SAF, Sustainable Aviation Fuels.

2.2. Energy Systems Optimization Modeling

The lack of a widely implemented transport policy further highlights the challenges associated with a low-carbon transport transition. Addressing the challenges of low-carbon transport, as with any energy transition, requires a comprehensive and holistic understanding of overall systems dynamics, including interactions across sectors, technologies, time and multi-scale perspective. This need can be addressed through the use of Energy Systems Models (ESMs), which are widely employed to analyze system-wide transitions and policy-driven structural changes [80,81].

ESMs are powerful analytical tools designed to assess how real-world energy systems may evolve in response to exogenous drivers such as climate mitigation strategies, technology deployment, and policy constraints [82]. By explicitly representing systems interactions over time, and at multi-systems and geographical scales, ESMs enhance the understanding of future energy transitions by providing both (i) a transitional perspective, describing how energy systems may develop to achieve specific objectives; and (ii) a long-term perspective, examining the configuration and performance of the systems as these objectives are met [83].

Within the broad family of ESMs, ESOMs are particularly effective at integrating techno-economic perspectives while ensuring system consistency, as they combine detailed technology representations with cost-minimization frameworks to describe the evolution of the entire energy system under resource, policy, and emissions constraints [82,84]. Integrated Assessment Models (IAMs), by contrast, adopt a broader perspective of systems, linking energy, land use, climate, and economic dynamics to explore long-term mitigation pathways [85]. However, this integrated scope often comes at the cost of reduced technological resolution. As an example, IAMs tend to represent carbon capture and utilization (CCU) routes in a low resolution manner, limiting their ability to fully capture the role of synthetic fuels [86]. This simplification may constrain the assessment of low-carbon transport pathways, given e.g., the prominent role envisaged for synthetic fuels, as SAF in the hard-to-abate aviation sector. Owing to their higher techno-economic detail and explicit representation of system dynamics, ESOMs are better suited to analyze low-carbon pathways, trade-offs, and feasibility under binding climate or policy constraints [87]. Accordingly, this thesis adopts an ESOM-based approach to assess the implications of alternative low-carbon transport transition pathways.

2.2.1. System Boundaries

By definition, ESOMs are bottom-up modeling frameworks characterized by a rich techno-economic representation of energy technologies and users [87]. These models allow for long-term accounting, which through "what-if" scenarios test how an energy system evolves over time by, typically, solving a cost-minimization problem subject to a set of technical, resource, policy, and emissions constraints [88]. A critical step in ESOMs development is the definition of system boundaries, involving the selection of variables, parameters, and modeling constraints [89]. These boundaries depend strongly on the chosen temporal resolution, spatial scale, and sectoral coverage, as model inputs and constraints assume different values respectively [90].

Multi-Scale Energy Systems Perspective

While ESOMs are typically consistent in their long-term temporal scope, often extending to mid-century in line with national and international climate targets, their spatial scope is considerably more heterogeneous. ESOMs display a high degree of flexibility in this regard, ranging from local (see e.g., [91]) representations to national (see e.g., [92–94]) and global (see e.g., [95,96]) scale. These spatial scale variations tend to reflect energy systems under consideration, as different applications require different spatial resolutions [97].

Certain sectors exhibit dynamics that are predominantly local, such as passenger road transport and space heating, mainly shaped by local aspects, e.g., end-user behavior, infrastructure availability, and socio-geographical conditions [8,98]. Other sectors, such as electricity generation, are commonly governed by national-level planning [99]. In contrast, hard-to-abate sectors, including aviation, shipping, and industrial feedstocks, due to their international-based activity benefit from a global understanding [100,101]. From this perspective, the choice of spatial scale should be understood as a deliberate modeling decision aimed at capturing the dominant dynamics of the energy sector under study rather than as a "one-size-fits-all" representation.

This thesis adopts a multi-scale (i.e., multiple spatial contexts are considered, i.e., local, national, and global) modeling perspective to reflect this heterogeneity in the context of low-carbon transport transitions. By considering a multi-scale perspective, the analysis avoids privileging a single set of dynamics and instead captures the sector-specific mechanisms governing transport low-carbon transition. **Papers I-II** focus primarily on road transport and therefore adopt a local perspective, complemented by a national representation, as discussed in the Licentiate thesis. This approach enables the analysis to capture context-specific differences between urban and non-urban settings, which are often obscured in national-level averages that tend to overvalue urban characteristics. In contrast, **Papers III-IV** adopt a global perspective, reflecting the international nature of liquid fuel supply chains, fuel trade, and aviation, which together play a decisive role in shaping future low-carbon transport pathways.

Cross-Sectoral Energy Systems Perspective

One of the key strengths of ESOMs lies in their sectoral coverage flexibility, allowing for the representation of different elements of the energy system, ranging from primary energy carriers to end-use demands [87]. Importantly, ESOMs also enable the consistent representation of single or multiple energy sectors within a single modeling framework [87]. Decisions regarding the sectoral scope, together with those concerning temporal and spatial resolution, are therefore a central component of system boundary design [90].

As a pillar of system boundary design, the choice of sectoral scale is strongly linked to the research question under investigation, as it determines which interactions ESOMs are expected to capture [87]. Some ESOM approaches treat individual energy sectors as standalone systems, an approach that is particularly suitable when the research scope is sector-specific, as it often allows for a high level of engineering detail and a focused assessment of policy impacts within that sector [102]. Thus, a standalone perspective focuses primarily on the internal dynamics of a specific sector. From such a perspective, cross-sectoral effects can still be considered, but they are introduced exogenously, for example through assumed energy prices, carbon intensities, or resource availability (see e.g., [103]). While this approach can provide valuable insights, it may limit the optimization process, as outcomes can become strongly influenced by predefined assumptions rather than emerging endogenously from system-wide interactions [88].

In contrast, other ESOMs adopt a cross-sectoral perspective, through shared primary resource constraints, sector-coupling technologies, and system-wide climate targets, such as NDCs or carbon budgets [102]. Thus, a cross-sectoral perspective explicitly captures interactions, competition, and synergies across multiple energy sectors. Under this framework, low-carbon pathways emerge endogenously from system-level trade-offs, rather than being imposed as external assumptions [104].

This thesis applies a cross-sectoral rationale, albeit with different degrees of endogeneity across the appended papers. In **Papers I-II**, and the Licentiate thesis, the focus is on understanding road transport dynamics and their interaction with urban versus non-urban settings. In this context, selected cross-sectoral interactions are incorporated exogenously. This approach allows the analysis to test different assumptions regarding energy carriers, such as electricity, H_2, and biomass, by varying their costs, emission factors, and local availability to reflect alternative production pathways, ranging from fossil-based to renewable. Furthermore, the availability of these energy carriers is constrained exogenously to the shares typically allocated to road transport in the literature, after accounting for projected use in other sectors.

By contrast, **Papers III-IV** expand the scope to include not only hard-to-abate transport segments but also industrial feedstocks, with a particular focus on how the role of liquid fuels evolves under different carbon budget constraints. In these papers, a fully endogenous cross-sectoral approach is applied. This enables the analysis to explore how a low-carbon transport transition unfolds when transport sectors both benefit from, and exert pressure on, other parts of the energy system undergoing the same transition. As a result, interactions between transport, industry, electricity and heating generation, as well as fuel production pathways are resolved within a unified optimization framework, ensuring system-wide consistency.

2.3. Socio-Technical Systems: Theoretical Perspective on Stakeholders Engagement

ESOMs are widely recognized for their ability to represent energy systems and their inherent complexities in a simplified yet structured manner [88]. Such representations facilitate a deeper understanding of the trade-offs among technology, resources, and emission constraints, as well as the underlying assumptions that might shape the system's techno-economic dynamics. Nonetheless, modeling assumptions should ensure that the simplifications introduced at the modeling level do not obscure or neglect critical interdependencies within the energy system [105].

Accordingly, a fair and robust representation of energy systems in ESOMs is closely linked to the capacity of these tools to acknowledge that energy systems transitions are inherently complex processes, driven by interactions and interdependencies among a wide range of social, technical, and contextual elements [106]. This complexity characterizes energy systems as socio-technical systems [107], in which different actors play a central role in shaping and steering transitions [108]. Understanding energy systems transitions can therefore benefit from comprehensive grasp of the relationships among the various actors involved commonly referred to as stakeholders.

Linked to ESOMs, relevant stakeholders involved often include industry players, technical experts, policymakers, and society, i.e., stakeholders defined as those whose decisions, behaviors, and interactions critically shape decision-making in the energy sector and influence the evolution of the energy system (see e.g., [109]). This definition is further applied in this thesis. Recognizing energy systems as socio-technical systems introduces an additional dimension to transition dynamics by explicitly linking energy and society through spatial interdependencies [110].

Consequently, given the close links between energy demand, economic growth, and population dynamics, energy systems transitions are inherently context-specific, as product of social patterns influenced by cultural, economic, and political factors, as well as everyday practices [111,112]. In this regard, effectively addressing a low-carbon transition of transport systems, like any energy transition, should therefore extend beyond purely theoretical optimization framework or techno-economic considerations and be grounded in assumptions that inherently reflect the dynamics of the specific system under study.

Understanding energy systems as socio-technical systems and thus, their low-carbon transition as context-dependent calls for a social dimension. Such a dimension enables a comprehensive illustration of how demand-side behaviors, preferences, and decision-making power influence the energy balance within a given context [113]. Accounting for this social dimension necessitates public engagement and inclusivity, thereby highlighting the importance of stakeholders participation in understanding and shaping low-carbon transition pathways [114].

2.3.1. The Role of Stakeholders Engagement

The role of stakeholders engagement in energy systems analysis has been widely discussed in the literature as an effective means of involving relevant actors and enhancing research outcomes through the integration of stakeholders experiences, tacit knowledge, and perspectives [115]. Moreover, stakeholders engagement is recognized as a valuable tool for identifying key dimensions associated with energy systems and planning processes, including temporal, spatial, and action-related dimensions [116].

In the context of energy transitions, stakeholders engagement facilitates, therefore, the integration of context-specific knowledge related to techno-economic, socio-geographic and political aspects. The inclusion of such expertise provides valuable insights into the dynamics of the system under study, its commitment to climate objectives, and the identification of system enablers (i.e., components that facilitate the implementation of actions without compromising system performance), as well as barriers (i.e., elements that increase system inertia and hinder transitions) [117–120]. By enabling this integration, stakeholders engagement can add a social dimension to energy systems analysis [121], highlighted as a crucial element of energy transition research and practice [122–125].

It is important to note that within the existing literature, stakeholders engagement is defined and framed using a variety of terms[1]. It is often referred to as, e.g., experts engagement, stakeholders integration, stakeholders interaction, stakeholders involvement, stakeholders participation, or participatory approach, reflecting differences in interpretation and implementation. The papers appended to this thesis address stakeholders engagement using different terms. Specifically, **Paper I** and **Paper II** adopt the term participatory approach. In contrast, **Paper III** uses the term stakeholders participation, while **Paper IV** refers to as experts engagement. In this introductory essay of the thesis, the term stakeholders engagement has been adopted. Such engagement, as further discussed later in this thesis, can take multiple forms (i.e., be more participative or not), varying according to the research scope and the types of stakeholders involved.

Moreover, the some studies (e.g., [126,127]) highlights that stakeholder engagement comes with several challenges, beyond the lack of standardized terminology on how to define stakeholders engagement. Other challenges suggest that (i) stakeholder inputs can be influenced by personal views, roles, and specific contexts, meaning they are not always consistent or neutral; (ii) stakeholders interactions may also capture only parts of the broader system, missing wider interactions and long-term dynamics; as well as (iii) translating qualitative stakeholder input into quantitative factors or structured analysis is time-consuming and can lead to a loss of detail or oversimplification. This thesis offers, in Chapter 6, a thorough discussion of the limitations associated with stakeholder engagement, based on experience gained over the past five years.

2.3.2. Expertise-Based Stakeholders Mapping

Stakeholders engagement has been applied in diverse forms within energy systems analysis (see e.g., [128]) and its implementation is linked to the types of stakeholders involved and to the specific dimensions of the energy system they represent [37].

Within energy systems research, stakeholders can be categorized according to their areas of expertise into seven dimensions, namely: (i) industry; (ii) technology; (iii) infrastructure; (iv) policy; (v) culture; (vi) science; and (vii) market users [129]. These seven dimensions can be further grouped into two overarching strands, specifically (i) decision-making; and (ii) technical understanding. The decision-making strand encompasses stakeholders related to policymaking and consumer behavior and thus includes all dimensions except science, while the technical understanding strand primarily corresponds to scientific expertise [130].

[1] In the literature, terms referring to stakeholder engagement are often also presented in possessive form, such as stakeholders' engagement, experts' engagement, stakeholders' integration, stakeholders' interaction, stakeholders' involvement, and stakeholders' participation.

Decision-making related stakeholders are particularly well suited to broad energy system analyses, in which the research problem is not fully defined at the outset of the interaction between researchers and stakeholders [131]. In such contexts, the research focus often emerges through a continuous interaction process to which stakeholders engagement contributes with interpretive feedback on theoretical framework and resulting analysis. In contrast, technical stakeholders typically do not necessarily shape the research scope itself but instead contribute to the technical resolution of the research questions by providing detailed and specialized knowledge about the system, or specific parts of it, under assessment [132].

Despite these differences, decision-making and technical understanding should not be treated as separate or independent strands. Rather, they are linked through a causal loop, in which decision-making drives the need for updated technical understanding, while technical knowledge provides well founded and tangible evidence to support informed decision-making [133]. Accordingly, energy systems analysis not only benefits from stakeholders engagement but should also ensure sufficient stakeholder heterogeneity to avoid research bias and to foster resilient low-carbon transitions [134]. This requires a balanced consideration of the multiple expertise-based stakeholders involved [135].

Existing research in energy systems analysis commonly tailors the type of stakeholders engagement to the specific research gaps and scope (see e.g., [128]). In the case of ESOMs, stakeholders mapping can be considered a component of system boundary design, determining both the types of knowledge that can be extracted from stakeholders interactions and the form that stakeholders involvement should be carried out [136].

Finally, this thesis proposes that the selection of stakeholder types is linked to the spatial scale of analysis. Decision-making stakeholders, owing to their context-dependence and spatial specific knowledge, are particularly relevant for analyses at smaller geographical areas allowing for high richness of details (high spatial resolution), such as local and national scales. Conversely, technical experts are generally better suited to global scale representations, where standardized and generalized system knowledge is beneficial.

Accordingly, in this thesis, both groups of stakeholders were included, namely decision-making stakeholders in **Papers I-III** as well as technical experts in **Paper IV**, as illustrated in Figure 6. Through interaction between researcher and decision-making stakeholders, modeling scenarios are, in this thesis and **Papers I-III**, designed to explore alternative "what-if" pathways, contributing with actionable insights to support informed decision-making. **Papers I-II** applies a local perspective, considering the participation of municipal officials, while **Paper III**, is centered around a local energy systems cluster, involving entities operating both at local and national level. By contrast, technical experts are defined in this introductory essay and **Paper IV**, as stakeholders with a notorious global expertise in specific areas of the energy sector, e.g., bioenergy and aviation dynamics.

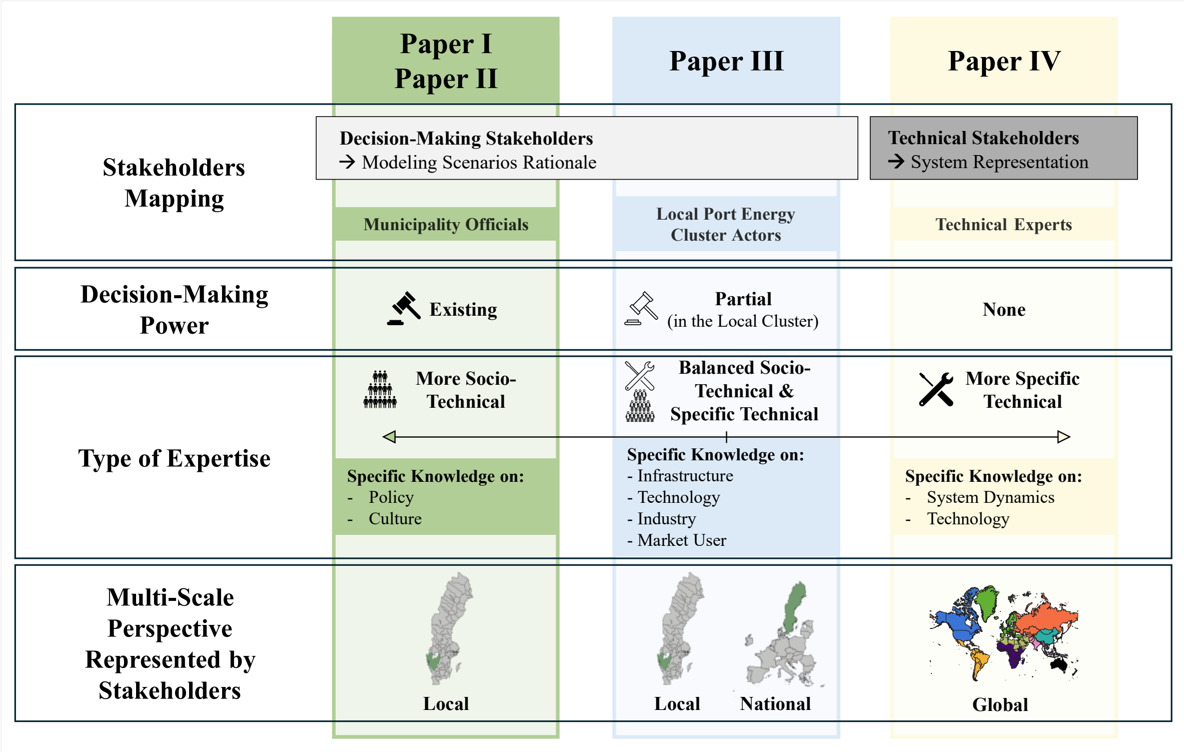


Figure 6 – Stakeholders mapping outlining type of stakeholders considered in each of the four papers appended in this thesis. Two overall types of stakeholders are considered in this thesis, i.e., decision-making stakeholders and technical stakeholders, contributing with different expertise to the analytical framework presented in this thesis. Decision-making stakeholders, as considered in **Papers I-III**, contributed to the development of modeling scenarios rationale, while technical stakeholders, as considered in **Paper IV**, added details to the system representation. The stakeholders are mapped according to three dimensions, i.e., (i) decision-making power (varying between existing (**Papers I-II**), partially existing (**Paper III**), and non-existing (**Paper IV**); (ii) type of expertise (varying between specific technical (**Papers I-II**), balanced specific technical and socio-technical (**Paper III**), and socio-technical (**Paper IV**); and (iii) spatial scale (varying between local (**Papers I-III**), national (**Paper III**), and global (**Paper IV**).

2.4. Soft-Link between ESOMs and Stakeholders Engagement

Existing literature has already extended stakeholders engagement to the realm of ESMs, as demonstrated in the case of IAMs [137] and Agent-Based Modeling (ABM) approaches [138]. These approaches are often developed collaboratively by modelers and stakeholders to enhance the relevance and credibility of modeling outcomes.

The benefits of incorporating stakeholders engagement in ESMs are also central to current energy system debates (see, e.g., [139]). Benefits suggested in literature include: (i) effectively bridging theoretical objectives with practically feasible and attainable targets [140]; (ii) improving the credibility and transparency of modeling outcomes [141]; (iii) updating modeling assumptions and redefining system boundaries based on real-world, context-specific knowledge [127]; and (iv) promoting legitimate decision-making by considering and weighing both positive and negative feedback from multiple potential outcomes within a holistic systems perspective [142].

Existing studies frequently apply stakeholders engagement both as a tool for model design and for evaluating the feasibility of modeling pathways. In particular, studies that explicitly reflect on interactions with stakeholders tend to recognize that the development and assessment of modeling pathways are widely used as a key approach to addressing the complexities associated with a low-carbon transition of society [143–146]. Pathways, often represented as modeling scenarios, can illustrate multiple possible futures and capture the interactions between technical and socio-economic transition elements within a specific context [119]. Consequently, joint generation and assessment of pathways through collaboration between researchers and stakeholders can help identify key strategies for energy transitions, including an effective informative resource allocation within transitioning systems [147–150].

2.4.1. Examples of a Continuous Interaction between ESOMs Stakeholders Engagement in Low-Carbon Transport Studies

Up to date, in low-carbon transport studies, stakeholders engagement is primarily applied in qualitative or scenario-based analyses, whereas ESOMs tend to represent transport in purely techno-economic terms. As a result, the soft-link established between stakeholders engagement and ESOMs remains limited.

Nonetheless, as summarize in Table 1, there are studies that explicitly integrate ESOMs with different forms of stakeholders engagement to examine low-carbon transport [151–155]. Overall, the existing studies agree that continuous interaction between research team and stakeholders is an effective means of introducing spatial and socio-technical dimensions into energy systems analysis. Within the five studies, different cross-sectoral perspectives are assumed, captured either by modeling not only the energy sector in focus, but part or the entire energy system (i.e., endogenously) [151,153,154] or through modeling assumptions and constraints (i.e., exogenously) [152,155].

Schmid and Knopf [151] combine participatory scenario development with ESOMs to assess mitigation pathways for Germany, explicitly including the domestic road passenger and freight transport segments. Stakeholders input is used to define socio-technical narratives, such as shifts in freight modal split, electrification of passenger transport, and reductions in mobility demand, which are then translated into model assumptions. While the model quantifies the impacts of these transformations, stakeholders play a key role in evaluating the plausibility and socio-political feasibility of the results. This highlights that stakeholder engagement primarily serves to interpret and challenge model outputs. McDowall [152] presents a conceptual framework that combines stakeholders interaction, used for developing socio-technical transition narratives, with quantitative ESOMs to assess the role of H_2 across multiple energy sectors, including road transport, in the United Kingdom (UK) context. The study emphasizes the importance of establishing a structured dialogue between stakeholders and ESOMs, arguing that modeling tools should not be interpreted as a numerical representation of participatory pathways but rather as a tool to analyze their constituent elements. Conversely, stakeholders engagement should be positioned as a means to critique, validate, and challenge ESOMs results. Venturini et al. [153] integrate stakeholders inputs on future transport drivers into a national-level Danish ESOM, accounting with road transport, aviation, and shipping segments. Stakeholders contributions are translated into quantitative assumptions and scenarios, thereby enriching the optimization exercise with spatial and contextual realism. The authors highlight that while ESOMs typically prioritize long-term techno-economic optimization, they often neglect behavioral, socio-political, and institutional barriers, aspects that can be addressed through participatory engagement.

Furthermore, Fortes et al. [154] compare low-carbon pathways for multiple economic sectors, including the three transport segments, road transport, aviation, and shipping, using stakeholders engagement and ESOM-based approaches at the national level in Portugal. They conclude that purely qualitative stakeholders participation-based pathways may struggle to capture long-term uncertainties and may therefore limit assessments of cost-effectiveness or technical feasibility, particularly in relation to quantitative mitigation targets. At the same time, the authors note that ESOM-based pathways may overlook strategies that are misaligned with prevailing socio-political and economic conditions. As a result, they advocate for an integrated approach that leverages the complementary strengths of stakeholders involvement and ESOMs. Finally, Forsberg [155] develops a regional-level ESOM for a Swedish county Sweden that incorporates local spatial differentiation by modeling municipalities of varying sizes. This approach enables the simultaneous evaluation of national CO_2 mitigation objectives and local air-quality targets. The modeling results, which describe the evolution of vehicle fleets and fuel consumption over time, are subsequently presented to municipal stakeholders through a participatory process. In this case, stakeholders engagement serves primarily as a validation mechanism, facilitating discussion of modeling assumptions, outcomes, and policy implications. By linking ESOMs outcomes with stakeholder deliberation, the study underscores the pivotal role of local governments in operationalizing national climate strategies and highlights stakeholders engagement as a critical component of effective energy system modeling.

Table 1 – Examples of existing state-of-the-art that combines stakeholders engagement with ESOMs, specifically applied to transport systems. In the column "Transport Segment in Focus", light blue colored studies represent those that focus in more than one transport segment, whereas white colored and light blue lined studies represent those that focus on one transport segment, in a standalone perspective. In the column "Stakeholders Mapping", studies are presented according to the type of stakeholders involved in the research, i.e., light grey represent decision-making stakeholders, while dark grey represent technical experts. The identification of each type of stakeholders is supported by quotes used in the respective study. In the "Multi-Scale Perspective", light green colored studies represent those that are applied at a national level, whereas white colored and light green lined studies represent those that are applied at a regional level. No study was found to be applied either at global or local level. In the "Cross-Sectoral Consideration" column, green colored studies represent those that assumed an endogenously cross-sectoral perspective, by modeling different energy sectors, whereas white colored and green lined represent studies that assume an exogenous cross-sectoral perspective. ESOM, Energy System Optimization Model; MARKAL, MARKet ALlocation; PA, Participatory Approach; REMIND, REgional Model of Investment and Development; TIMES, The Integrated MARKAL–EFOM System; UK, United Kingdom.

Study	ESOMs Applied	Transport Segment in Focus	Stakeholders engagement Role	Stakeholders Mapping	Multi-Scale Perspective	Cross-Sectoral Consideration	Main Conclusions
Schmid and Knopf [151]	REMIND	Wide Transport Sector (including road transport, rail, and shipping)	Development of national socio-technical narratives and evaluation of model results	Decision-making stakeholders (*"civil society organization (CSO) stakeholders"*)	National level (Germany)	Endogenously (electricity and heating sectors, both at residential and commercial level)	Stakeholders can shape scenario assumptions and critically assess model outputs, especially regarding behavioral and infrastructural changes in transport
McDowall et al. [152]	UK MARKAL	Road Transport	Development of national socio-technical scenario towards road transport decarbonization	Decision-making stakeholders (*"UK and international hydrogen stakeholders, … part of … business strategies and government policies"*)	National level (United Kingdom)	Exogenously (electricity and heating sectors)	Energy transitions can benefit from integrating ESOMs with stakeholders engagement. ESOMs are notuantified representations of stakeholders engagement, but as tools for analyzing socio-technical scenarios. PAs should be used to interpret ESOMs results
Venturi et al. [153]	TIMES-DK	Wider Transport Sector (including road transport, aviation and shipping)	Model formulation, by translating stakeholders input into modeling scenarios and assumptions on road transport decarbonization	Decision-making stakeholders (*"state organizations, interest organizations, public transport companies, agencies and independent environmental organizations"*)	National level (Denmark)	Endogenously (electricity and heating sectors, both at residential and industrial level)	ESOMs overlook critical behavioral, socio-political, and economic barriers, which can be addressed by integrating a participation of stakeholders
Fortes et al. [154]	TIMES-PT	Wider Transport Sector (including road transport, aviation and shipping)	Qualitative discussion on the potential outcome that different scenarios might have on the future energy supply portfolios for different energy sectors, including road transport	Decision-making stakeholders (*"national stakeholders,… business managers,… policy makers and national experts*") Technical experts (*"national stakeholders,… university professors"*)	National level (Portugal)	Endogenously (electricity and heating sectors at residential and commercial level, industrial energy demands, as well as agricultural feedstock)	Stakeholder engagement alone may overlook long-term uncertainties, while ESOMs may fail to capture socio-political context. Integrating both approaches improves the understanding of energy transitions
Forsberg et al. [155]	TIMES-SE	Road Transport	Validation metric and discussion tool on model assumptions, scenarios, results, and implications related to road transport decarbonization	Decision-making stakeholders (*"local municipality practitioners"*)	Regional level (Swedish County), desegregate at the municipal level	Exogenously (different energy carriers' cost and carbon content)	A feedback loop between ESOMs and stakeholders engagement highlights that stakeholders engagement is an important feature to add to the ESOMs, emphasizing that local actions are required to implement ESOMs cost-efficient solutions

2.5.Research Gaps

Although the literature on low-carbon transport transitions has advanced significantly, this thesis addresses related research gaps that remain insufficiently explored within the assessment of this transition.

First, conventional ESOM applications to low-carbon transport transitions may overlook how transition dynamics depend on spatial scale. Within ESOMs, transport transitions often dismiss a discussion on how such a transition might change according to local (e.g. urban versus non-urban), national, and global contexts. This omission limits the understanding of low-carbon transport as a context-dependent process and neglects the fact that different transport segments are governed at different scales. The absence of a multi-scale perspective therefore constrains the ability of ESOMs to capture the heterogeneous nature of transport transitions.

Second, existing modeling approaches frequently treat transport systems in isolation, despite their deep interconnections with the wider energy system. Low-carbon transport transition unfolds alongside parallel transitions in other energy-using sectors, all operating under shared climate constraints. Assessing transport transitions from a standalone perspective risk overlooking cross-sectoral interactions, including competition, trade-offs, and synergies related to energy carriers that are finite yet highly flexible across sectors (i.e., referred to in this thesis as systems-integrators). A cross-sectoral perspective is therefore essential for understanding how low-carbon transport pathways interact with and influence the broader energy system transformation.

Relatedly, the lack of combined multi-scale and cross-sectoral perspectives in ESOM research might limit reflection on transport systems as socio-technical systems. As such, existing studies often suggest establishing a soft-link between ESOMs and stakeholders engagement as a means of accessing context-specific knowledge that is critical for representing transport system dynamics accurately. While some scholars advocate stakeholders engagement to inform modeling scenarios through context-specific narratives, others emphasize stakeholders input to enhance system representation and technical resolution based on spatial dynamics, both approaches are typically applied in isolation. This results in limited stakeholder heterogeneity challenging a fair representation of both contextual and technical dimensions, therefore, hindering transport systems to be understood through a socio-technical lens.

Notably, no study within the ESOMs literature was found that simultaneously: (i) respects a stakeholder heterogeneity by integrating stakeholders engagement both to incorporate spatial dynamics into scenario development and to enhance technical resolution through the validation of modeling assumptions and the fairness of system representation; (ii) embeds stakeholder–model interactions within combined multi-scale and cross-sectoral perspectives; and (iii) explicitly investigates the impacts of low-carbon transport transitions across diverse transport segments and the wider energy system. Responding to these gaps, and as shown in Section 1.3., this thesis advances multi-scale modeling framework to assess low-carbon transport transitions as context-dependent processes.

3. Method

In this chapter, the method developed and applied in this thesis, is presented.

3.1. A Continuous Interaction between ESOMs and Stakeholders Engagement

The main analytical tool applied in this thesis is based on ESOMs rationale (**Paper II-Paper IV**). ESOMs typically operate according to three core objectives, often conceptualized as a "triangle" (see e.g., [136]) balancing economic feasibility, environmental compliance, and load-balancing requirements. Thus, in conventional ESOMs applications, system boundaries are usually defined in a way that excludes socio-technical dynamics. As a result, context-specific factors relevant to low-carbon transitions are often overlooked, which in turn may lead to the neglect of social acceptance considerations [136].

In this respect, the thesis critically assesses commonly applied ESOM approaches by introducing an additional analytical dimension. Specifically, stakeholders engagement is explicitly integrated into the modeling framework reflecting a socio-technical dynamics dimension. Different types of stakeholders, either participating in deliberations on modeling scenario rationale or contributing with specialized knowledge on system representation are incorporated into the ESOM-based analysis. Consequently, as illustrated in Figure 7, this thesis proposes a single modeling framework built on continuous interaction between ESOMs and stakeholders engagement. Each of these components is described in detail in the following chapters.

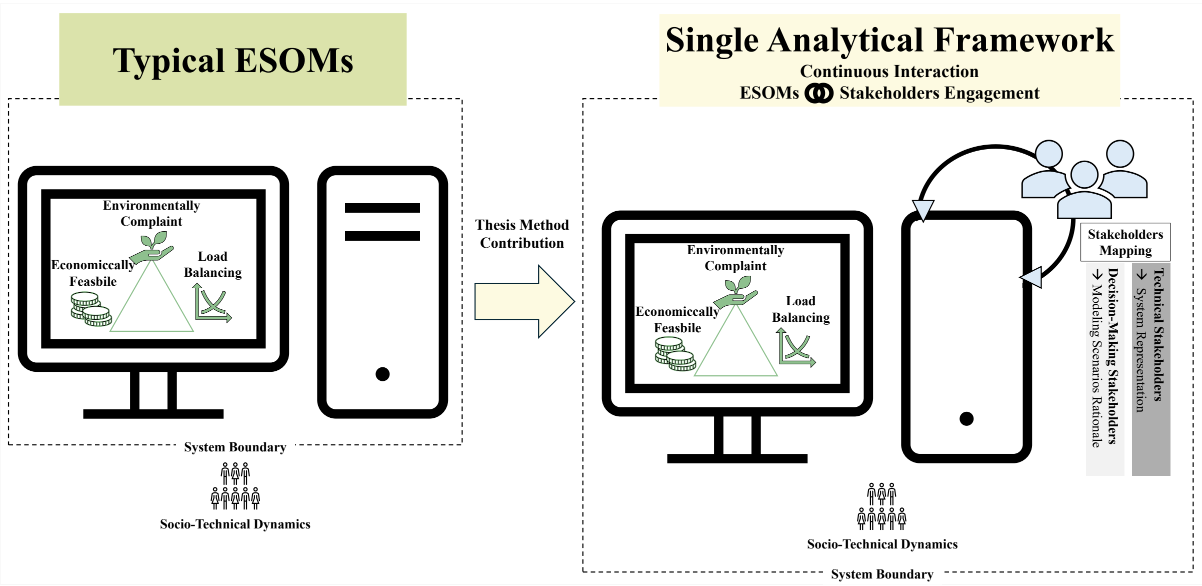


Figure 7 – Overview of the method developed and applied in this thesis. This thesis develops a single analytical framework that expands a typical ESOMs' framework to endogenously include socio-technical dynamics as part of the system boundary, through stakeholders engagement. In this thesis, stakeholders engagement includes both decision-making stakeholders and technical stakeholders.

3.1.1. Stakeholders Engagement: Modeling Scenarios vs System Representation (Papers I-IV)

Stakeholders engagement constitutes one of the two main pillars structuring this thesis and occupies a significant role in each of the four appended papers, as illustrated in Figure 8. Given the diverse research scopes of the four papers, different types of stakeholders, as previously presented, were involved across the studies. These stakeholders are broadly categorized into (i) decision-making stakeholders, engaged in **Papers I- III**; and (ii) technical experts, engaged primarily in **Paper IV**. It is important to note that the stakeholders engagement presented in **Paper II** is an expansion of the interaction established in **Paper I**.

Decision-making stakeholders are defined in this thesis as actors whose interaction with the research process can influence the analytical focus through interactive and continuous exchanges. In this regard, local municipal officials (**Papers I-II**) and actors within a local energy and port cluster (including representatives from Swedish ports and confined companies and thus, depicting a local and national perspective) (**Paper III**) were engaged. In this thesis, these stakeholders are considered to have decision-making power not only because of their ability to shape the research focus through interaction with the researcher, but also because they are capable of directly influencing the dynamics of their respective contexts through policy, investment, or operational decisions.

By contrast, technical stakeholders, as considered in **Paper IV**, are defined as experts with specialized knowledge relevant to the scope of the scope of the thesis, serving as key sources of domain-specific information necessary to ensure a robust representation of the modeled system. Their role is primarily to enhance the technical fidelity of the modeling framework by informing assumptions, constraints, and system boundaries.

Given these differences among stakeholder groups, the thesis adopts distinct interaction formats between the researcher and stakeholders. In **Papers I-III**, stakeholders engagement required a high level of active participation to capture a detailed understanding of the contextual dynamics underpinning the transition under study. These interactions addressed social, political, economic, and regulatory dimensions specific to each context. In **Papers I-III**, such engagement, as commonly presented in literature (see e.g., [136]), was established partly using semi-structured interviews, which allow for both guidance and flexibility in stakeholder discussions. In the context of this thesis, the nature of semi-structured interviews provided a creative space for dialogue, enabling participants to express individual perspectives while reducing the risk that divergent views are lost through premature consensus typically associated with, e.g., workshop formats. This approach further facilitated the identification of potential tensions and synergies by exploring individual motivations and worldviews prior to collective discussions.

A recommended research practice following semi-structured interviews is to conduct follow-up interactions. After the initial data have been filtered and thematically structured by the researcher, stakeholders should be invited to follow-up interactions and hence ensure transparency and legitimacy of researcher’s interpretations. This process acknowledges that statements can be expressed or understood differently and therefore benefit from verification. Accordingly, in this thesis, semi-structured interviews were followed by meetings (**Papers I-II**) and workshops (**Paper III**).

The interactions with decision-making stakeholders in **Papers I-III** primarily focused on the co-development and deliberation of modeling scenarios. Through continuous exchanges between the researcher and stakeholders, scenario development enabled the explicit integration of socio-technical dynamics into the modeling framework. Similarly, continuous interaction between ESOMs and stakeholders engagement allows for gathering interpretive feedback on modeling results. Hence this approach recognizes that scenario development can expand system boundaries beyond purely techno-economic considerations to encompass the socio-political context within which transitions occur, thereby providing a platform to discuss key drivers and trends with relevant actors.

In **Paper IV**, the focus of stakeholders engagement shifted towards technical expertise. Stakeholders engagement was therefore conducted through targeted technical meetings, allowing in-depth discussions of specific system components. This process ensured that model simplifications did not obscure critical dynamics and that the modeled system remained representative of real-world constraints. In **Paper IV**, academic experts in bioenergy and aviation were consulted to ensure a comprehensive and global representation of techno-economic constraints and potential bottlenecks across diverse fuel production pathways, supply chains, and energy conversion pathways.

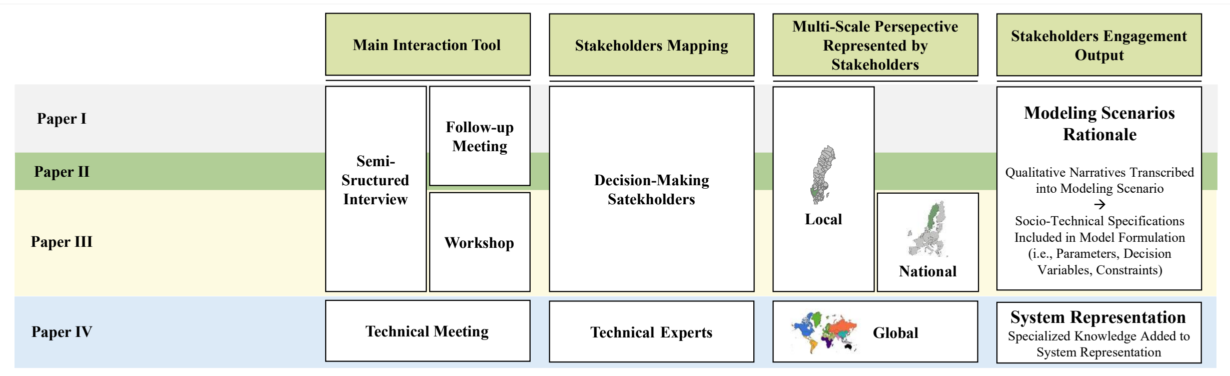


Figure 8 – Overview of the stakeholders engagement carried out in the different papers appended to this thesis. Decision-making power stakeholders were engaged in this thesis through semi-structured interviews (**Papers I-II**), following-up meetings (**Papers I-II**), and workshops (**Paper III**). Technical experts were considered in this thesis through technical meetings (**Paper IV**). While local and national-based decision-making power stakeholders contributed to the development of modeling scenarios rationale of the appended work (**Paper I-III**), global technical experts contributed to enhance the system representation to be modeled (**Paper IV**). Stakeholders engagement presented in **Paper II** is a modeling expansion of the qualitative interaction established with local stakeholders in **Paper I**.

3.1.2. Energy Systems Optimization Models (Papers II-IV)

As presented in Figure 9, two cost-optimization models are developed in this thesis based on the Integrated MARKAL–EFOM System (TIMES) framework (**Paper II** and Licentiate thesis) [82] and the Global Energy Transition (GET) framework (**Paper III** and **Paper IV**) [156]. The development and continuous updating of the TIMES modeling framework are coordinated by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy

Agency (IEA), whereas GET is an in-house modeling framework that has been developed and maintained by several researchers over time.

Both modeling frameworks underpin deterministic linear programming models that combine flexible temporal resolution with detailed sectoral representation and an explicit spatial dimension. In particular, both TIMES and GET allow for the representation of spatially disaggregated regions, enabling the analysis of heterogeneity within and across regions. This modeling approach can capture differences on both the supply and demand sides, as well as socio-geographic, economic, and political heterogeneity across multiple spatial scales, including: (i) global analyses disaggregated in multiple world regions (**Paper III** and **Paper IV**); (ii) national-level assessments (Licentiate thesis); and (iii) sub-national analyses at local level of municipalities (**Paper II**). Through this structure, and further based on perfect foresight, the models represent the dynamic evolution of energy systems over time, explicitly linking decisions made in one time step to their implications for future periods.

Both the TIMES and GET frameworks follow a bottom-up modeling philosophy. Accordingly, these ESOMs are technology-explicit, allowing for a detailed techno-economic characterization of the energy systems under study. This is complemented by their partial-equilibrium formulation, which captures the interactions between energy carriers, conversion technologies, and end-use services within the energy sector.

However, due to their partial-equilibrium nature, neither TIMES nor GET endogenously represent interactions between the energy system and the wider macro-economy. As a result, these models are limited in their ability to assess economy-wide feedback effects, such as impacts on overall economic output, employment, or income distribution, which constrains the scope for broader societal impact analysis of policy interventions.

As cost-optimization models, both TIMES and GET identify the lowest-cost system configuration that satisfies future exogenously modeled energy demands under different modeling constraints and assumptions over the entire modeled time horizon. Thus, the objective function represents the total system cost, expressed in Equation (1):

$$Total\ System\ Cost = \sum\nolimits_{region,t} \frac{Annual\ \ Cost\ (region, t)}{(1+r)^{t-t_{ref}}} \tag{1}$$

The *Total System Cost* represents the minimized total systems cost over the chosen modeled time horizon. The term *Annual Cost (region, t)* is composed of the annual cost for a specific modeling region (*region*) in a given year (*t*).

For **Paper II** and Licentiate thesis, the term *Annual Cost (region, t)* is a sum of (i) annual investments in new vehicles, local variable renewable energy sources (VRESs) production technologies, 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.

For **Paper III** and **Paper IV**, *Annual Cost (region, t)* aggregates multiple cost components, including expenditures associated with primary energy supply extraction and trade, investments in technologies and infrastructure, fixed and variable O&M costs, carbon storage costs, and the costs of transporting energy carriers.

For both TIMES and GET, over the entire modeled time horizon, all included costs are discounted for each modeled time period relative to the reference year (t_{ref}) (i.e., base year-2019 (**Paper II** and Licentiate thesis) and 2010 (**Paper III** and **Paper IV**), respectively. Within the TIMES framework, this thesis applies a social discount rate (r) of 4%, applied to all technologies and modeling regions, while a discount rate of 5% is used in the GET framework.

Both models also have a strategy for investments that have not yet reached their technical lifetime at the end of the modeled time horizon. TIMES accommodate such residual value as a so-called salvage value, meaning that the expected resale value of goods, the salvage value, ensures that new investments within the assessed energy system with remaining lifetimes continue to be economically viable at the end of the modeled time horizon. In GET, expanding the time horizon to 2100-2150 is a buffer assumed long enough to avoid end-of-time effects.

TIMES (Paper II and Licentiate Thesis)

The TIMES model was developed and applied in this thesis to represent road transport systems, as presented in **Paper II** and the Licentiate thesis. The model was run at the local level for the four participating Swedish municipalities (**Paper II**) and complemented by runs at the Swedish national level (Licentiate thesis). These analyses capture how road transport low-carbon transition may unfold across different socio-geographical contexts and spatial scales. Both local and national scales tested according to TIMES framework are presented in Appendix A1.

Although not the central focus of the TIMES-based appended work, public transport (buses) and freight transport (trucks) were partially included in the modeling exercise at the Västra Götaland regional level. Expanding the modeling scope to include these transport modes was a key element in the discussion of potential cross-sectoral fuel competition under selected local modeling scenarios.

Furthermore, different modeling constraints reflecting climate commitments at different spatial levels were considered within this TIMES framework, including the Västra Götaland 2030 commitment (i.e., at each municipal level, the total CO_2 emissions are constrained to be reduced by 80%, compared to the 2010 level [79]) and the national carbon neutrality commitment for 2045 (i.e., both at each municipal level but also at the Swedish national level total CO_2 emissions are constrained to be zero by 2045 [157]). In the case of the national perspective modeled in the Licentiate thesis, an intermediate goal is considered according to which the total CO_2 emissions are constrained to be reduced by 70%, compared to the 1990 level [157].

It is important to note that while the TIMES model represents road transport as a standalone system, additional modeling assumptions were introduced to support discussion of cross-sectoral effects; that is, the model adopts an exogenously defined cross-sectoral perspective. Specifically, the carbon intensity and cost of energy carriers such as electricity and H_2 were assumed to vary over time, reflecting changes in production pathways across the modeled years. In the specific case of electricity cost, this parameter was added to vary according to the local level of the four different participating municipalities and Swedish national level. Moreover, through one of the local socio-technical modeling scenarios developed in collaboration between researchers and municipal officials (the "Bio-locked Scenario", as presented in **Paper II**), the use of biofuels was constrained to biomass available at the local municipal level. This allowed an assessment of how such resource allocation would occur across different road transport modes.

Moreover, within the scope of the appended papers, several spatial-specific parameters were incorporated in the modeling exercise, as better depicting context-specific socio-geographical factors. In particular, (i) future transport demand; (ii) occupancy rate; (iii) fuel economy; (iv) annual mileage; and (v) average trip distance, were introduced as socio-geographically specific model parameters, varying across the four participating municipalities (**Paper II**) and at the national level for Sweden (Licentiate thesis).

Detailed descriptions of the modeling framework, input data, and associated modeling assumptions for the developed TIMES model are provided in the Supplementary Material of **Paper II**. The national-level assumptions, as presented in the Licentiate thesis, are described in Appendix (see A2.1.).

GET (Paper III and Paper IV)

Two versions of the GET model are presented in this thesis. The GET 11 version was used to explicitly represent the transport sector as an integrated component of the broader energy system, thereby enabling an endogenous cross-sectoral perspective. This formulation allows the model to capture interactions and competition across sectors for shared energy carriers that serve as systems-integrators. The global perspective tested according to GET framework is presented in Appendix A1.

This thesis also contributes to the development of the updated GET 13 version. In **Paper IV**, GET 13 explicitly incorporates the dynamics of a low-carbon transition in the aviation sector. This includes a detailed representation of a wide portfolio of SAF production pathways and a transparent depiction of competition for shared energy carriers across multiple end use sectors. In addition, GET 13 introduces differentiation between aviation segments by representing heterogeneity across short-haul, medium-haul, long-haul, and freight aviation categories.

Both GET 11 and GET 13 rely on exogenously specified energy service demands. These demands are derived from assumptions consistent with the Shared Socioeconomic Pathways (SSPs) framework [158]. The SSPs were developed by the climate research community and formally integrated into climate scenario analysis in the Sixth Assessment Report of the IPCC in 2021 [159]. By defining five distinct narratives of socio-economic development, the SSPs characterize alternative futures across a broad range of demographic, economic, and policy dimensions, thereby shaping long term energy demand trajectories. As recognized in the literature, the SSP framework constitutes an effective tool for analyzing low-carbon transitions as context-dependent processes, since it captures regional differences in GDP growth, population development, and urbanization patterns, all directly influencing future energy demand (see e.g., [160]).

Within this thesis, and to better capture spatial-specific trends among the different world regions, three SSPs were applied in GET 11, while GET 13 was based on one single SSP. **Paper III** aimed to assess how future demand for liquid fuels could evolve under contrasting global development pathways and potential levels of climate constraint. For this purpose, three representative SSPs were selected to span a wide range of plausible futures, from a sustainability-oriented pathway with low climate mitigation and adaptation challenges (SSP1) to a pathway characterized by regional rivalry and higher challenges (SSP3). An intermediate pathway, SSP2, represented "middle of the road", providing a midpoint reference between these two extremes. The selection of these SSPs was undertaken jointly by researcher team and relevant stakeholders to ensure coverage of diverse global developments.

Both GET 11 and GET 13 are governed by an overarching climate constraint in the form of a cumulative carbon budget covering the period from 2010 to 2100, consistent with RCPs related assumptions. In **Paper III**, SSP1, SSP2, and SSP3 are linked respectively to RCP 1.9, RCP 2.6, and RCP 3.4. Although **Paper IV** adopts only the socioeconomic assumptions of SSP2, the same set of RCP-based carbon budgets tested in **Paper III**, is applied, to ensure consistency and comparability across the analyses.

In contrast to the TIMES framework applied in **Paper II** and Licentiate thesis, GET 11 and GET 13 endogenously represent cross-sectoral interactions, as they explicitly model the entire energy system rather than focusing on a single energy sector in isolation. Furthermore, both GET versions also test specific energy system characteristics that can play a role in shaping the overall systems dynamics, given a cross-sectoral perspective. Factors included are carbon storage potential and the availability of key energy carriers, particularly those facilitating linkages across sectors and thus, defined as systems-integrators in this thesis.

Comprehensive descriptions of the modeling structure, input data, and associated assumptions for GET 11 and GET 13 are provided in the Supplementary Materials of **Paper III** and **Paper IV**, respectively.

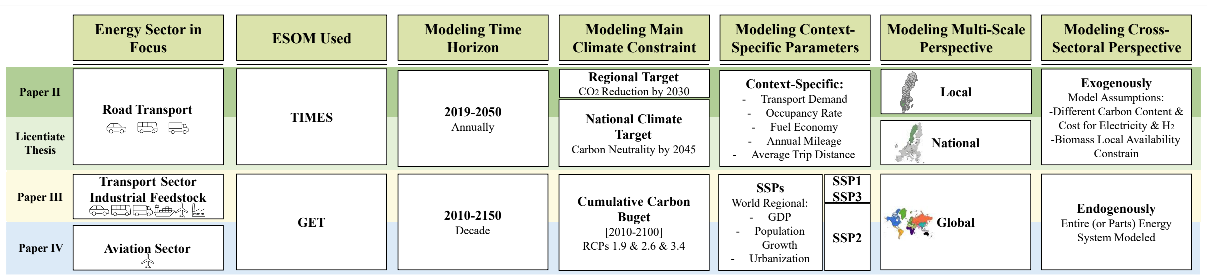


Figure 9 – Overview of the two ESOMs, i.e., TIMES (**Paper II** and Licentiate thesis) and GET (**Papers III-IV**), developed and applied in the appended papers. According to each of the two ESOMs, not only different energy sectors in focus were considered, but also different modeling (i) time horizon; (ii) main climate constraint; (iii) context-specific parameters; (iv) multi-scale perspective; and (v) cross-sectoral perspective.

TIMES versus GET: Passenger Cars Modeling Rationale

While road transport, and in specific segment passenger cars, are modeled within the TIMES framework, ranging from a local perspective (**Paper II**) to a national perspective (Licentiate thesis), its representation in the GET model captures a more global perspective (**Papers III–IV**).

Within these two frameworks, different modeling assumptions are incorporated to capture the dynamics of this transport segment. In both frameworks, road transport is based on a projected future demand that must be met. This demand is expressed in energy terms, requiring both models to rely on assumptions regarding annual mileage, car occupancy, and fuel economy.

In the TIMES framework, these three parameters vary by municipality (**Paper II**) or country (Licentiate thesis), reflecting differences in travel behavior and thus capturing context-dependent characteristics. In contrast, in the GET model (**Papers III-IV**), these parameters are highly aggregated, incorporating some regional variation; however, fuel economy is assumed to improve annually. Moreover, the TIMES framework disaggregates the annual mileage of the considered municipalities into a trip-length distribution, distinguishing the share of trips that, over the course of a year and on average, are short (up to 100 km) or long (above 100 km).

Another key difference between the two modeling frameworks lies in the representation of battery electric vehicles (BEVs). While the TIMES framework considers two BEV sizes, i.e., a small BEV (a proxy for a 20 kWh battery) and a large BEV (a proxy for a 40 kWh battery), GET assumes only an average BEV. Additionally, and contrary to the GET model, the TIMES framework considers different charging profiles for these two BEV types. These profiles vary depending on the type of charger (either standard public charging or fast charging) as well as charging patterns (home, work, or other non-specified events).

Furthermore, both TIMES and GET frameworks test a potential ban on new ICEVs post-2035. While TIMES framework considers this ban in all modeling scenarios of **Paper II** and Licentiate thesis, in the case of GET this ban is tested in the "Ambitious Scenario" of **Paper III**. Similarly, both modeling approaches assume an average lifetime for passenger cars and apply a probabilistic function to represent vehicle retirement. Similarly, in both approaches, alternative powertrains are modeled with decreasing investment costs over the modeling period. The specific input data used for passenger cars are presented in the corresponding appended papers.

3.1.3. A Single Analytical Framework: A Soft-Link Approach (Papers I-III)

One pillar of this thesis builds on understanding how a soft-link established through continuous interaction between research-based tools and stakeholders engagement enables a better representation of specific spatial dynamics and context-dependent transition narratives. Specifically, through **Paper II**, which applies the stakeholders engagement described in **Paper I**, as well as the method developed in **Paper III**, this thesis further develops an analytical framework that demonstrates how sustained dialogue between energy modelers and stakeholders can be mutually beneficial. This thesis adopts an interactive and context-specific analytical framework that integrates qualitative stakeholders engagement with literature-based insights and ESOMs to develop socio-technical transition pathways according, to the spatial dynamics of the context under assessment.

As illustrated in Figure 10, the method presented in this thesis unfolds across three main stages: (i) preparation through data gathering and literature review; (ii) qualitative stakeholders engagement; and (iii) scenario development, as a way to capture spatial specific dynamics. Across the last two stages, the approach relies on continuous interaction between the research team and context-specific stakeholders, enabling a soft-link between qualitative narratives and analytical tools. This design allows spatial dynamics (i.e., economic, market-based, infrastructure, or policy-based) and therefore socio-technical constraints to be explicitly reflected in the identification of scenarios.

In **Paper I**, the framework is applied to road transport low-carbon transitions in non-urban municipalities through coupling different phase of conceptual literature review and engagement with municipal officials. As an output of the preparation stage, Representative Scenarios (i.e., "Conceptual Pathways" as defined in **Paper I**) are identified based on the most common solutions for road transport decarbonization as suggested in the literature. During this phase, context-specific data capturing the spatial dynamics, like municipality's mobility trends and energy demand statistics, of the participating municipalities are also collected, providing a grounded basis for the subsequent stakeholders interaction.

In the second stage, through stakeholders engagement, the Representative Scenarios are filtered and refined via semi-structured interviews, ensuring alignment with local energy system characteristics, governance capacities, and socio-economic conditions. This alignment enables an assessment of the scenarios' implementation potential at the local level. Scenarios that are positively evaluated through this process are defined in this thesis as Working Scenarios (i.e., "Feasible Conceptual Pathways" as defined in **Paper I**). The first and second stage are complemented with complementing rounds of interaction between analytical tools and follow-up meetings with the involved municipality officials.

By doing so, and to address not only the implications of Working Scenarios, as presented in this thesis, for the local road transport sector itself, but also their broader impacts on the local energy system, cross-sectoral implications are subsequently incorporated. Accordingly, and consistent with **Paper I**, a second round of literature review is conducted to investigate how the strategies represented in the Working Scenarios interact with and affect the wider energy system. This step results in the identification of, as presented in this thesis, Final Scenarios (i.e., "Identified Pathways" as defined in **Paper I**), integrating a qualitative mapping of their local implementation challenges and potential. This interactive loop between literature review and stakeholders engagement, as developed in **Paper I** and further tested in **Paper II**, strengthens the credibility of the identified pathways ensuring their socio-technical dimension and therefore supporting the co-production of context-sensitive transition narratives.

In **Paper III**, the same overarching logic is retained but operationalized through a tighter soft-link between stakeholders engagement and the GET model. Stakeholders from a local energy port cluster contribute directly to structuring scenario narratives by collaborating with the research team to combine different SSPs with locally identified decisive model parameters (i.e., "specific model parameters to vary", as defined in **Paper III**). During the preparation stage, the research team gathers context-specific data through an analysis of sustainability reports from participating cluster actors, as well as relevant legislation shaping local dynamics. This preparatory work informs the case study description and guides the formulation of questionnaires used in the semi-structured interviews, thereby initiating the stakeholders engagement stage.

Through the semi-structured interviews, the research team identifies and documents local factors perceived by stakeholders as potentially shaping a low-carbon transition in their energy port cluster. This initial interaction is followed by continuous engagement through a series of follow-up workshops, during which preliminary modeling results are iteratively fed back into the stakeholder dialogue for validation and refinement of modeling assumptions. This process enables the identification of Working Scenarios, assessing how different SSPs may influence low-carbon transition trajectories. The selection of SSPs is conducted collaboratively between the research team and stakeholders, ensuring coverage of a broad range of futures (i.e., "Representative SSPs", as defined in **Paper III**).

Following these initial modeling runs, the Working Scenarios are further discussed in a second workshop round, where collaborative dialogue leads to the identification of Final Scenarios (i.e., "Final Modeling Scenarios", as defined in **Paper III**). These scenarios integrate a qualitative selection of key modeling parameters with the different SSP narratives. In the specific case of **Paper III**, stakeholders engagement enables for capturing spatial specific dynamics and later transform stakeholder insights into quantitative scenario assumptions Including spatial specific modeling assumptions in the modeling rationale situates global modeling outcomes within local and nationally grounded strategic discussions.

Across both papers, the developed framework demonstrates how continuous dialogue between stakeholders (categorized in both cases as decision-making stakeholders) and the research team enables mutually beneficial learning. Through this interaction, stakeholders contribute to improving the contextual resolution and thus, plausibility of the scenario narratives, while the modeling exercises and their resulting insights support and inform decision-making processes oriented toward more efficient, long-term low-carbon transitions.

It is important to note that, although **Paper IV** also considered knowledge shared by technical experts (i.e., technical stakeholders), it did not explicitly examine or discuss the effects of sustained interaction between ESOMs and stakeholder's engagement. As such, the analytical focus on continuous, and interactive dialogue between modeling and stakeholders engagement processes mainly reflects the **Papers I–III** appended to this thesis.

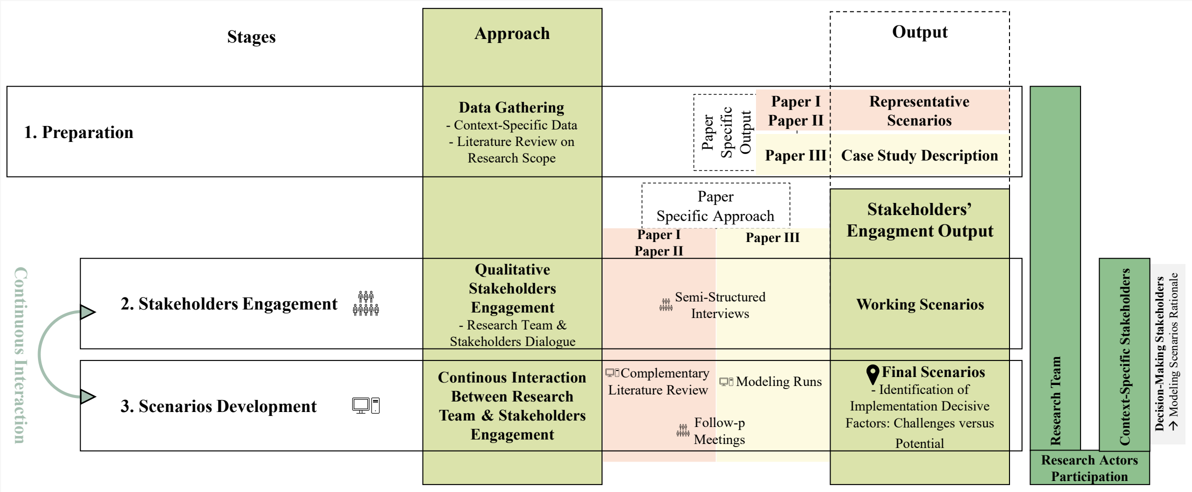


Figure 10 – Overview of the continuous interaction established between research-based tools and stakeholders engagement, as tested in **Papers I-III**. In the referring three appended papers, stakeholders engagement is centered around the participation of decision-making stakeholders, whose interactions are transcribed into modeling scenarios that capture context-dependent parameters

4. Main Results

This chapter presents the selected results of the method developed and applied in this thesis, encompassing the main findings of **Papers I–IV**. It is complemented by the discussion presented in the Licentiate thesis. To facilitate the interpretation of the results, the chapter is structured into three main sections:

- A multi-scale perspective is introduced, drawing directly on the findings of **Paper II**, **Paper III**, and the Licentiate thesis. This section highlights passenger road transport low-carbon transition as a strongly context-dependent process, emphasizing how such a transition changes according to local, national, and global perspectives;

- A cross-sectoral perspective is presented to enable the identification of systems-integrators. This perspective is explored through two complementary viewpoints:

  (i) Cross-sectoral interactions as an endogenous model assumption, as highlighted in **Paper II**;

  (ii) Cross-sectoral interactions as an exogenously modeled feature, as demonstrated in **Paper III** and **Paper IV**.

- A continuous interaction between ESOMs and stakeholders engagement, achieved through a soft-linking approach. Reflecting on both **Papers I-III**, this section illustrates how interactive feedback loop between model-based analysis and stakeholders engagement supports robust scenario development but also system representation, enhancing the relevance of modeling outcomes for decision-making.

4.1. A Multi-Scale Perspective on Road Transport Low-Carbon Transition: A Context-Dependent Process

The evolution of road transport, specifically the passenger car fleet, towards a low-carbon transition is presented in Figure 11 from a multi-scale perspective, highlighting differences across local (urban and non-urban municipalities), national (Sweden), and global levels.

At the local level, results combine urban and non-urban municipality perspectives, consistent with the framework presented in **Paper II**. The local fleet evolution is shown under the "Climate Policy Scenario", reflecting compliance with the Västra Götaland target of an 80% reduction in GHG emissions by 2030 relative to 2010, the national net-zero target for 2045, and the set of climate policies highlighted in green in Figure 5. The national perspective represents Sweden under an equivalent "Climate Policy Scenario", including the national net-zero emissions target for 2045 and the same portfolio of climate policies indicated in Figure 5. The global perspective illustrates fleet evolution under the most ambitious climate scenario assessed in this thesis, corresponding to the "Ambitious Scenario" (i.e., composed by SSP1 RCP1.9), presented in **Paper III**. This scenario reflects a stringent global transition pathway, enabling comparison with national and local dynamics under similarly ambitious policy conditions.

From 2020 real data, the fleet was dominated by ICEVs and Hybrid-Electric Vehicles (HEVs), regardless of spatial scales. By 2030, results show that differences in passenger cars' fleet, among different spatial scales, commence to emerge. At the local level, non-urban municipalities remain largely dominated by ICEVs and HEVs, whereas urban municipalities show a substantially higher uptake of BEVs and Plug-in Hybrid-Electric Vehicles (PHEVs), where direct electrifications (i.e., BEV) already represent 57% of the whole fleet. Similar trend is gauged at the national level, with BEVs accounting for 55% of the fleet by 2030, while at the global level, as tested in the "Ambitious Scenario" of **Paper III**, BEVs increase to around one-third of the fleet, indicating a slower transition compared to assessed national and urban contexts.

By 2050, the fleet composition converges towards a BEV-dominated structure across all spatial scales. BEVs reach or approach full dominance in non-urban, urban, and national fleets, while the global fleet also exhibits a strong majority of BEVs with only marginal remaining shares of ICEVs and HEVs as well as PHEVs. Overall, the results highlight a consistent long-term shift towards electrification, while revealing pronounced differences in the timing and pace of the transition between local, national, and global levels, particularly in the near to mid-term.

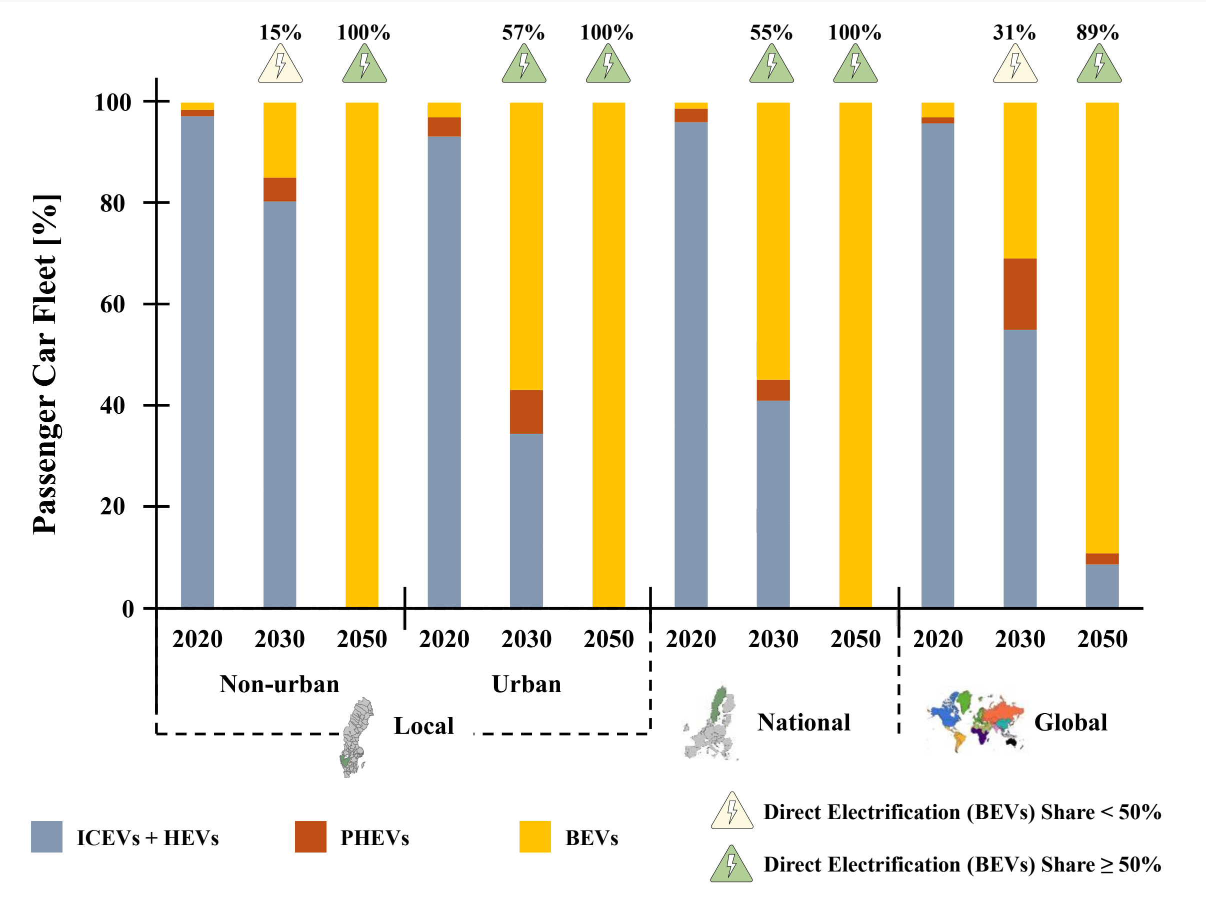


Figure 11 - –Passenger car fleet, split among the different powertrains shares and at the four spatial scales included in this thesis (i.e., Local – non-urban and urban – National, and Global). Local, national, and global perspectives and corresponding passenger road transport modeling assumptions are thoroughly presented in **Paper II**, Licentiate thesis, and **Paper III**, respectively. Both local and national perspectives depict "Climate Policy Scenario", as presented in **Paper II** and Licentiate thesis, while global perspective depicts the "Ambitious Scenario", as presented in **Paper III**. Main modeling scenarios assumptions are presented in Appendix A2.2. BEVs, Battery Electric Vehicles; HEVs, Hybrid Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

Despite the clear electrification uptake in passenger road transport, Figure 12 shows the evolution of cost-effective liquid energy carrier types used in passenger cars across local (non-urban and urban), national, and global levels.

In 2020, liquid road transport energy demand was, in line with real data, dominated by crude oil-based fuels across all spatial scales. By 2030, the share of synthetic liquid fuels (in **Paper II** and Licentiate thesis represented by two categories of biofuels, i.e., biodiesel and ethanol, and in **Paper III** characterized by bio-based and electrofuel methanol (MeOH)) increases particularly at non-urban and national levels. At these specific levels, synthetic fuels account for roughly half of liquid energy fuels use by 2030, whereas at the national and global level they remain a smaller but growing share. In all tested spatial scales, the used synthetic liquid fuels are 100% bio-based.

By 2050 passenger car fleet is modeled to be fully electric at all spatial scales, except according to a global perspective. On a global scale, as tested in the "Ambitious Scenario" of **Paper III**, passenger car fleet still accounts for about 10% being allocated to both ICEVs and HEVs, those that are, as seen in Figure 12, predominantly crude oil-based. Still, synthetic fuels are registered in mid-century, with a shift in a fully bio-based production pathway to biofuels accounting for approximately 59% and electrofuels 41% of total synthetic liquids use.

Together with the fleet composition results, these trends indicate a declining role for liquid fuels over time alongside fleet electrification, while highlighting persistent liquid fuel demand in the system and clear differences in the composition and timing of liquid energy transitions across local, national, and global scales. Moreover, synthetic liquid fuels can be interpreted as a bridging option in the system. In earlier years, when the passenger car fleet still contains a substantial share of ICEVs and HEVs, synthetic fuels enable emissions reductions within a cost-optimized framework. As fleet electrification progresses over time and BEVs become dominant, the reliance on liquid fuels decreases, and synthetic fuels gradually lose significance. In this sense, synthetic fuels facilitate a cost-efficient transition towards a largely electrified passenger car system rather than representing a long-term dominant solution.

Similarly, the observed similarities between the local and national perspectives, and their contrast with the global perspective, reflect differences in modeling approaches and constraints rather than pure differences in spatial scale. Both the local and national cases are constrained by a fixed net-zero emissions target to be met by 2045, implying that road transport, which was modeled as a standalone system, is required to achieve full decarbonization within a defined time-frame. Under these conditions, compliance with the net-zero target necessitates a rapid phase-out of ICEVs and HEVs relying on liquid fuels. In contrast, the global perspective is constrained by a cumulative carbon budget and incorporates a cross-sectoral modeling framework (further discussed in Section 4.2). This formulation provides the system with greater temporal and sectoral flexibility, allowing road transport to continue relying on ICEVs and HEVs for a longer period while emissions reductions are achieved through interactions with other sectors and carbon removal technologies. As a result, differences between local and national with global trends primarily reflect varying system boundaries, constraint formulations, and sectoral coupling mechanisms, rather than only differences in spatial resolution itself.

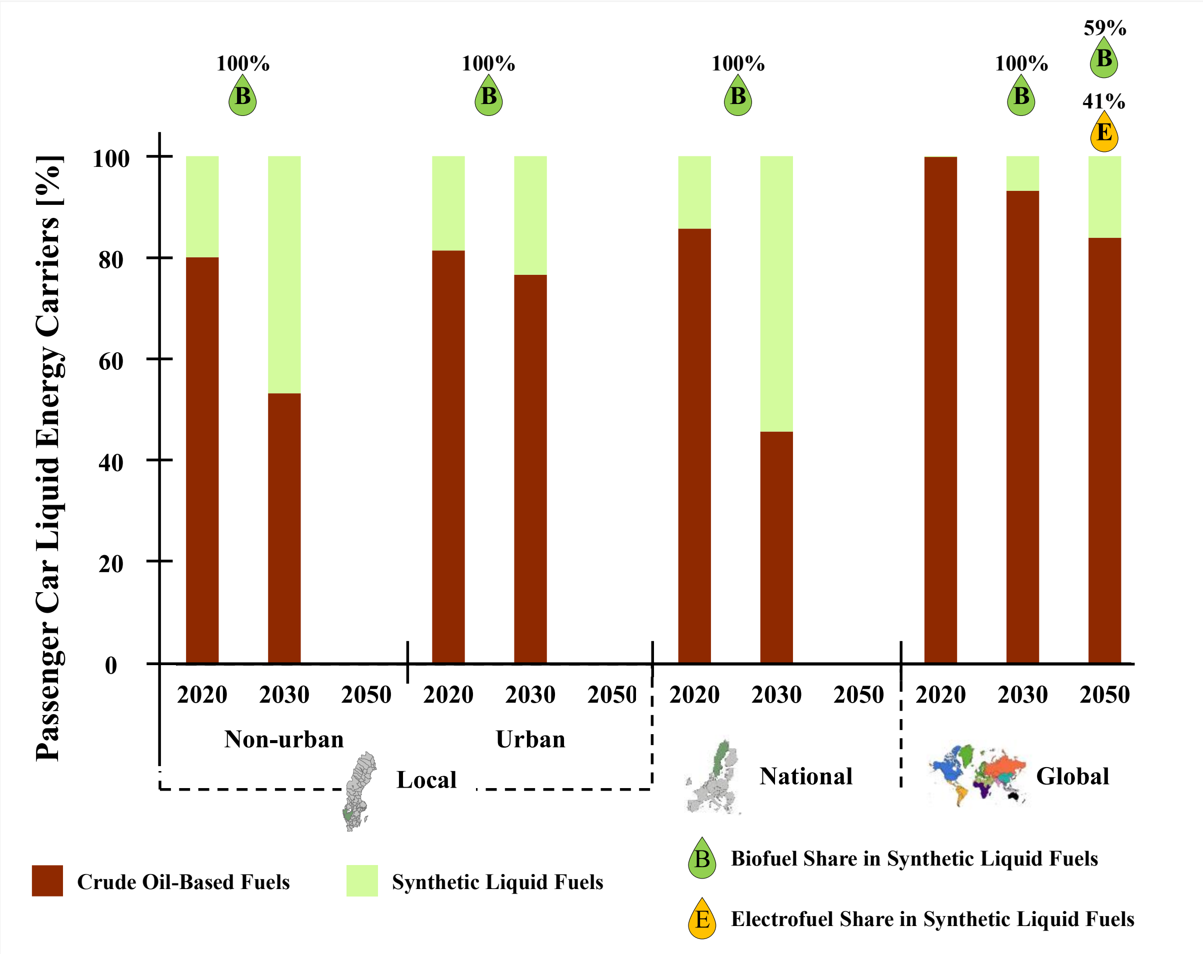


Figure 12 –Consumption of liquid energy carrier types in passenger cars, at the four considered spatial scales in the appended papers. Local, national, and global perspectives and corresponding passenger road transport modeling assumptions are thoroughly presented in **Paper II**, Licentiate thesis, and **Paper III**, respectively. Both local and national perspectives depict "Climate Policy Scenario", as presented in **Paper II** and Licentiate thesis, while global perspective depicts the "Ambitious Scenario", as presented in **Paper III**. In **Paper II** and Licentiate thesis, synthetic liquid fuels are represented by both biodiesel and ethanol, while in **Paper III**, synthetic fuels are represented by methanol (MeOH), an energy carrier that can be either fossil, bio-based or electrofuel. Main modeling scenarios assumptions are presented in Appendix A2.2.

This thesis argues that not only passenger road transport, but energy transitions more broadly, are inherently context-dependent. Accordingly, a robust understanding of such transitions requires treating energy systems as socio-technical systems, in which diverse socio-geographical factors shape transition pathways and outcomes. Such trends can be observed in **Paper II** and Licentiate thesis, where the passenger car fleet composition is further contextualized by the spatially specific modeling parameters shown in Figure 13 (b-d).

Differences in average annual mileage, trip length distribution, and vehicle fuel economy across local, national, and spatial contexts (Figure 13 b and d) coincide with the differentiated uptake of drivetrain technologies (Figure 13 a). Non-urban context is characterized by higher average mileage and a larger share of longer trips, while urban contexts show lower mileage and predominantly shorter trips. At the national level, these parameters, generally, take intermediate values, reflecting an aggregation of diverse local travel patterns.

These spatial differences align with the observed fleet compositions, where small BEVs dominate urban and national fleets earlier, while average-sized BEVs are more prominent in non-urban contexts. The higher mileage and longer distances in non-urban areas correspond to drivetrain options with lower overall driving costs despite higher upfront investments, whereas urban travel patterns favor technologies with lower purchase costs, given their travel patterns. Furthermore, the results indicate that the national fleet composition is closer to urban contexts, even though it is based on weighted-average spatial modeling parameters. This trend is especially visible in the strong presence of small BEVs at the national level, matching the urban pattern rather than the non-urban one. An explanation lies in how the trip length distribution (Figure 13b), showing that the national share of short trips is much closer to the urban distribution.

This shows that the trip length distribution has a stronger influence on cost-optimal drivetrain choices than the other parameters. As a result, the national results follow the urban fleet structure even when other inputs are more balanced. Taken together, the fleet outcomes and underlying parameter values show that spatially differentiated travel behavior is strongly associated with divergent cost-optimal drivetrain choices, reinforcing the importance of incorporating spatially resolved demand characteristics when analyzing passenger car fleet transitions.

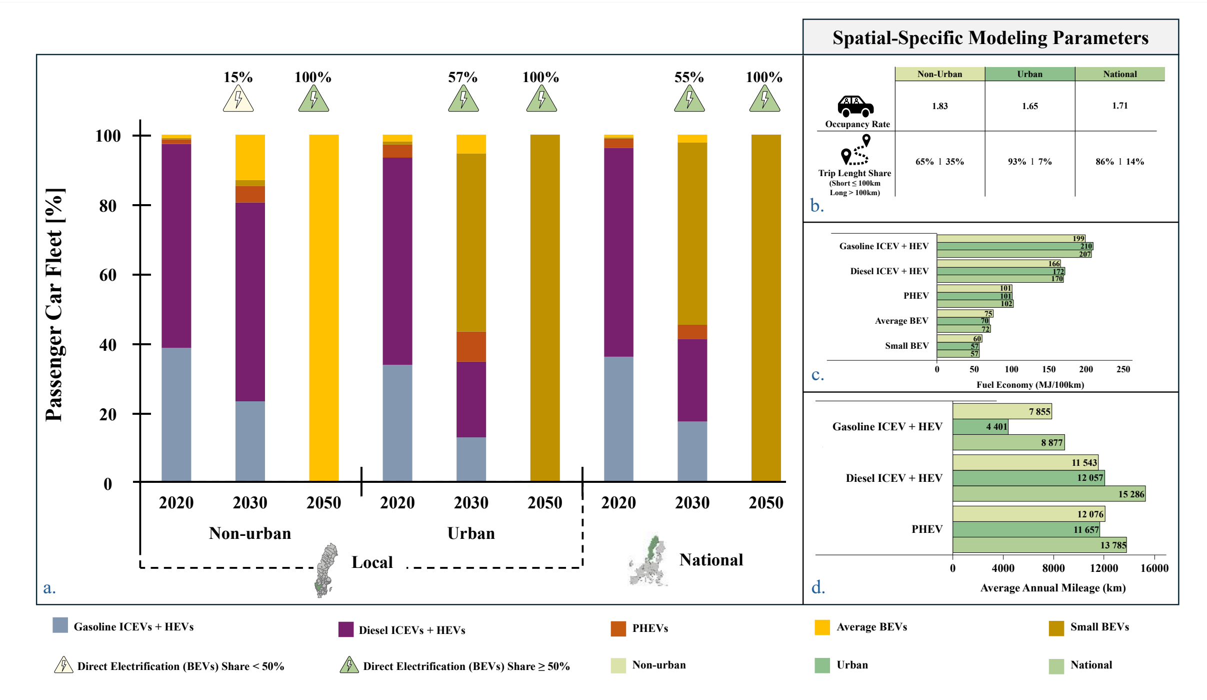


Figure 13 – Fleet mix presented according to the share of the different considered powertrains (graph a) at local and national perspectives. Local and national perspectives as well as corresponding passenger road transport modeling assumptions are thoroughly presented in **Paper II** and Licentiate thesis, respectively. Triangle above each scathed column represents electrifications shares above 5%. For electrification shares above or equal to 50%, the symbol of electricity is green color. Socio-geographical and spatial-specific average values, i.e., occupancy rate, trip distribution, fuel economy, and annual mileage, are also presented in graphs b-d. Only the annual mileage of vehicles that changed between the considered spatial scales are presented in graph d. Small BEVs are modeled as a proxy for a 20 kWh battery, while the average BEV is a proxy for a 40 kWh battery. Both local and national perspectives depict "Climate Policy Scenario", as presented in **Paper II** and Licentiate thesis, respectively. Main modeling scenarios assumptions are presented in Appendix A2.2. BEVs, Battery Electric Vehicles; HEVs, Hybrid Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

Overall, the results show how a multi-scale modeling framework can represent low-carbon transport transitions as context-dependent processes by explicitly differentiating spatial demand characteristics, system boundaries, and constraint formulations across local, national, and global levels. Differences in passenger car fleet evolution and energy use emerge not only from spatial scale in specific, but also from how travel behavior and climate constraints are modeled at each of the three spatial dimensions considered (i.e., non-urban, urban, and national). This confirms the need for multi-spatially resolved representations when analyzing low-carbon transport pathways specifically, and energy systems in general.

4.2. A Cross-Sectoral Perspective: Identification of Systems-Integrators

This thesis further assesses the impact of adopting a cross-sectoral perspective on the low-carbon transition of transport. This perspective is examined through both exogenous (**Paper II**) and endogenous (**Papers III-IV**) approaches. An exogenous cross-sectoral perspective is represented by the use of modeling parameters that constrain interactions between sectors, whereas an endogenous perspective is grounded based on an integrated modeling of the entire energy system, encompassing not only transport, but also electricity, heat, and industry sectors.

4.2.1. Exogenous Cross-Sectoral Perspective

In **Paper II**, an exogenous cross-sectoral perspective is examined through a set of "Local Scenarios" developed in collaboration with municipal officials. The developed scenarios represent a holistic view of the local context, encompassing not only the transport sector but the entire local energy system. As a result, differences in assumed cross-sectoral conditions lead to divergent passenger car fleet compositions over time.

Figure 14 presents passenger car fleet outcomes under two cross-sectoral scenarios, where electricity and biofuels act as exogenously defined systems-integrators linking road transport with local electricity and heating systems.

In the "Self-Sufficiency Electricity Scenario", VRESs local availability strongly pressures the fleet composition. In both urban and non-urban municipalities, limited local VRESs capacity constrains direct electrification in the short-term, resulting in continued reliance on ICEVs and HEVs up to 2030 (in comparison to trends presented in Figure 11 and Figure 13). In urban municipalities, this constraint only allows for relatively low direct electrification, through small BEVs. In medium to long-term this trend leads to the emergence of fuel cell electric vehicles (FCEVs) as the dominant low-carbon option by mid-century, whereas non-urban municipalities transition towards BEVs once additional local VRESs capacity becomes available. The divergence between municipal fleet outcomes reflects differences in land availability for VRESs expansion and, consequently, different degrees of coupling between passenger car electrification and the local electricity system is observed.

In the "Bio-Locked Scenario", constraining biofuel availability to regional production alters fleet dynamics across both municipality types. Limited biofuel supply is preferentially allocated to other road transport segments (principally freight road transport, as presented in **Paper II**), accelerating the electrification of passenger cars. BEVs exceed 50% of the fleet in both urban and non-urban municipalities already by 2030. The composition of the electrified fleet remains spatially differentiated, with small BEVs dominating urban municipalities and average BEVs becoming cost-competitive in non-urban areas by 2030.

Across both scenarios, the results demonstrate that treating electricity and biofuels as exogenous cross-sectoral constraints fundamentally reshapes cost-optimal passenger car transitions, highlighting how interactions with neighboring energy sectors condition electrification uptake.

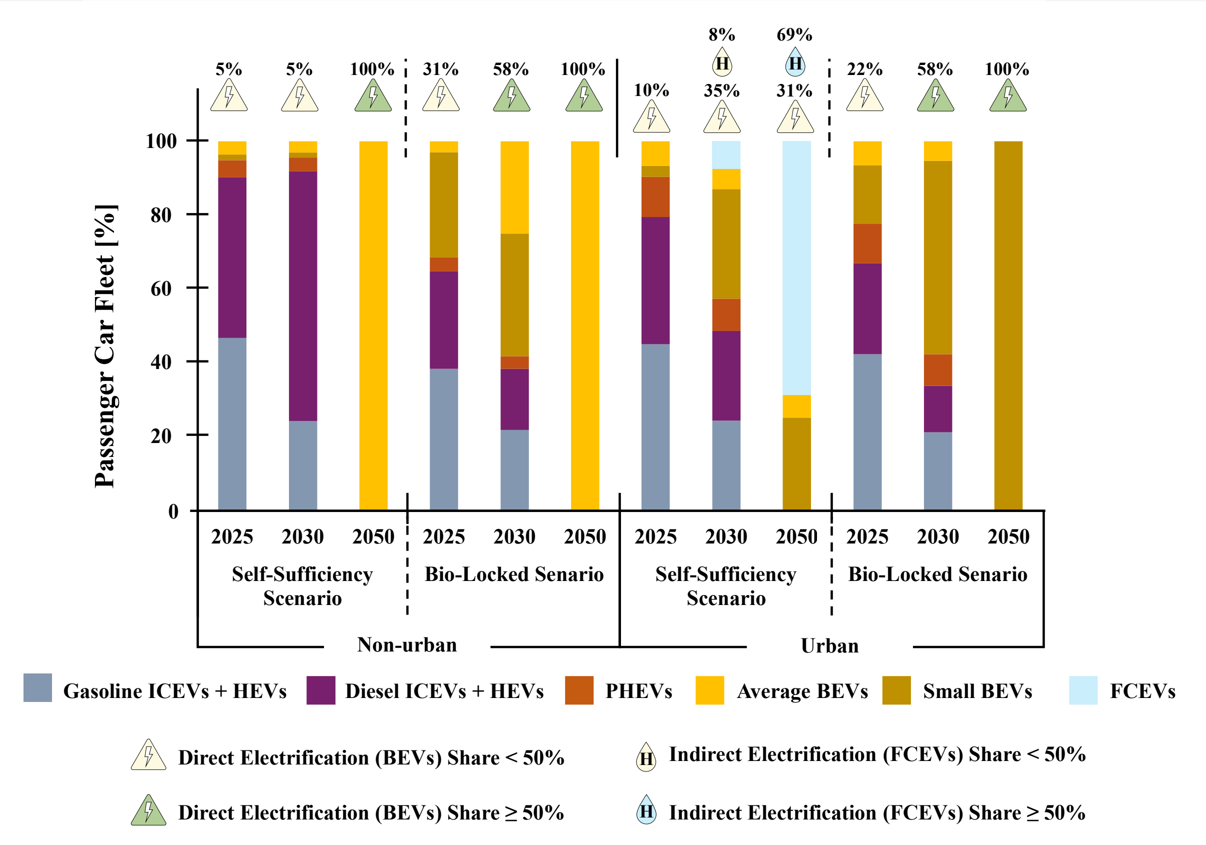


Figure 14 - Fleet mix presented according to the share of the different considered powertrains, by comparing two "Local Scenarios", presented in **Paper II** within a non-urban and urban perspective. Local, perspective and corresponding passenger road transport modeling assumptions are thoroughly presented in **Paper II**. Triangle above each scathed column represents direct electrification shares above 5%. For electrification shares above or equal to 50%, the symbol of electricity is green color. The drop represents indirect electrification, i.e., FCEVs, shares above 5%, becoming blue-colored when those shares are above 50%. Small BEVs are modeled as a proxy for a 20 kWh battery, while the average BEV is a proxy for a 40 kWh battery. Main modeling scenarios assumptions are presented in Appendix A2.2. BEVs, Battery Electric Vehicles; FCEVs, Fuel Cell Electric Vehicles; HEVs, Hybrid Electric Vehicles; ICEVs, Internal Combustion Engine Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles.

4.2.2. Endogenous Cross-Sectoral Perspective

Papers III-IV adopt an integrated systems perspective, providing a global representation disaggregated according to different world regions, encompassing not only multiple transport segments but also other energy sectors, including electricity generation, heating systems, and industrial feedstock.

The Role of Carbon Capture Storage and Bioenergy Availability

Figure 15 presents how the liquid fuels consumption changes over time and according to an endogenous perspective assumed at a global energy systems level. This trend is grounded in the modeling exercise conducted in **Paper III**, testing a range of scenarios reflecting different socio-geographical development pathways, represented through the SSPs, in combination with varying carbon budgets, depicted through RCPs. As presented in **Paper III**, "Ambitious Scenario" combines SSP1 with RCP1.9, "Incremental Scenario" combines SSP2 and RCP2.6, and "Conflictual Scenario" combines SSP3 with RCP3.4.

As illustrated in Figure 15, liquid fuels are shown to be cost-effective in 2070, mainly across the transport and industrial feedstock sectors. Yet at what extent their consumption prevail is gauged to be a function of global carbon storage capacity (Figure 15 a–c) and annual biomass availability (Figure 15 d–f). Despite other modeling parameters have been tested in the Monte Carlo Analysis, consistently across all scenarios, these two parameters emerge as the only binding ones (i.e., $R^2 > 0.1$).

In this thesis liquid fuels can be either crude oil-based, or synthetic, that depending on their carbon atom origin can be fossil-, bio-, or electrofuel-based. As shown in Figure 15, crude oil-based liquid fuels display a strong positive correlation with carbon storage capacity, particularly in the "Ambitious Scenario" (with R^2 varying between 0.42 and 0.60), indicating that higher availability of carbon storage enables continued oil use despite stringent climate constraints. In contrast, electrofuels show weak sensitivity to carbon storage, while bio-based synthetic fuels exhibit moderate correlations that strengthen under stricter climate targets.

Biomass availability primarily affects the deployment of bio-based synthetic fuels, with R^2 values between 0.29 and 0.38, most notably in the "Conflictual Scenario". Under limited trade conditions, and regional biomass availability strongly influences liquid fuel supply, while looser climate constraints allow crude oil-based fuels to remain competitive. Across all cases, synthetic liquid fuels predominantly serve hard-to-abate sectors (i.e, in **Paper III** presented as aviation, shipping, and industrial feedstock) rather than road transport, as electrification and other solutions are more cost-effective where available.

Overall, Figure 15 illustrates how, under an endogenous cross-sectoral framework, sectoral interactions jointly shape liquid fuel use, highlighting that global transport outcomes are tightly coupled to developments in the wider energy system rather than determined by transport-specific conditions alone. Moreover, the results expand the discussion by showing that low-carbon transition pathways are shaped not only by transport-specific dynamics, but also by CCS availability and biomass resource constraints. Given their positive and system-wide effects, these technologies and resources are identified in this thesis as being systems-integrators, facilitating cross-sectoral synergies by allowing emission reductions, and resource use, to be balanced across sectors. In this way, sectors with greater mitigation flexibility can compensate for more constrained sectors within an integrated energy system.

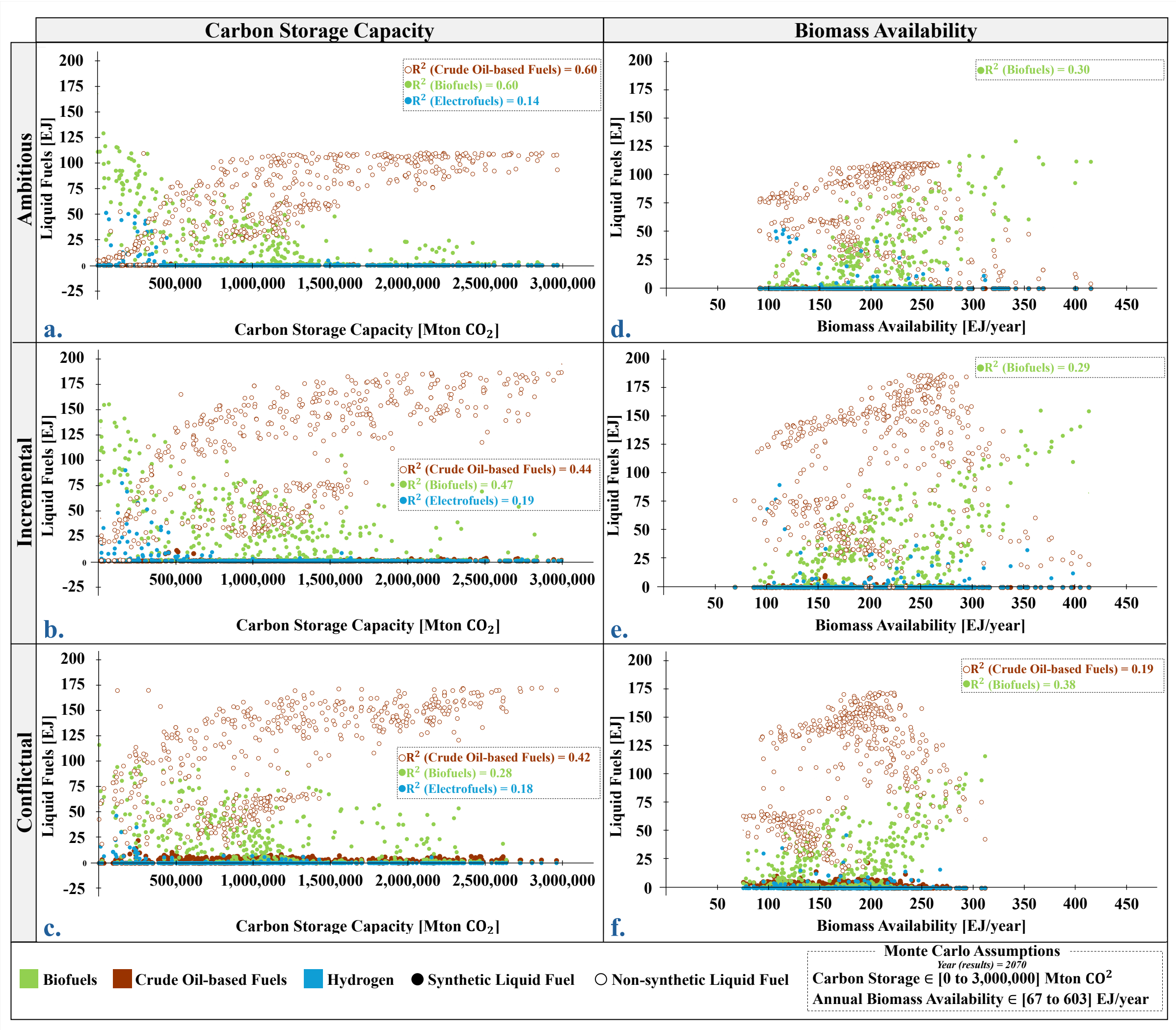


Figure 15 –Monte Carlo analysis results for the year 2070, showing parameters with an R^2 above 0.1 for the three modeling scenarios of **Paper III**, i.e., (i) "Ambitious Scenario", that tests SSP1 and RCP 1.9 (a and d); (ii) "Incremental Scenario", that tests SSP2 and RCP 2.6 (b and e); and (iii) "Conflictual Scenario", that tests SSP3 and RCP 3.4 (c and f). Specific data and modeling assumptions to the three modeling scenarios is thoroughly presented in **Paper III**. Graphs a–c present the impact of varying carbon storage capacity on liquid fuel use across the three modeling scenarios, while graphs d–f show the impact of varying annual biomass availability. Liquid fuels include both crude oil-based fuels (white circles outlined in brown) and synthetic liquid fuels produced via different pathways (colored dots). Trendlines are shown only for correlations with R^2 values above 0.1. Carbon storage capacity is tested as a lump sum of the three considered CCS technologies (i.e., Carbon Captured from Flue Gases from the Combustion of Fossil Fuels (CC), Bioenergy with Carbon Capture (BECC), and Direct Air Capture (DAC). Main modeling scenarios assumptions are presented in Appendix A2.2.

Systems-Integrators Impact: A Cross-Sectoral Mechanism

Within an integrated and endogenous energy system, as illustrated in Figure 16, aviation, emerging as the main hard-to-abate sector, benefits from system-level flexibility, and thus, cross-sectoral mitigation. Figure 16 present the three scenarios tested in **Paper IV**, where, based on SSP2, different carbon budgets, i.e., RCP 1.9, RCP 2.6, and RCP 3.4, were tested. Across all scenarios and segments total aviation energy demand increases steadily over time, as a result from the increase in both GDP and population, both parameters depicted in SSP2.

Overall, fleet and fuel choices remain dominated by conventional aircraft flying on liquid fuels, particularly fossil-based kerosene, with a gradual uptake of SAF, primarily HEFA and FT-kerosene. Important to note is that throughout the modeling exercise and corresponding results, FT-kerosene is always represented by an electrofuel-based SAF, despite its bio-based route possibility. Similarly, AtJ-kerosene, according to the cost-optimal modeling results, is always represented through a methanol-to-jet route (primary based on a bio-based route).

Disaggregating aviation energy consumption by flight distance and freight activity reveals that the pace and extent of aviation's low-carbon transition are strongly segment-dependent. Across all scenarios, short-haul aviation (Figure 16 a–c) exhibits the greatest flexibility, with earlier diversification of energy carriers and a clear uptake of SAF, complemented to a limited extent by alternative options such as cryogenic fuels and electricity. This reflects the lower range and energy-density requirements assumed in GET 13. In the model, direct electrification is restricted to flights below 500 km, while cryogenic fuels (Liquefied Methane (LCH_4) and Liquefied Hydrogen (LH_2)) can serve ranges of up to 7,000 km and 3,700 km, respectively. Their limited deployment in short-haul suggests that they act as complementary options to other constrained low-carbon alternatives. Among the different aviation segments, short-haul aviation also has the lowest absolute energy demand and is assumed to undergo more frequent fleet renewal, enabling a faster transition toward more efficient aircraft. Together, these factors support a more dynamic fuel shift, including the earlier adoption of more complex and costly SAF pathways such as AtJ-kerosene, particularly under stricter carbon constraints.

In contrast, medium- and long-haul passenger aviation (Figure 16 d–f) follow similar and more constrained transition pathways. In both segments, SAF penetration increases gradually over time, while fossil-based kerosene remains dominant throughout the modeling horizon. The model further indicates that under looser carbon budgets, reduced competition for biomass and electrofuels from other sectors allow them to be cost-effectively used in aviation.

Freight aviation (Figure 16 g–i) displays patterns similar to medium- and long-haul passenger segments, reflecting comparable exogenous demand and energy-use profiles. Fossil-based kerosene remains the dominant fuel, with gradual SAF uptake over time. Under stricter carbon budgets, however, freight aviation also shows a delayed shift towards more advanced SAF pathways such as AtJ-kerosene, mirroring trends observed in short-haul passenger aviation.

Overall, scenario differences are most pronounced in short-haul aviation. Under stricter carbon budgets, as tested in the "Low-Carbon Scenario" (Figure 16 a), more complex SAF pathways and alternative energy carriers such as cryogenic fuels and electricity emerge earlier, and SAF penetration accelerates compared to the "Base Case" (Figure 16 b). In this segment, alternative carriers are favored over electrofuel-based SAF due to higher energy efficiency and more efficient use of scarce low-carbon resources, preserving electrofuels for longer-distance applications. In contrast, under looser carbon budgets, as tested in the "High-Carbon Budget Scenario" (Figure 16 c), fuel substitution is delayed. Across all scenarios, medium- and long-haul as well as freight aviation, however, remain largely insensitive to scenario variation due to constraints related to range, energy density, and fuel certification. As a result, aviation's overall transition remains structurally constrained by these segments, reinforcing its characterization as a hard-to-abate sector.

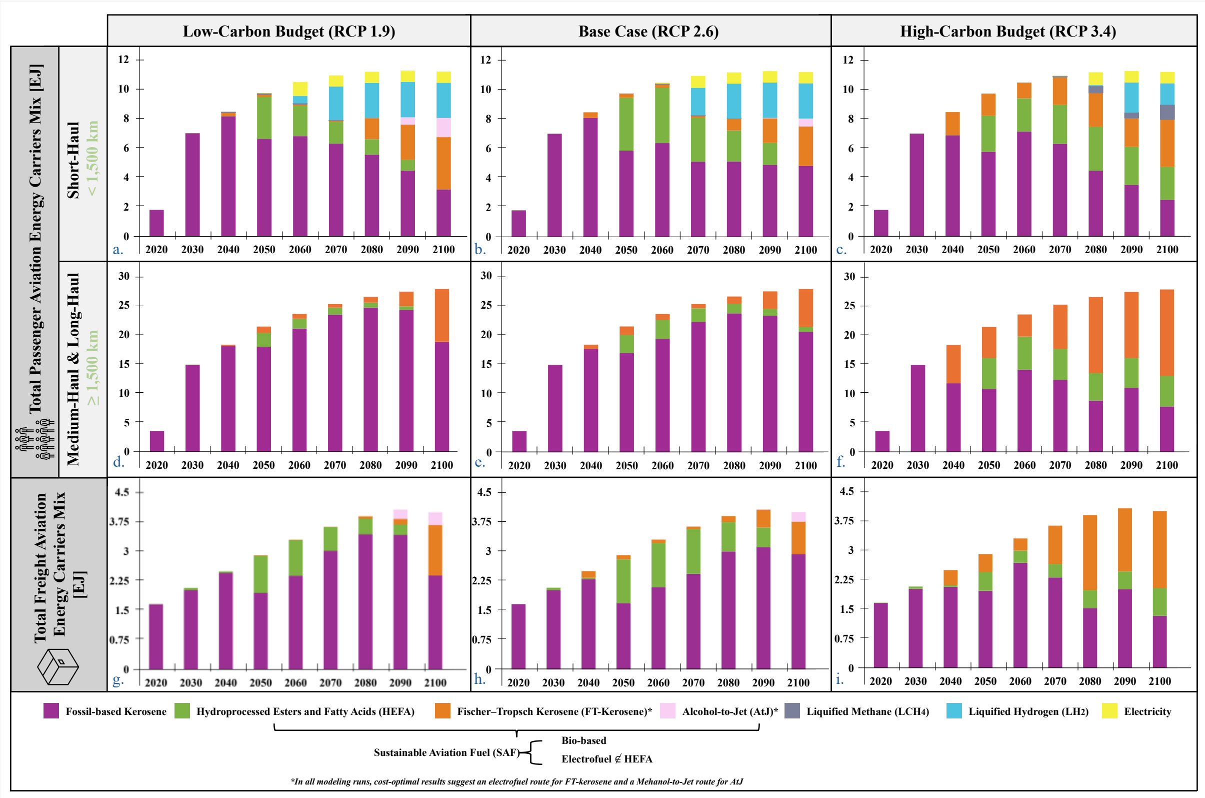


Figure 16 – Cost-effective mix of aviation energy carriers (EJ) presented for each of the four aviation segments, i.e., short-, medium, long-haul and freight, and for the three different modeling scenarios (i.e., "Low-Carbon Budget Scenario", "Base Case", and "High-Carbon Budget Scenario"), with different climate targets, as investigated in **Paper IV**. Specific input data and modeling assumption about the three modeling scenarios is thoroughly presented in **Paper IV**. The medium- and long-haul segments are aggregated together, given the similarities in trends. SAF, based on their production pathway, can be either bio- or electrofuel-based, except for HEFA that is exclusively bio-based. It may be noted that, according to the model outcomes, FT-kerosene is only produced through the electrofuels pathway in these runs, while AtJ-kerosene is only produced trough biobased Methanol-to-Jet. Modeling assumptions on aviation representation and related techno-economic considerations are presented in **Paper IV**. Main modeling scenarios assumptions are presented in Appendix A2.2. RCP, Representative Concentration Pathways.

Nonetheless, it is important to note that in the absence of binding climate constraints, the model consistently favors continued reliance on fossil-based kerosene, as reflected in the observed "back-and-forth" shifts in energy carriers, as presented in Figure 16. This pattern can be explained from a cross-sectoral perspective, according to which a faster low-carbon transition in other sectors allow aviation to sustain or even expand fossil fuel use. Such a trend can be understood by the system-wide evolution of primary energy carriers, as depicted in Figure 17.

Under different carbon-budget scenarios mitigation efforts are redistributed across sectors over time. The rapid decline of coal and the gradual reduction of crude oil at the system level are accompanied by a large-scale expansion of wind, solar, but also carbon capture technologies, indicating that low-carbon pressure is primarily absorbed by sectors with high mitigation flexibility, such as electricity and heat production.

Within this context, the "back-and-forward" pattern observed between crude oil-based fuels and electrofuels-SAF in aviation, is a direct consequence of cross-sectoral cost optimization. As other sectors move towards low-carbon systems more rapidly and free up carbon budget and mitigation capacity, aviation, which by itself is structurally constrained by energy-density and range requirements, can continue relying on crude oil-based kerosene, as far as this energy carrier remains the lowest-cost option. When system-level constraints tighten (e.g., increased competition for biomass or growing pressure to meet carbon-budgets), FT-kerosene temporarily substitutes fossil-based kerosene, reflecting a shift towards pathways in which the carbon atom becomes more valuable to re-use than send to carbon storage. As an electrofuel, FT-kerosene allows captured carbon to be reutilized within the system. However, this substitution is reversed whenever systems-wide conditions again favor lower-cost conventional fuels, highlighting that fuel choice follows cost-optimal system dynamics rather than a linear decarbonization trajectory. Importantly, looking at both Figure 16 and Figure 17 simultaneously shows that fuel availability follows systems dynamics rather than sector-specific targets. The alternating dominance of fossil-based kerosene and SAF therefore reflects a reallocation of mitigation effort across the energy systems, not instability in aviation technology pathways. Aviation consistently shifts to the cheapest liquid fuel compatible with global constraints, while deeper low-carbon transition is achieved elsewhere through electrification, renewables expansion, and carbon capture. In this sense, the observed "back-and-forward" behavior is an indication of system-integrators operating across sectors, enabling aviation to remain a late-transition, hard-to-abate sector and according to which FT-kerosene is identified as a cost-effective energy carrier.

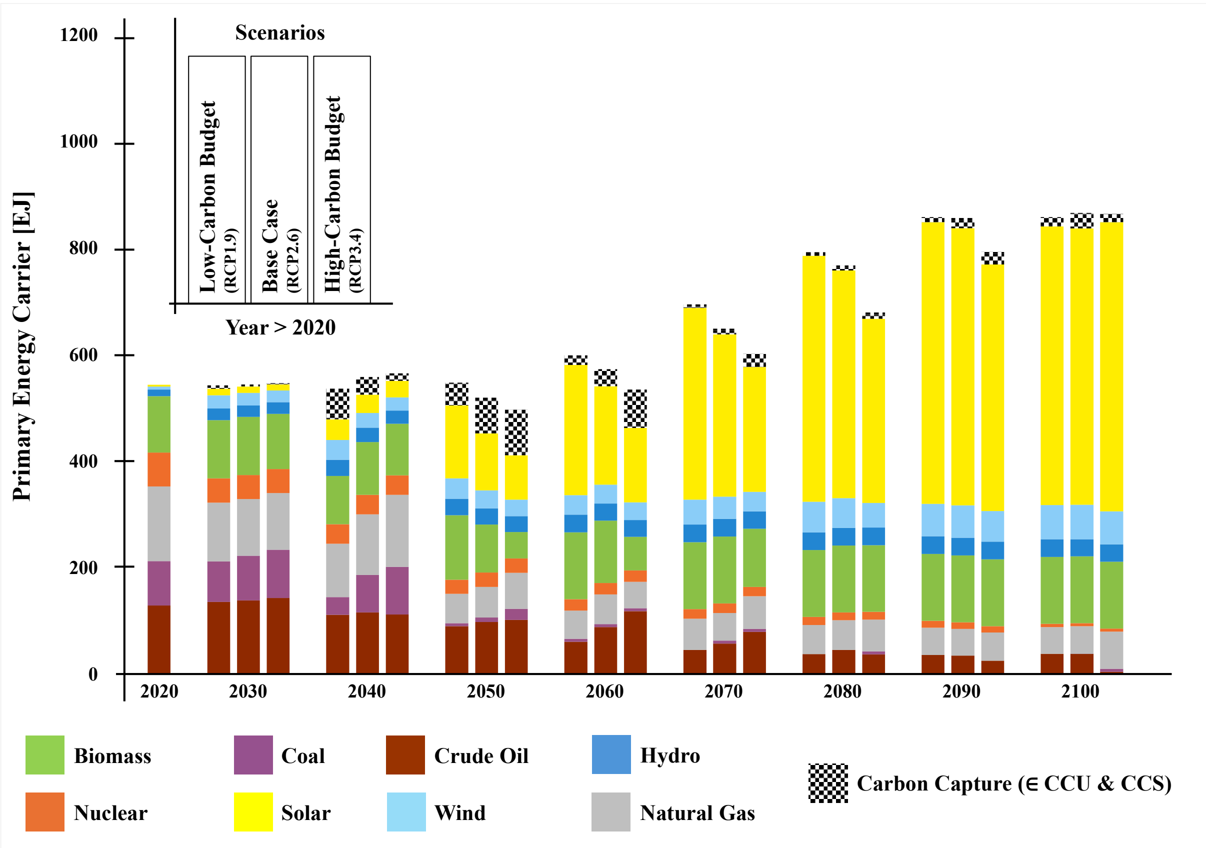


Figure 17 – Primary energy mix supplied summed over the 10 GET regions, as presented in **Paper IV**. The year 2020 is calibrated with real data for all three scenarios, being constant throughout the three scenarios. For years 2030–2070, the bars present result for the three scenarios from left to right representing the "Low-Carbon Budget Scenario", "Base Case", and "High-Carbon Budget Scenario", respectively. Carbon capture technologies are connected to crude oil, coal, natural gas, and biomass-based power plants. Modeling assumptions on primary energy carriers availability as well as other techno-economic considerations are presented in **Paper IV**. Main modeling scenario assumptions are presented in Appendix A2.2.

The Role of Co-Products

As discussed previously, understanding how low-carbon transition unfolds requires a systems-level perspective to better capture systems-integrators behavior. Thus, carbon mitigation in aviation is found to be closely tied to the availability and allocation of biomass resources across the entire energy system.

Biomass is subject to annual availability constraints and is simultaneously demanded by multiple sectors, making its cost-optimal allocation, as well as value of associated co-products, a central determinant not only of low-carbon aviation transition, but the overall low-carbon energy systems. The model's cost-optimal choice of what end-use product the different types of biomass is used for, under the three modeled scenarios, as tested in **Paper IV,** is presented in Figure 18.

Across all scenarios, biomass is distributed among electricity generation, heating, liquid and gaseous fuel production (notably HEFA, biodiesel, ethanol, and methane (CH_4)), syngas production, pyrolysis oil synthesis, and pathways combined with carbon capture. These patterns underline biomass as a scarce and highly contested systems-integrator resource, whose allocation reflects both direct energy needs and the cross-sectoral value of co-products generated along specific conversion pathways, rather than sector-specific preferences alone.

Lipid-based biomass (Figure 18 a) is allocated to HEFA and biodiesel, with a higher share of HEFA under looser carbon budgets, as tested in the "High-Carbon Budget Scenario" presented in **Paper IV**. Lignocellulosic biomass and Municipal Solid Waste (MSW) (Figure 18 b), the largest and most flexible biomass-based resource, show strong sensitivity to carbon constraints. In specific, as tested in the "Low-Carbon Budget Scenario" of **Paper IV**, the use of this type of biomass shifts away from direct heat towards conversion pathways to syngas in early decades. Under looser budgets, these resources, although they also favor syngas production in the long-term, remain largely tied to conventional heating demands.

Organic waste streams (Figure 18 c) are exclusively used for CH_4 production across all scenarios, with limited variation due to their narrow use and scale, although their value increases under stricter carbon constraints. Similarly, sugar and starch (Figure 18 d) are fully allocated to ethanol production early on, often coupled with carbon capture, with higher system value under tighter carbon budgets, as tested in the "Low-Carbon Budget Scenario".

These allocation patterns help explain aviation outcomes, suggesting that under stringent carbon budgets, strong competition for biomass constrains SAF deployment and prolongs reliance on fossil-based kerosene, whereas looser budgets ease competition and enable greater SAF use. Overall, Figure 18 highlights that aviation's transition is driven less by sector-specific factors than by system-level biomass allocation.

Another evidence of the importance of assuming systems perspective is to acknowledge that SAF are not produced as standalone fuels but alongside co-products (e.g., biodiesel, FT-diesel, biogasoline) that have a cross-sectoral supply role. As tested in **Paper IV**, Figure 19 further shows how these co-products are linked from aviation to the broader energy system and influence cost-optimal resource allocation. Across all scenarios, co-product output grows with SAF deployment, initially driven by lipid pathways as well as FT-routes. While FT-routes are suggested to have a special importance under looser carbon budgets (see “High-Carbon Budget Scenario”, Figure 19 c), AtJ routes might increase at the end of the century, especially under tight carbon budgets (see “Low-Carbon Budget Scenario”, Figure 19 a). These co-products deliver additional mitigation by displacing fossil fuels in transport, heating, and industry, improving the systems-level cost-effectiveness of SAF. Overall, SAF pathways are best understood as systems-integrators whose value depends strongly on their co-products, not aviation alone.

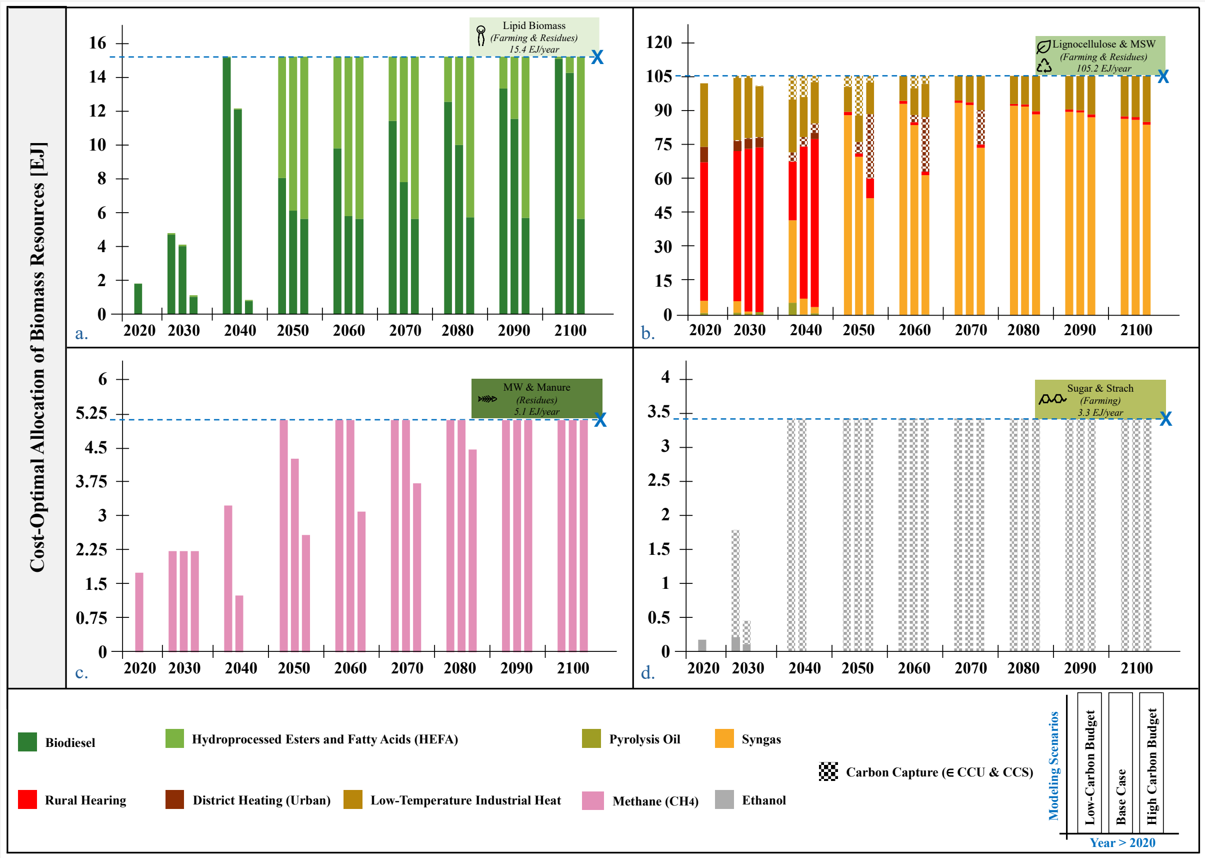


Figure 18 – Allocation of four biomass resource types across alternative conversion pathways under three modeling scenarios presented in **Paper IV**, expressed in primary energy terms. Lipid-based biomass is shown in graph a; lignocellulosic biomass and municipal solid waste (MSW) in graph b; organic waste streams, including municipal waste (MW) and manure, in graph c; and sugar and starch in graph d. The year 2020 is calibrated with real data for all three scenarios, being constant throughout the three scenarios. For subsequent years, each panel includes three columns corresponding to the three carbon budget scenarios, as indicated in the figure legend. For each biomass type, the horizontal blue dashed line denotes the maximum annual availability. Notably, in the “High-Carbon Budget Scenario”, the model does not identify methane production from organic waste streams in 2040 as cost-optimal. Similarly, ethanol production is not found to be cost-optimal between 2030 and 2040. Modeling assumptions on biomass resources availability, sectoral application, as well as other techno-economic considerations are presented in **Paper IV**. Main modeling scenarios assumptions are presented in Appendix A2.2. CCU, Carbon Capture and Utilization; CCS, Carbon Capture and Storage; MSW, Municipal Solid Waste; MW, Municipal Waste.

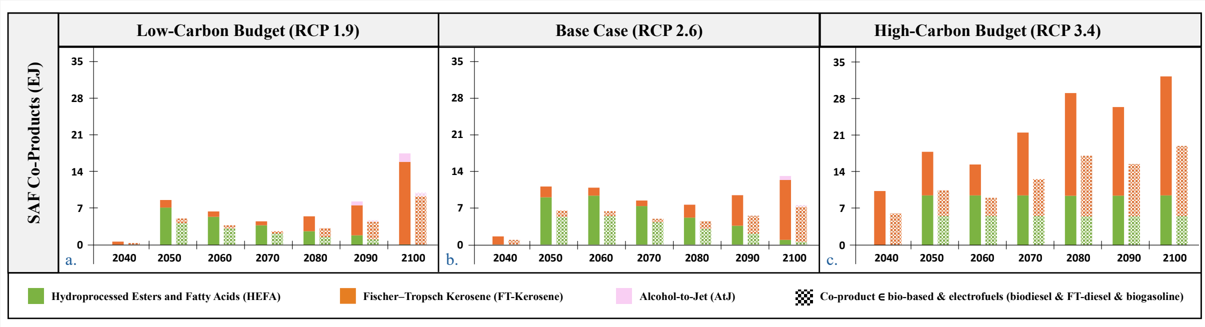


Figure 19 – Production of SAF and associated co-products across the three scenarios tested in **Paper IV**, i.e., "Low-Carbon Budget Scenario" (a); (ii) Base Case (b); and (iii) "High Carbon Budget Scenario" (c). HEFA produces biodiesel, FT-kerosene produces FT-diesel, and AtJ produces biogasoline. Results are shown only for years in which SAF shares exceed 5%, except for 2040 in the "Low Carbon Scenario", which is included for consistency among the other two modeling scenarios. For each year, two columns are displayed: the left represents SAF production, and the right (square pattern) shows co-product production. Modeling assumptions on co-product production as well as other techno-economic considerations are presented in **Paper IV**. Main modeling scenarios assumptions are presented in Appendix A2.2.

Overall, this thesis highlights that a cross-sectoral perspective fundamentally alters cost-effective low-carbon transport pathways by embedding transport within system-wide resource and constraint interactions. System wider-electrification, carbon capture, biomass availability, and co-products act as systems-integrators, allowing sectors with higher mitigation flexibility to low-carbon transition compensate for a potentially slower transition at the level of hard-to-abate sectors. In the specific case of this thesis, this redistribution enables aviation and long-distance transport to retain conventional fuels longer while low-cost mitigation is realized elsewhere. Synergies emerge through fuel co-products and shared resource use, enhancing system-level cost-efficiency. At the same time, trade-offs arise from competition over scarce resources such as biomass showing hence that low-carbon transport transition related outcomes are shaped less by sector-specific optimization than by cross-sectoral allocation mechanisms within an integrated energy system.

4.3. A Continuous Interaction between ESOMs and Stakeholders Engagement

Across **Paper I** (and **Paper II**, where the outcomes of **Paper I** are applied to an ESOM rationale) as well as **Paper III**, the soft-linking of stakeholders engagement with ESOMs generates a set of consistent and complementary insights that enhance both analytical outcomes and decision-making relevance within a single analytical framework. In both cases, as illustrated in Figure 20, continuous interaction between the research team and decision-making stakeholders leads to the development of modeling scenarios that explicitly capture socio-technical constraints such as spatial, institutional, and socio-economic dynamics. These scenarios move beyond purely technological or cost-optimal driven representations by embedding local constraints, governance structures, and demand-side characteristics into the analytical process.

A key result emerging from **Paper I** and **Paper III** is the convergence in the identification of decisive local factors shaping low-carbon transition. Through stakeholder engagement, similar thematic categories are independently identified in both case studies, including economic viability, infrastructure conditions, market and demand dynamics, and policy support. Importantly, these factors are not predefined by the analytical framework, but emerge inductively from stakeholders engagement, indicating that a common set of socio-technical conditions mediates transition feasibility across different contexts. While the specific expressions of these factors differ (i.e., budget constraints and car-dependent demand in the participating non-urban municipalities versus business-driven dynamics, technology lock-ins, and niche low-carbon markets in an energy port cluster), the underlying categories remain consistent.

As illustrated in the analytical framework presented in Figure 20, the identification of decisive local factors serve two complementary analytical functions. First, they are expressed by stakeholders as locally experienced conditions that shape perceived implementation potential. In **Paper I**, they take the form of limited municipal investment capacity, insufficient transport alternatives as well as related infrastructure, and challenges of multi-level coordination. In **Paper III**, they emerge as infrastructure lock-ins, uncertain policy frameworks, and market-driven viability considerations linked to liquid fuels, specifically low-carbon variants. Second, the identified decisive local factors are translated into analytical functions within ESOMs, where they inform plausibility of low-carbon strategies, guide scenario narratives' development, and provide a continuous discussion about modeling assumptions.

A further result concerns the way soft-linking renders enablers, barriers, and system-level trade-offs explicit for decision-making. In **Paper I**, qualitative performance assessments reveal how economic viability, infrastructure readiness, transport mode availability, and trip-planning requirements influence the relative feasibility of alternative road transport pathways. In **Paper III**, stakeholder input highlights how market conditions, policy alignment, and infrastructure characteristics shape the future role of liquid fuels under different socio-economic pathways. Across both studies, these findings demonstrate that transition outcomes are not determined by technological performance alone, but are strongly mediated by governance capacity, investment constraints, demand structures, and policy effectiveness.

The results further highlight mutual learning effects enabled by the two-way interaction between stakeholders and modeling exercises. In **Paper I**, stakeholder engagement enhances the interpretation of pathway impacts by revealing cross-sectoral synergies and competition for local resources, such as biomass and derived biofuels, as well as renewable electricity. In **Paper III**, the comparison between global modeling results and stakeholder expectations prompts reflection on scale effects, sectoral coverage, and underlying assumptions. In this process, ESOMs' outputs provide system insights and long-term trade-offs that inform stakeholders strategic thinking, while stakeholders perspectives provide an interpretive discussion around scenario narratives and modeling assumptions. This reciprocity strengthens both analytical framework robustness while providing systems insights that might guide stakeholders decision-making.

Finally, the combined findings demonstrate that soft-linking stakeholder engagement with ESOMs enhances decision support under long-term uncertainty. As explicitly discussed in **Paper I** and **Paper III**, rather than identifying a single optimal transition pathway, the framework shows that multiple trajectories can contribute low-carbon transition, depending on local priorities, resource endowments, governance capacity, and policy conditions. In **Paper I**, this leads to differentiated prioritization of road transport pathways at the municipal level, while in **Paper III** it clarifies how the future role of liquid fuels may evolve across socio-economic contexts. By situating modeling results within locally grounded strategic discussions, the developed single analytical framework of **Paper III** supports more adaptive, transparent, and informed decision-making for low-carbon transport transitions and the wider energy system.

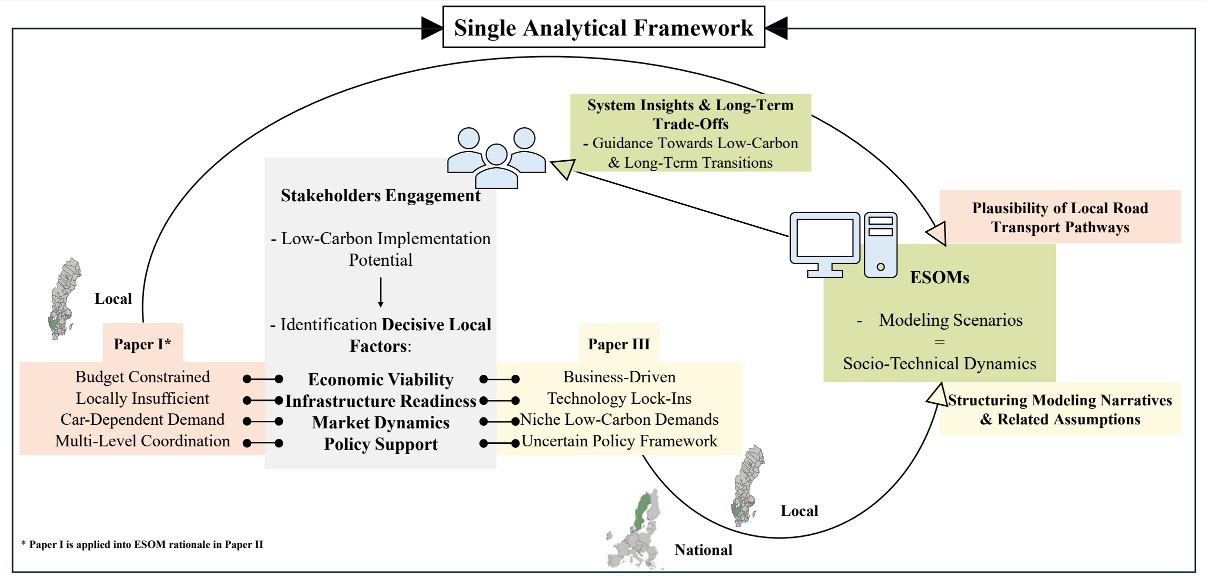


Figure 20 – Single analytical framework developed according to the appended papers in this thesis, as a result from a continuous interaction between ESOMs and stakeholders engagement. In **Papers I-III** the stakeholders involved were defined as decision-making stakeholders, with local (**Paper I-III**) and national (**Paper III**) influence. In **Papers I-II** (where **Paper II** applies the stakeholders engagement of **Paper I** to an ESOM framework), stakeholders engagement resulted in identification of plausible low-carbon strategies to be implemented locally, i.e., "Identified Pathways", as presented in **Paper I**. In **Paper III**, stakeholders engagement contributed to interpretative discussion on modeling narratives and related assumptions. Stakeholders engagement is described in detail in **Papers I-III**. ESOMs, Energy Systems Optimization Models.

5. Discussion and Conclusions

This chapter synthesizes the main findings of this thesis and discusses their implications considering the research gaps identified in Chapter 2 (see Section 2.5). This thesis sets out to address key limitations in the existing literature on low-carbon transport transitions, namely the lack of (i) multi-scale perspectives, (ii) cross-sectoral integration, and (iii) explicit interaction between energy ESOMs and stakeholder engagement. By developing and applying a single analytical framework that combines a continuous interaction between ESOMs and stakeholders engagement, this thesis advances the understanding of low-carbon transport transitions as context-dependent and socio-technical processes.

As a conclusive discussion, this chapter is further structured around the three research questions. First, it examines how a multi-scale modeling framework enables the representation of low-carbon transport transitions as context-dependent processes (RQ1). Second, it discusses the role of cross-sectoral interactions and system-integrators in shaping cost-effective transition pathways (RQ2). Third, it evaluates the contribution of soft-linking ESOMs with stakeholder engagement through continuous interaction within a unified analytical framework (RQ3). Together, these discussions provide a comprehensive reflection on how energy systems modeling can better support the analysis and governance of low-carbon transitions.

5.1. RQ1: Context-Dependency of a Low-Carbon Transport Transition: A Multi-Scale Energy Systems Modeling Framework

RQ1 explores how a multi-scale framework can be structured to better represent low-carbon transport transition as a context-dependent process. Under this specific RQ, this thesis evaluates how low-carbon road transport transition, and for the specific case of passenger cars, might unfold across local, national, and global scales (see Figure 11-12). Moreover, this analysis is complemented by an assessment of how this transition, from a local perspective, varies between non-urban and urban municipalities (see Figure 13).

Overall, this thesis demonstrates that low-carbon transport transition benefits from being understood as context-dependent processes rather than uniform developments across scales (see Figure 11-14). As depicted, low-carbon passenger transport transition is shaped by socio-geographical factors such as travel behavior, infrastructure availability, as well as by climate commitments that vary depending on the scale of analysis. These variations need to be explicitly represented within modeling frameworks in order to capture the diversity of transition pathways.

Adopting a multi-scale perspective is therefore essential. Any analysis confined to a single spatial scale inevitably highlights specific system dynamics while abstracting from others, meaning that single perspectives cannot fully represent the complexity of an energy transition. By examining local, national, and global scales in parallel, this thesis uncovers dynamics that remain hidden in single-scale models, including the tendency for aggregated national analyses to obscure non-urban transport dynamics.

Within this multi-scale context, certain parameters emerge as particularly influential in shaping model outcomes. For example, as tested among non-urban and urban municipalities, as well as at the national case (see Figure 13), trip-length distributions can play a decisive role in determining cost-optimal solutions, illustrating the importance of accurately representing scale-specific demand patterns. This underscores the need for careful attention to how demand is characterized across different spatial levels.

At the same time, differences observed across scales are not solely a function of spatial resolution. They are also shaped by how system boundaries and constraints are defined, such as whether transport is modeled as a standalone system or as part of an integrated energy system. Hence, cross-sectoral modeling choices are demonstrated in this thesis as significantly influencing the modeling outcomes.

Furthermore, this thesis provides a discussion that is particularly relevant for policy interpretation. Specifically, policies derived from national-level averages may align relatively well with urban conditions but risk misrepresenting the needs and characteristics of non-urban areas (see Figure 13). This observed trend further strengthens the argument put forward in this thesis regarding the importance of incorporating spatial differentiation into transport and energy planning processes, not only across different spatial scales but also within a single scale (local, national or global) that encompasses diverse socio-geographical contexts (i.e., non-urban and urban context).

In brief, this thesis demonstrates that a multi-scale modeling framework can be structured to represent low-carbon transport transitions as context-dependent processes, by incorporating modeling assumptions that capture the socio-geographical characteristics of the context (e.g. demand behavior) under transition. Moreover, the developed multi-scale energy systems modeling framework recognizes its broader applicability beyond road transport. In specific, a multi-scale energy systems modeling framework can support a more general understanding of energy transitions as context-dependent providing an analytical foundation for analyzing such transitions across different energy sectors and spatial scales.

5.2. RQ2: The Role of a Cross-Sectoral Perspective: The Importance of Systems-Integrators

The developed analytical framework in this thesis did not only consider a multi-scale perspective but expanded its systems boundary to add a cross-sectoral understanding. Accordingly, RQ2 analyzes how a cross-sectoral perspective might influence the cost-effectiveness of a low-carbon transition (see Figure 14-19). By doing so, this thesis explores the role that some energy carriers (Figure 14-15 and Figure 17-19), play as system-integrators. Such a role is also tested according to its sensitivity to different carbon budgets (see Figure 16).

The importance of adopting a systems-integrated perspective within the rationale of ESOMs is underscored by the findings presented in this thesis. In summary, a cross-sectoral approach shifts the identification of cost-effective transport pathways away from purely transport-specific techno-economic assumptions. Instead, a cross-sectoral perspective interlinks transport modeling outcomes with interactions with the electricity, heating, and industrial sectors, where mitigation options might be more readily available. Central to this dynamic is the role of so-called system-integrators, which in this thesis are identified as electricity (see Figure 14 and Figure 17), biomass (see Figure 14-15 and Figure 18), and CC technologies (see Figure 15), as well as related co-products (see Figure 19). These elements function as cross-sectoral linking mechanisms, connecting transport transitions to broader energy systems developments and enabling coordination of mitigation efforts across sectors.

Such integration enables important synergies through the shared use of resources and co-products. For instance, this thesis demonstrates that SAF co-products (see Figure 19) can provide additional cost-effective opportunities for the energy system by displacing fossil fuels in other sectors. This highlights the value of solutions that, if produced as standalone energy carriers for a given sector, would not be economically viable, but, when generated as co-products, offer additional low-carbon flexibility and enhance overall system cost-effectiveness. However, these benefits are accompanied by trade-offs, particularly under conditions of resource scarcity, as tested in the case of local land availability for VRESs' investment (see "Self-Sufficiency Scenario" in Figure 14) and annual biomass availability (see Figure 14-15 and Figure 18). Competition for limited resources, especially those acting as system-integrators, can constrain certain transport pathways. Such a trend is especially experienced at the level of urban municipalities, where land constraints for new local VRESs investment might suggest that passenger road transport requires the use of bridging solutions such as biofuels and indirect electrification (see Figure 14). This discussion is also grounded in the large-scale deployment of certain SAF pathways, which, under stringent climate targets, may avoid relying on cheaper bio-SAF options (see Figure 16), e.g., HEFA. This is demonstrated by the finding that, under strict climate targets, biomass resources are allocated more efficiently to sectors other than aviation from a cost-optimal perspective.

Incorporating a cross-sectoral perspective into ESOM frameworks is also demonstrated, in this thesis, as potentially affecting the timing of transitions across sectors. With a systems perspective, sectors with greater mitigation flexibility might transition earlier, effectively easing systems-wide constraints. By doing so, harder-to-abate sectors, such as aviation (see Figure 16), may be able to delay their transition, while the energy system still complying with overall climate objectives. The timing of transitions may also be influenced, as demonstrated in this thesis, by the role of CC technologies in reshaping low-carbon pathways under varying storage potentials (see Figure 15) and carbon budgets (see Figure 17). In particular, greater storage potential provides additional flexibility for hard-to-abate sectors, allowing them to maintain a reliance on fossil-based fuels while still meeting overall system-level climate constraints. Furthermore, this thesis shows that the system-integrator role of CC technologies varies depending on the carbon budget. Under more stringent carbon constraints, CC technologies become essential as a carbon storage solution, whereas under less stringent climate targets, they primarily function as a source of carbon feedstock for electrofuels, supporting, especially, the structure and dynamics of hard-to-abate sectors.

Briefly, and as demonstrated in this thesis, adopting a cross-sectoral perspective within ESOM frameworks enhances the robustness of modeling scenarios and the interpretation of outcomes. In specific, this thesis advocates that cost-effective transport transitions are inherently contingent on cross-sectoral allocation mechanisms, implying that transport sector outcomes cannot be reliably assessed without explicitly representing system-integrators and their interactions across the wider energy system. Despite the strong focus that this thesis offers on transport systems, these insights can be further applied more broadly to any energy demand sector undergoing a transition.

5.3. RQ3: A Continuous and Interactive Soft-Link between ESOMs and Stakeholders Engagement: A Single Analytical Framework

One of the main contributions of this thesis is the development of a single analytical framework that establishes a soft-link between different phases of ESOMs and stakeholders engagement. In response to RQ3, this thesis further expands the discussion on the insights that can emerge from this integration, highlighting the mutual benefits that these two strands can offer when used in combination. It also demonstrates how their combined application can enhance the understanding of low-carbon transport systems.

In this thesis, soft-linking ESOMs with stakeholders engagement reveals a convergence of decisive socio-technical factors that might impact a low-carbon transport transition, across different contexts and scales (see Figure 20). In specific, across local and national scales, economic viability, infrastructure conditions, market demand, and policy alignment were identified in this thesis as key determinants of low-carbon transition feasibility. Nonetheless, although certain factors that determine low-carbon transitions may appear to be transferable across contexts, their specific impacts, as demonstrated in this thesis, remain strongly dependent on the context under transition. This is because different spatial scales interpret and experience these determinants in distinct ways, i.e., a given socio-technical factor might not carry the same meaning or implications across scales (see Figure 20).

Expanding on the broadly aligned low-carbon agendas among participating decision-making stakeholders, this thesis highlights that a key strength of the unified analytical framework lies in its capacity to translate context-specific and socio-technical knowledge into analytical logic. As demonstrated, through stakeholders engagement, context-specific constraints and opportunities can be systematically incorporated into modeling exercises in the form of scenario narratives and interpretation and legitimacy filter of underlying modeling assumptions. This strengthens the contextual grounding of ESOMs analyses, while likely enhancing the plausibility of modeling assumptions, through improving their capacity to capture real-world dynamics.

By doing so, this thesis advocates that integrating stakeholders insights enhances the resolution of modeling scenarios beyond purely cost-optimal frameworks. Moreover, depending on the type of stakeholders involved, modeling frameworks can be redefined across multiple dimensions. In particular, the involvement of decision-making stakeholders allows scenario development to expand beyond purely cost-optimal representations to reflect broader socio-technical dimensions, including institutional capacity, behavioral patterns, and governance constraints. Similarly, the inclusion of technical experts enhances the technical resolution of different components of the system. Combining these insights enables a more interpretive discussion of the modeling framework and its outcomes, helping to guide how the modeling framework can be refined.

Furthermore, this thesis reinforces the idea that ESOMs and stakeholder engagement should be understood as complementary rather than substitutive approaches. ESOMs provide a consistent system representation, long-term perspectives, and the ability to analyze cross-sectoral trade-offs, as well as to explore resources, technologies, and emission constraints through "what-if" scenarios. In contrast, stakeholders contribute context-specific insights related to feasibility, governance structures, behavioral patterns, and demand characteristics. Combining these two strands within a single analytical framework strengthens the overall analysis without conflating optimization logic with stakeholders qualitative judgments.

As a result of their complementary nature, integrating these two approaches into a single analytical framework can foster mutual learning by balancing the limitations associated with each of the approaches when applied as standalone tools. This thesis shows that stakeholders engagement can enhance scenario development and improve the representation of systems conditions, for example through participation in deliberative discussions on system boundaries. Similarly, modeling results play an educative role by illustrating systems-level consequences, trade-offs, and transition dynamics. In this sense, ESOMs' outputs can provide stakeholders with a clearer understanding of long-term system implications, while stakeholder input enables modelers to identify blind spots related to behavioral change and low-carbon implementation dynamics. This, in turn, helps refine modeling assumptions and supports the interpretation of results within specific spatial and socio-geographical contexts.

Accordingly, this thesis demonstrates that continuous interaction contributes to strengthening model legitimacy and decision relevance. Such a soft-link can foster stakeholder trust in modeling outcomes and enhances the role of ESOMs as deliberative decision-support tools for low-carbon transport transitions and the wider energy system. Furthermore, this approach improves decision-making under long-term uncertainty. Rather than converging on a single optimal pathway, the ability of ESOMs to test different "what-if" scenarios enables the exploration of multiple transition trajectories, allowing decision-makers to prioritize strategies aligned with local conditions and policy environments.

More broadly, this thesis extends its application to low-carbon transport systems to any energy sector, by arguing that soft-linking ESOMs with stakeholder engagement can be considered a form of good modeling practice. Therefore, establishing an explicit dialogue between these two approaches through continuous interaction within a single analytical framework is demonstrated to be able to support more robust and context-dependent analyses. This, in turn, enables energy system transitions to be treated as socio-technical processes, particularly in settings characterized by uncertainty, institutional complexity, and competing policy objectives.

6. Reflection on Limitations and Future Research Directions

While this thesis advances the understanding of low-carbon transport transitions as a socio-technical process through the integration of multi-scale and cross-sectoral, several limitations should be acknowledged. These limitations stem both from method choices as well as from the scope and assumptions underlying the developed single analytical framework. In particular, simplifications related to data availability, model structure, and the representation of socio-technical dynamics through stakeholders engagement influence the results and their interpretation.

Moreover, given that this thesis establishes a soft-link between ESOMs and stakeholders engagement, the identified limitations are associated not only with each approach when applied independently, but also with the way this interaction is structured within the proposed framework. This includes, for instance, limitations in how qualitative stakeholder input is transcribed into modeling assumptions, as well as in how interactive feedback between models and stakeholders is structured.

Additional reflections also relate to the representativeness of specific spatial scale assumed in this thesis, particularly at the local scale, where data constraints, system boundary definitions, and context-specific assumptions may influence the generalizability of the results.

Recognizing these limitations is essential not only for contextualizing the findings of this thesis but also for identifying opportunities to further refine and expand the application of soft-linking ESOMs and stakeholders engagement. Accordingly, this section critically reflects on these constraints and outlines directions for future research aimed at improving the robustness, resolution, and applicability of energy systems modeling for not only transport systems, but any low-carbon transitions.

6.1. Energy Systems Optimization Models

ESOMs are at the core of the two analytical tools used and combined in the single analytical framework 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 should use this tool with some care.

A key limitation of ESOMs relates to their relatively simplified representation of demand behavior. ESOMs typically assume price-inelastic and fully rational decision-making, which limits their ability to capture behavioral heterogeneity and non-economic drivers of energy demand. In this context, the choice of discount rate plays a particularly important role. ESOMs commonly adopt relatively low discount rates, often reflecting a societal perspective. This assumption enables an exploratory approach, where model behavior can be assessed through sensitivity analyses and scenario exploration, with the objective of understanding system dynamics rather than prescribing specific decisions. Such assumptions tend to favor longer technology lifetimes, lower discounting of future costs, and results that are more generalizable across contexts.

However, it is important to recognize that higher discount rates, often interpreted as proxies for individuals or private decision-making perspectives, can significantly influence model outcomes. Higher discount rates likely penalize capital-intensive technologies by reducing the present value of long-term benefits, thereby shifting investments toward later years or toward lower upfront-cost options. While such assumptions may be less suitable for systems-level exploration (i.e., higher discount rates are likely to biasing decisions toward short-term outcomes and undervaluing systems-wide trade-offs over time), they can provide valuable insights when the objective is to understand how specific investment behaviors or decision logics may affect transition pathways.

Another important limitation concerns the dominance of cost-optimality as the primary decision criterion. ESOMs typically determine investment pathways based on systems-integrated cost-minimization, thereby overlooking individual economic aspects as well as non-economic considerations such as risk perception, system inertia, social acceptability, and strategic behavior. As a result, model outputs may not fully reflect real-world decision-making processes, where such factors play a critical role.

Relatedly, ESOMs are based on different assumptions, and there is always a risk these assumptions reflect modelers perceptions of what is reasonable, meaning that one should be critical whether cost-optimization results represent cost-optimal system outcomes or are reflections of underlying modeling assumptions. While constraints and assumptions are necessary to represent complex energy systems, an excessive number of constraints may reduce the flexibility of the model and shift its rationale closer to simulation rather than optimization. This raises important considerations regarding the balance between reality and analytical flexibility in model framework formulation.

Furthermore, ESOMs commonly rely on perfect foresight assumptions, requiring knowledge of future technology costs, policy targets, and system conditions over long time horizons. While this approach enables internally consistent optimization, it introduces uncertainty when interpreting results as representations of real-world transition pathways, where such information is inherently uncertain. Similarly, ESOMs may also underestimate energy security and system resilience considerations. These aspects are often simplified or treated indirectly, limiting the ability to assess how energy systems respond to disruptions, supply constraints, or unexpected shocks. As a result, the robustness of modeled transition pathways under real-world uncertainties may not be fully captured.

Finally, the representativeness of the case study constitutes an important limitation of this thesis. The analysis is partly grounded in a Swedish context, including a comparison between urban and non-urban transport dynamics. While Sweden is often recognized for its strong sustainability performance and high GDP per capita, these conditions may facilitate the achievement of climate targets compared to lower-income contexts. In countries with lower GDP levels or higher rural population shares, the socio-economic conditions, infrastructure availability, and definitions of urban and non-urban contexts may differ significantly. If testing higher effective discount rates in future research, model rationale might constrain the adoption of capital-intensive low-carbon technologies, such as electric vehicles, adding extra pressure on the cross-sectoral of finite resources acting system-integrators, such as biomass. Still, while the specific results of this thesis may not be directly transferable across different contexts, the method developed in this thesis, particularly the integration of spatial and cross-sectoral dynamics into modeling frameworks, remains broadly applicable.

Overall, ESOMs are inherently evolving tools. Thus, addressing these limitations requires careful model design and continuous future modeling updates as well as the use of complementary analytical approaches. Scenario analysis based on "what-if" questions can help explore the implications of key assumptions, while sensitivity analyses allow for the identification of parameters that are most influential in shaping model outcomes. This enables the distinction between robust insights and results that are highly contingent on specific techno-economic, policy, or resource assumptions. Such approaches can guide modelers in defining appropriate system boundaries, identifying which system components can be represented in a simplified manner and which require more detailed characterization.

Ultimately, it is important to recognize that "all models are wrong, but some are useful" [161] In this thesis, the ESOMs developed and applied prove to be valuable tools for exploring low-carbon transport transitions and their interactions with the wider energy system and according to a multi-scale perspective. While their results should be interpreted with caution, they provide meaningful insights into systems dynamics, trade-offs, and the conditions under which different transition pathways may emerge.

6.2. Stakeholders Engagement

Besides ESOMs, this thesis also applies stakeholders engagement as a core pillar within the developed single analytical framework. While stakeholders engagement offers valuable perspectives, such as enhancing social inclusivity, supporting climate resilience, and strengthening decision legitimacy, this thesis, in line with the existing literature, also discusses some associated limitations that must be carefully considered.

A first challenge relates to the conceptual ambiguity and evolving use of stakeholders engagement in literature. Terms such as participatory approach, stakeholders or actors involvement, engagement, and interaction are often used interchangeably, despite often referring to similar practices. This reflects the relatively novel nature of combining ESOMs with stakeholders-based methods to low-carbon energy studies, while highlighting the lack of standardized guidance for integrating these approaches within a single analytical framework.

At the empirical level, this thesis involved the engagement of different type of decision-making stakeholders and technical experts, whose contributions illustrate important inherent limitations. Particularly, stakeholders stated preferences do not always align with their revealed preferences, as responses are shaped by individual priorities, institutional roles, and context-specific interests. More broadly, stakeholders may express their perspectives in diverse ways and may find it difficult to articulate value-neutral opinions. As a result, this thesis agrees with the literature that stakeholders input might function as a "black box," where responses are grounded on short-term priorities, sector-specific goals, or normative values, rather than reflecting a holistic systems perspective.

This also relates to the risk of bias and partial representation of certain decisive socio-technical factors. Stakeholders engagement tends to revolve around relatively narrow thematic or sectoral perspectives, limiting the ability to capture long-term dynamics, cross-sectoral interactions, and systemic uncertainties. Although this thesis addresses this limitation by including a heterogeneous group of stakeholders (i.e., decision-making stakeholders and technical experts) across the different appended papers, ensuring broader systems representation remains a key challenge. In future work, stakeholders engagement could further expand the heterogeneity of involved stakeholders, ensuring broader representation across sectors, institutional levels, and socio-economic contexts. This would enhance the robustness and inclusiveness of perspectives, improving, thus, their contribution to the analysis of socio-technical energy transitions.

Another important limitation concerns the transcription of qualitative stakeholder input into analytical and quantitative representations. Converting stakeholders perspectives into conceptual structures, scenario narratives, or modeling assumptions is a resource-intensive process that requires careful interpretation. There is an inherent risk of oversimplification or misrepresentation when formalizing complex socio-technical insights into model-based frameworks. To mitigate these challenges, this thesis adopted continuous dialogue between the researchers and stakeholders, allowing for clarification, interactive reflections, interpretive results discussion, and in-depth exploration of key issues. It provided the flexibility to probe responses, resolve ambiguities, and ensure a more accurate interpretation of stakeholder perspectives. Furthermore, follow-up discussions and interactions strengthened the integration of stakeholder input by enabling the revision of assumptions and contextualization of findings.

Despite meaningful stakeholder engagement remaining a time- and resource-intensive process, stakeholder engagement remains a critical component for capturing the socio-technical and context-dependent nature of low-carbon transitions. As demonstrated in this thesis, stakeholders engagement enables the integration of context grounded knowledge, institutional realities, and behavioral dynamics. Thus, this thesis advocates that stakeholders engagement, when carefully designed and continuously applied, provides a valuable pathway for improving the relevance, interpretability, and real-world applicability of not only low-carbon transport systems but any energy systems analyses.

6.3. General Reflections

A central contribution of this thesis lies in demonstrating that the limitations associated with ESOMs and stakeholders engagement can be partially addressed through their combined use. ESOMs provide a consistent systems-wide representation, enabling long-term accounting of resources, technologies, and emissions under explicit constraints, while supporting transparent exploration of trade-offs and “what-if” scenarios. However, they remain limited in capturing behavioral, institutional, and implementation dynamics. Conversely, stakeholders engagement provides context-specific knowledge, insights into feasibility, and a deeper understanding of institutional conditions, while remaining inherently biased and unable to ensure system-level consistency. By establishing an explicit and continuous dialogue between these two approaches, this thesis shows that their integration forms a complementary strategy, where the limitations of one approach are, to some extent, offset by the strengths of the other. In this sense, the soft-link developed in this thesis enables more robust, transparent, and decision-relevant analyses of low-carbon transport transitions and the wider energy system.

Beyond this integrative contribution, the thesis advances three key insights:

- Conceptually, low-carbon transport transitions should be analyzed as context-dependent, multi-scale, and socio-technical processes, rather than as uniform, national, and globally averaged techno-economic transitions. According to this thesis methods' contribution, it shows that stakeholders engagement can be soft-linked to ESOMs in two complementary ways, i.e., (i) by informing the development of modeling scenarios; and (ii) by legitimating the representation of system structures, assumptions, and constraints. It further highlights that the feasibility, timing, and cost-effectiveness of low-carbon transport pathways are strongly shaped by system-integrators, such as electricity, biomass, CC technologies, and co-products, as well as by their interactions across sectors.

- This thesis also provides important application-oriented insights into how low-carbon transport transitions unfold in practice. The findings show that such transitions are strongly context-dependent, varying across spatial scales, socio-geographical conditions, and cross-sectoral interactions. Particularly, local dynamics, resource constraints, and competition for system-integrators significantly influence the feasibility and timing of transition pathways, reinforcing the need for more spatially differentiated and system-integrated analyses.

- While stakeholders engagement enhances the contextual relevance, plausibility, and interpretability of modeling results, this thesis recognizes that stakeholders engagement does not inherently improve predictive accuracy or validate model outcomes. Stakeholder knowledge remains partial, situated, and shaped by institutional contexts, power relations, and individual perspectives. Similarly, the soft-link established in this thesis does not fully internalize behavioral, institutional, or political dynamics within optimization models. Rather, it provides a structured approach to inform, contextualize, structure, and interpret model-based analyses. Recognizing these limits is essential to ensure transparency and rigor in how model-based insights are deliberated and applied.

Through soft-linking ESOMs and stakeholders engagement, while applying it to understand how low-carbon transport transition might unfold, this thesis reinforces the idea that no single method can fully capture the complexity of socio-technical transformations. Progress therefore lies in the careful combination of complementary approaches, supported by critical reflection on their respective strengths and limitations.

Finally, the insights shared in this thesis also contribute to the knowledge base supporting the 2030 Agenda for Sustainable Development. The findings are especially relevant to Sustainable Development Goals (SDGs) (i) 7 (Affordable and Clean Energy) by enhancing modeling approaches for assessing cost-effective and system-integrated low-carbon energy transitions; (ii) 11 (Sustainable Cities and Communities) by reflecting upon the role of multi-scale heterogeneity and the context dependency of low-carbon transport pathways, especially highlighting the risks associated with standardized solutions, particularly when comparing urban and non-urban passenger road transport contexts; and to SDG 13 (Climate Action) by supporting the analysis of mitigation strategies for transport systems under different climate constraints and according to a cross-sectoral dynamics.

By advancing an analytical approach that capture the context-dependent and multi-scale nature of low-carbon transport transitions, this work supports the development of more inclusive, efficient, and resilient energy and transport systems. While not directly prescribing solutions, the proposed framework provides insights that can inform policy discussions and planning efforts aligned with these global sustainability objectives. In this sense, the framework developed in this thesis should be seen as a step towards more integrated, reflexive, and context-aware approaches to analyzing and governing not only transport systems, but any low-carbon transitions.

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Appendix

A1. Spatial-Scales Definition

A1.1. Local and National

Situated in Northern Europe, Sweden is widely acknowledged for its strong commitment to sustainability. The country consistently ranks among the top performers in global sustainability assessments and is currently placed second in the Country Sustainability Ranking [162], which evaluates the progress of the 193 United Nations Member States toward achieving the 17 Sustainable Development Goals (SDGs). This strong performance makes Sweden a particularly relevant case for the objectives of this thesis related to local and national scales.

As outlined earlier, this research seeks to highlight the role of a multi-scale perspective, and therefore, a spatial dynamic in assessments of low-carbon transport transition. Specifically, as appended in **Paper I** and **Paper II**, this thesis investigates how pathways for decarbonizing road transport differ across socio-geographical contexts. Sweden's 290 municipalities vary widely in terms of population size, energy use patterns, VRESs potential, financial conditions, policy priorities, and social characteristics. Within this national context, the Västra Götaland Region offers a particularly diverse setting, encompassing municipalities of different scales and profiles. Consequently, the region was selected as an appropriate case study to examine variations in road transport decarbonization when analyzed at: (i) the national versus municipal level; and (ii) across urban and non-urban environments.

According to the Swedish Association of Local Authorities and Regions (SALAR), municipalities within Västra Götaland can be categorized based on demographic characteristics and commuting patterns [163]. Following this classification, the region includes four main municipality types: "storstäder" (large cities), "mindre stad/tätort" (small cities), "pendlingskommun nära mindre stad/tätort" (commuting municipalities near small cities), and "pendlingskommun nära större stad" (commuting municipalities near medium-sized cities). For analytical clarity, this thesis defines only municipalities classified as "storstäder" as urban, while the remaining categories are treated as non-urban.

To adequately capture socio-geographical heterogeneity and assess the relevance of local spatial dynamics, four municipalities were selected, each representing one of the identified municipality types. Gothenburg represents a large city, characterized by a population exceeding 200,000 inhabitants in its main urban area. Lidköping is included as a small city, defined by a minimum of 15,000 residents within its largest urban area. Skara exemplifies a commuting municipality near a small city, where either more than 30% of the working population commutes to a small city or over 30% of the daytime working population resides outside the municipality. Finally, Grästorp represents a commuting municipality near a medium-sized city, with more than 40% of its working population commuting to such a city. The geographical location of the four selected municipalities is illustrated in Figure A 1.

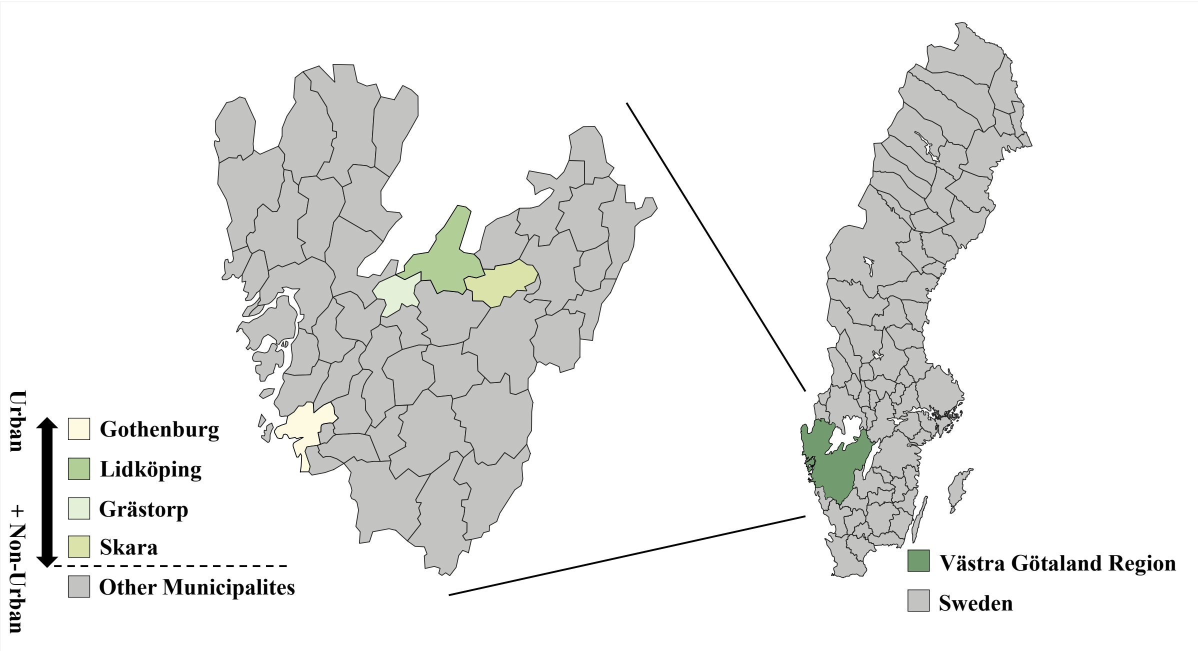

Figure A 1 – Map of the municipalities considered in **Paper I** and **Paper II**. Maps were generated using the Quantum Geographic Information System (QGIS) 3.36.2 [164].

Located on the west coast of Sweden, the Port of Gothenburg is considered to be the largest and busiest Port within Scandinavia [165,166]. Besides the owned company Port of Gothenburg, this Scandinavian Port gathers other key activities as well as local and national actors influencing the also its dynamics. Those actors, defined as the involved decision-making stakeholders in **Paper III** include refineries, storage, energy, and shipping companies. As depicted in Figure A 2, the Port of Gothenburg's operations are split into three terminals, handling a wide range of both liquid bulk and refined products, such as crude oil, gasoline, diesel, fuel oil, and other oil-based products (e.g., biofuel).

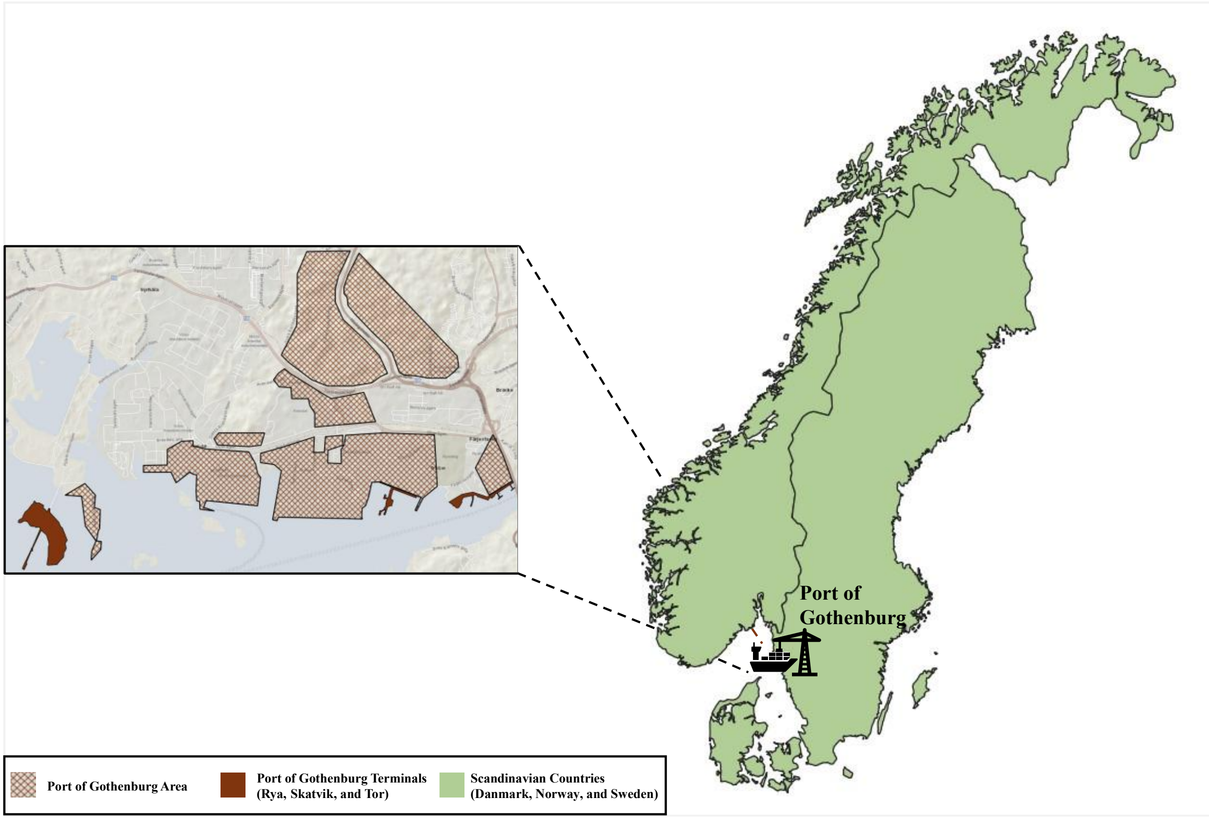

Figure A 2 – Port of Gothenburg map generated for the specific purpose of this Thesis, using the Quantum Geographic Information System (QGIS) 3.36.2 [164].

A1.2. Global

In line with the multi-scale approach adopted in this thesis, a global perspective is incorporated in **Paper III** and **Paper IV** to more effectively capture the dynamics governing hard-to-abate transport sectors, such as aviation and shipping. Assessing these sectors on the global scale allows for a more comprehensive understanding of their systemic characteristics and transition challenges. To further account for global diversity, the analysis is disaggregated into ten world regions, as depicted in Figure A 3, enabling the representation of heterogeneity in economic development, population size, and urbanization patterns, which in turn significantly influence energy demand and transport activity.

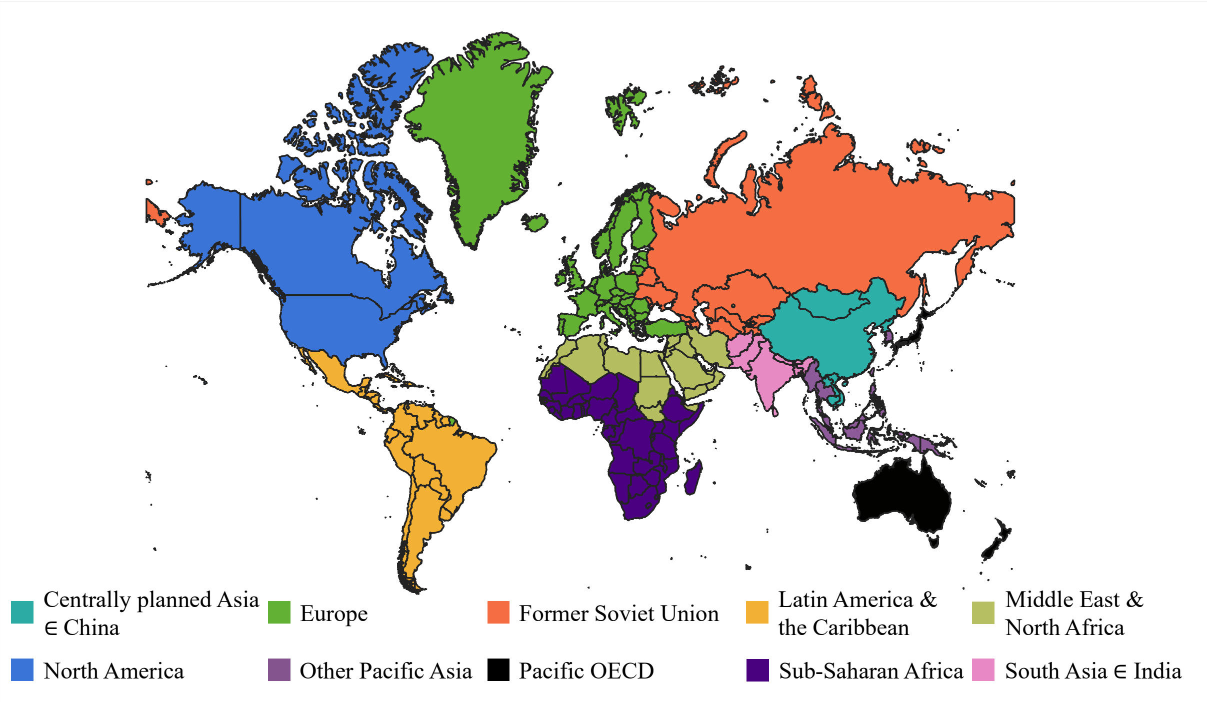

Figure A 3 - Map of the global perspective considered in **Paper III** and **Paper IV**, disaggregated in ten world regions. Map was generated using the Quantum Geographic Information System (QGIS) 3.36.2 [164].

A2. Additional Information about Method, Input Data, and Modeling Scenarios

A2.1. TIMES

TIMES framework was applied to **Paper II** and Licentiate thesis. The modeling framework as well as related modeling assumptions are presented in the Supplementary Material presented in the published version of **Paper II**.

Figure A 4 illustrates the TIMES framework applied in the Licentiate thesis, where a national perspective was added, to the low-carbon road transport transition.

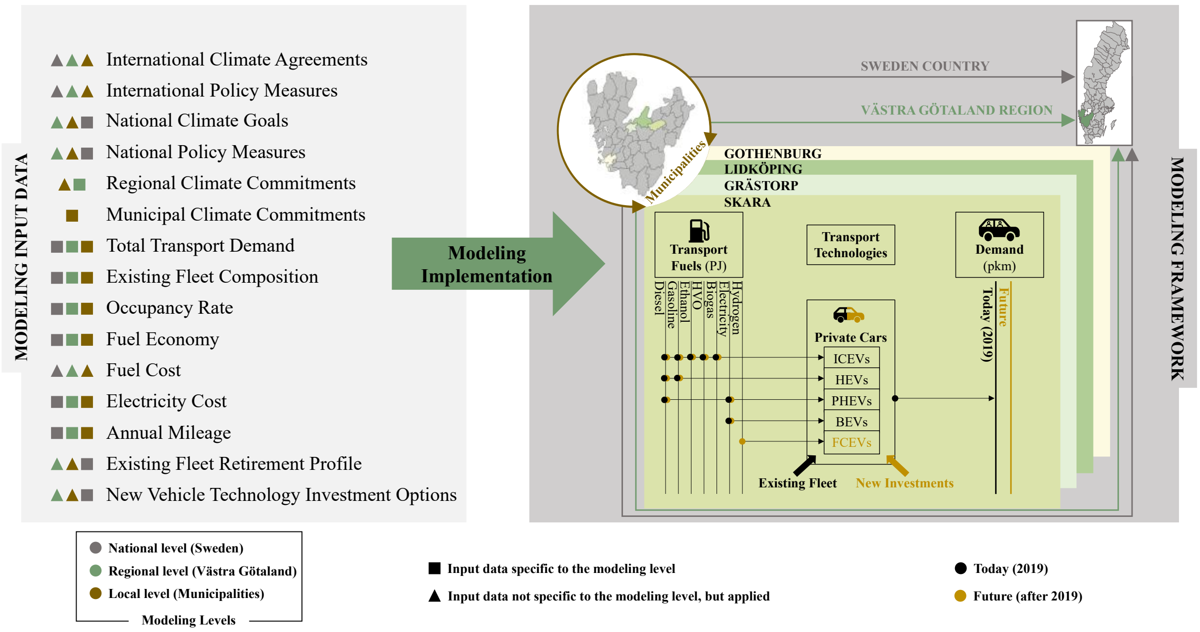

Figure A 4 - The TIMES model framework developed and applied in **Paper II** and the Licentiate thesis. The modeling-specific input data is marked on the left side in the light-grey-shaded rectangle. The input data varies according to the three considered modeling levels – national (Licentiate thesis), regional (**Paper II**), and local (**Paper II**). 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.

A2.1.1. National Modeling Input Data and Related Assumptions

Tables A1-A5 present national specific input data and related modeling assumption at the national level of low-carbon passenger road transport, as considered in the Licentiate thesis.

Table A 1 – Existing Swedish stock for passenger cars for the base year, 2019, and the calibrated year, 2022. Data retrieved from [92,167–170]. 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 [171]. 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 [76,92,172]. 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		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	17	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 [68–71]. 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

Table A 5 – Fuel economy for passenger cars for the whole model horizon. Data retrieved from [173–175]. 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

A2.2. Modeling Scenarios

The modeling scenarios presented in this thesis are thoroughly described in the corresponding appended work. Table A6 summarized key modeling assumptions of the modeling scenarios presented in this thesis, as a guidance to better interpret the selected results.

Table A 6 – Key modeling assumptions of the modeling scenarios presented in this thesis. Thorough description and related assumptions is presented in the corresponding appended work.

Scenario Name	Appended Paper	Multi-Scale Perspective	Climate Constraint	Post-2035 ICEVs Ban
Climate Policy	Paper II	Local	**Intermediate Target:** Total CO_2 emissions are constrained to be reduced by 80%, compared to the 2010 level. **Long-term Target:** The total CO_2 emissions are constrained to be zero by 2045.	Yes
Local Self-Sufficiency Scenario	Paper II	Local		Yes
Bio-Locked Scenario	Paper II	Local		Yes
Climate Policy	Licentiate thesis	National	**Intermediate Target:** Total CO_2 emissions are constrained to be reduced by 70%, compared to the 1990 level. **Long-term Target:** The total CO_2 emissions are constrained to be zero by 2045.	Yes
Ambitious Scenario	Paper III	Global	**Carbon Dioxide Budget** [2010-2100] = 700 $GtCO_2$	Yes
Incremental Scenario	Paper III	Global	**Carbon Dioxide Budget** [2010-2100] = 905 $GtCO_2$	No
Conflictual Scenario	Paper III	Global	**Carbon Dioxide Budget** [2010-2100] = 1,225 $GtCO_2$	No
Low-Carbon Budget Scenario	Paper IV	Global	**Carbon Dioxide Budget** [2010-2100] = 700 $GtCO_2$	No
Base Case	Paper IV	Global	**Carbon Dioxide Budget** [2010-2100] = 905 $GtCO_2$	No
High-Carbon Budget Scenario	Paper IV	Global	**Carbon Dioxide Budget** [2010-2100] = 1,225 $GtCO_2$	No

A3. The Story Behind the Cover

Some days before printing my thesis, my three-year-old nephew asked my mum why they would visit Sweden in a few weeks. My mum told him that the trip was because I was "writing a book". My newphew promptly asked whether I was writing a book for children like him, as otherwise, he said, he would not want to come to Sweden.

While debating whether to include a cover illustration or not, this moment inspired me to shape my thesis in a way that I could tell "my story" to my nephews, and perhaps one day make it their favorite book. To check whether my cover would be simple and engaging enough (i.e., I really had to convince my three-year-old nephew that his trip to Sweden would be worthwhile), I asked my mother, a primary school teacher, to invite her nine- to ten-year-old students from Class 4B at Agrupamento de Escolas Martim de Freitas in Coimbra, Portugal, to draw what they imagined when hearing my title. Their drawings, as presented in Figure A 5, further inspired me in creating the cover and I am very grateful to all of them for helping me make my cover special.

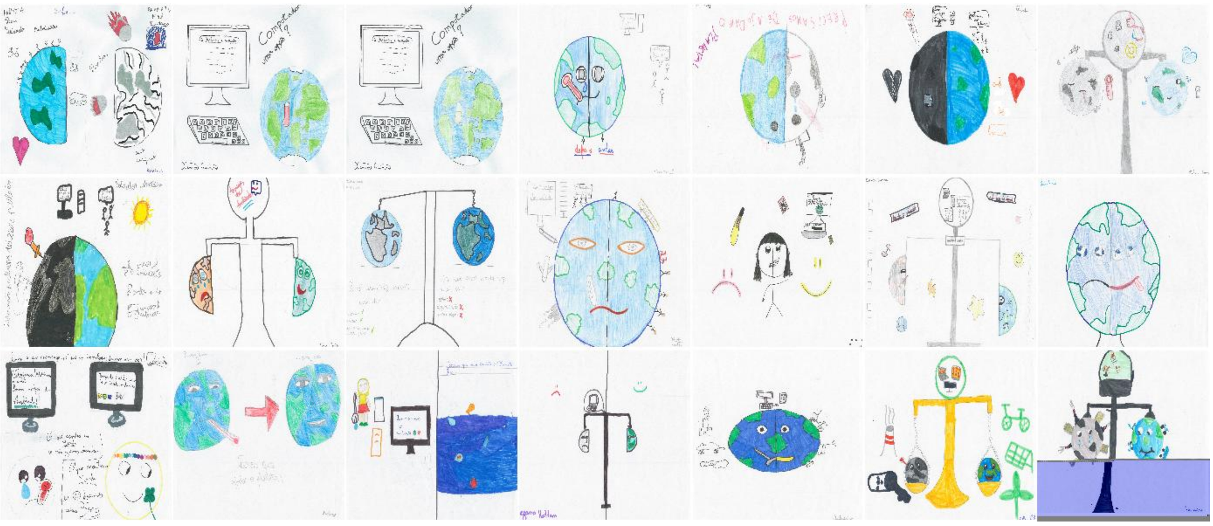

Figure A 5 – Collage of 21 drawings created by students from Class 4B at Agrupamento de Escolas Martim de Freitas in Coimbra. The students were asked to draw what they associate with the title of my thesis, translated into Portuguese as "Conversas entre computadores e sociedade: A descarbonização do setor dos transportes".