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AN INTEGRATED APPROACH TO ASSESSING ROAD PASSENGER TRANSPORT DECARBONISATION PATHWAYS

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Alīna Safronova (signature)

Date:

The Doctoral Thesis has been written in English. It consists of an Introduction, three chapters (Literature Review, Methodology, and Results), Conclusions and Recommendations, 14 figures, and three tables; the total number of pages is 56. The Bibliography contains 102 titles.

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INTRODUCTION

Human activity, primarily the burning of fossil fuels for energy, is the greatest contributor to climate change. The importance of this lies in the wide-ranging impacts of climate change on ecosystem sustainability, food and water security, economic stability, social conditions, and human health. Despite the growing global awareness of the negative consequences of burning fossil fuels, related to greenhouse gas (GHG) emissions and their impact on climate change, the demand for fossil fuels remains high.

The transport sector remains a major emitter, accounting for approximately 23 % of global energy-related CO₂ emissions and around 15 % of total global GHG emissions. This sector is among the top three emitting sectors worldwide [1].

The European Union (EU) goal of achieving climate neutrality by 2050 also considers transport sector requirements. Transport accounts for 31 % of energy consumption in the EU [2]. In the EU, the transport sector is especially significant because, despite a slight decline in emissions since 2005, fuel combustion in the sector is a major contributor, and in 2023, the volume of emissions generated by the sector accounted for more than 27 % of all emissions in the EU [3]. Significant reductions in transport sector emissions in the EU have already been discussed in White Paper 2011, and a number of regulatory policies have been implemented regarding alternative fuels and their refuelling/charging infrastructure [4]. At the same time, the problems are still urgent and unresolved.

The primary challenge in the transport sector is currently thought to be the heavy reliance on fossil fuels. EU's average rate of renewable energy use in the transport sector in 2023 was only 10.8 %. The EU's experience with the 2020 renewable energy target for transport shows that setting quantitative targets does not guarantee their achievement. Although Member States were required to achieve a 10 % share of renewable energy in transport, in 2020 15 member states, including Latvia, failed to meet this target [5]. Among other challenges, high dependence on private cars is often mentioned, which only emphasises the need to develop alternative modes of transport and influence behavioural change. Without this dimension, even the most modern technological and political initiatives are unable to achieve significant emission reductions. Behavioural factors directly determine both demand and mode of transport, as well as the effectiveness of technological and political interventions. The success of the implemented policies largely depends on public acceptance, which, in combination with technological and infrastructural interventions, provides the best outcomes. Given their significance, behavioural factors are also studied in the Thesis.

A large part of the emissions of the transport sector is related to road transport, which comprises two- and three-wheelers, passenger cars, light- and heavy-duty vehicles. This is because road transport is dominant in terms of emissions from the large number of vehicles, the use of fossil fuels and the volume of passenger and freight movement [6]. As road transport has a dominant role in transport-related emissions and passenger mobility is important within this sector, the Thesis is focused specifically on the decarbonisation of road passenger transport.

Decarbonisation of the road passenger transport sector is one of the world's major challenges, as it involves a wide range of issues, from the high costs of green technologies to infrastructure gaps [7]. Infrastructure gaps are characterised by insufficient charging/fuelling networks and grid integration, which limit electric/hydrogen adoption [7], [8]. Moreover, policy and institutional barriers, as well as resource constraints, are considered major challenges for transport decarbonisation [9], [10]. Behavioural and demand factors, such as rising travel demand, car ownership and resistance to modal shift from private cars to public transport or active mobility, further complicate the transition to sustainable transport systems [9], [11]. Furthermore, economic and social equity concerns, such as transition costs, funding gaps, and the risk of excluding low-income groups, may limit the feasibility and acceptance of decarbonisation measures [10], [11].

This evidence indicates that the complexity of the transport sector's decarbonisation necessitates a well-defined analytical framework. One widely used approach to structure the transition of the existing transport system towards sustainability is the avoid-shift-improve (ASI) approach. This approach combines reducing the need for trips, shifting to more sustainable modes of transport and improving vehicle efficiency and technology. This framework is useful because it shows that decarbonisation of transport cannot be achieved through technological improvements alone, but requires a combination of demand-side, modal shift and technological measures.

In the Thesis, the decarbonisation of road passenger transport is studied through three interrelated dimensions: technological transition, behavioural change and policy implementation. Together, these dimensions influence transport activity, modal choice and fuel technologies, and therefore the realistic GHG emission reduction potential. The technological dimension includes the introduction of low-emission vehicles, alternative fuels and the necessary infrastructure. The behavioural dimension refers to transport habits, travel mode choices, public support and the willingness of citizens to change their daily mobility habits. The policy dimension combines bottom-up and top-down approaches, linking strategic planning and regulation at the national level with the practical implementation of measures at the local level and the response of the citizens targeted by these measures.

Research topicality

The relevance of this research is especially evident in Latvia, where the transport sector's emissions remain high despite long-term climate neutrality goals. In the case of Latvia, the transport sector in 2023 generated 31.4 % of all emissions produced in the country (excluding land use, land-use change, and forestry and including indirect carbon dioxide (CO₂) emissions) and was the second largest source of emissions in the country after the energy sector. There is also an alarming trend in Latvia: rather than reducing emissions, the country had increased emissions by 3 % by 2023 compared to 1990, which is inconsistent with achieving the goals of the Green Deal [12]. This indicates that the current level of initiatives is insufficient and urgently requires improvement. In general, Latvia can be described as a country with a high use of fossil fuels, a low use of renewable energy, a growing car fleet per 1000 inhabitants that remains below the European average, and an outdated car fleet.

Without additional decarbonisation measures, Latvia risks not only failing to meet the existing objectives but also facing increasing environmental, economic and social costs related to delayed technological transition, fossil fuel dependence, and inefficient mobility patterns. Furthermore, Latvia faces rising expenditures associated with fines, fuel prices, and technical backwardness, all of which have an impact on society's overall well-being.

Previous studies on Latvia's transport sector have examined the viability of natural gas with biomethane in Latvia [13]. Following the alterations in the political landscape in Europe in 2022, the potential of utilising natural gas in transport is mainly seen as a way of easing the transition to renewable energy sources [14]. Electrification options were also explored for passenger and freight transport, both road and rail [15]–[17], which is now Latvia's central strategy for achieving decarbonisation. The studies have also examined the impact of environmental taxes [18] and different policy combinations, identifying public transport, alternative fuel integration and improvement of vehicle efficiency as capable of significantly reducing current emissions [19]. The latest studies, in turn, examine Latvia's potential to integrate hydrogen and synthetic fuels [20]–[22].

These studies provide an essential basis for understanding specific technologies, policy instruments and emission reduction measures. However, there is a lack of an integrated methodology that simultaneously assesses the decarbonisation of road passenger transport using technical transitions, behavioural change and policy implementation. This creates a research gap in understanding the interaction of these dimensions and the conditions under which they can realistically contribute to GHG emission reductions.

The Latvian National Inventory Document (NID) showed that the largest sources of emissions in the transport sector are road transport, followed by rail transport [12]. Together, these two sectors include both passenger and freight transport, and their combined impact accounts for 99.7 % of the total reported emissions from the Latvian transport sector [12]. Therefore, this Thesis focuses on road passenger transport, while public transport and rail are discussed primarily in terms of modal shift and policy scenarios.

Aim and objectives

This Thesis aims to develop and apply an integrated approach to assessing options for decarbonising road passenger transport, linking technological transition, behavioural change and coordinated policy implementation.

Research questions

1. What factors and barriers affect the technological transition of road passenger transport to low-emission alternatives?
2. How can national and local government policy measures be interconnected to promote the decarbonisation of road passenger transport?
3. What factors affect mobility habits, public support and willingness to switch from private cars to more sustainable modes of transport?

Objectives

1. Assess the theoretical and policy context of road passenger transport decarbonisation, identifying the main technological, behavioural and policy implementation challenges.
2. Assess the potential of low-emission transport technologies and policy measures using multi-criteria, cost-benefit and system dynamics analysis methods.
3. Analyse the interaction of national and local government policy measures in the context of decarbonisation of road passenger transport in Latvia.
4. Investigate the mobility habits of residents, public support and the importance of behavioural change in the implementation of transport decarbonisation measures.
5. Develop and test an integrated analytical approach that links technological transition, behavioural change, and coordinated policy implementation to assess solutions for decarbonising road passenger transport.

Hypothesis

An integrated analytical approach that incorporates technological, behavioural and multi-level policy implementation factors provides a more comprehensive and realistic assessment of road passenger transport decarbonisation pathways than a technology-only assessment.

Novelty

The scientific novelty is the development of an integrated analytical approach for assessing solutions for the decarbonisation of road passenger transport, in which technological transition, behavioural change, and coordinated policy implementation are analysed as interrelated dimensions. In contrast to studies that look at each dimension independently, this research integrates all three dimensions into a unified analytical logic to evaluate the potential for realistic GHG emission reduction for road passenger transport.

The Thesis contributes to the systematic integration of multiple research methods, including multi-criteria decision-making, cost-benefit analysis, bibliometric analysis, causal loop analysis, system dynamics modelling and empirical behavioural data. Each of these methodologies is widely used in isolation, but the combined approach provides a comprehensive evaluation of decarbonisation options by integrating technological feasibility, policy relevance, implementation conditions and public acceptance.

The Thesis makes an important contribution to transport decarbonisation modelling by evaluating behavioural factors such as travel patterns, perceived costs, mode choice preferences and willingness to change mobility behaviour through system dynamics. This allows for the evaluation of not only technically feasible emission reduction potential but also a more realistic transition potential influenced by user behaviour and policy acceptance.

Another contribution is the multi-level policy implementation perspective applied to the Latvian situation. The Thesis connects national-level policy planning with municipal implementation and citizen response, demonstrating that road passenger transport decarbonisation is dependent on the coordination of policy instruments across governance levels, as well as the interaction of technological, behavioural, and institutional factors.

Practical relevance

The Doctoral Thesis' practical significance is associated with the potential to facilitate the selection, comparison, and implementation of effective decarbonisation policies for road passenger transport. The created framework allows for the prioritisation of technologies and policy instruments, the evaluation of the impact of individual and combined policy scenarios, and the connection of national, municipal, and individual-level activities to reduce transport emissions.

The results of the research can be used to compare different technologies and policy measures for decarbonising road passenger transport, considering not only the emission reduction potential but also costs, implementation complexity, infrastructure needs and public support.

The developed approach allows for the assessment of the potential impact of both individual policy measures and their combinations on reducing GHG emissions. This is particularly important because the decarbonisation of transport requires a coordinated set of measures rather than a single instrument.

The research results show how national-level policy objectives and regulations can be linked to local implementation options and citizens' mobility choices. This can help to reduce the gap between strategic goals and practically achievable emission reductions.

Incorporating behavioural factors and public support allows to assess which measures are not only theoretically effective but also practically feasible and acceptable to citizens.

Approbation of the research results

The results of the Doctoral Thesis have been presented at six international scientific conferences.

1. Kirsanovs, V., Barisa, A., **Safronova, A.** Cost-Benefit Assessment of Electric Vehicles vs Internal Combustion Engines in Latvia. *IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2020)*, Nov. 5-7, **2020**.
2. Barisa, A., Kirsanovs, V., **Safronova, A.** Renewable Transport Challenge: A Comprehensive Policy Assessment Model. *International Conference on Applied Energy*, Thailand/virtual, Nov. 29 – Dec 5, **2021**.
3. **Safronova, A.**, Barisa, A., Kirsanovs, V. Linking Sustainable Mobility Criteria to Policymaking: Results of Multi-Criteria Analysis. *EAI Mobility IoT 2021 – 8th EAI International Conference on Mobility, IoT and Smart Cities*, Dec. 10, **2021**.
4. **Safronova, A.**, Barisa, A., Kirsanovs, V. Incorporating User Behaviour into System Dynamics Modelling: A Case Study of Private vs Public Transport in Latvia. *International Scientific Conference of Environmental and Climate Technologies (CONNECT2022)*, Riga, Latvia, May 11–13, **2022**.
5. **Safronova, A.**, Barisa, A. Realizing a Green Hydrogen Economy: An Examination of Influencing Factors. *International Scientific Conference of Environmental and Climate Technologies (CONNECT2023)*, Riga, Latvia, May 10–12, **2023**.

6. **Safronova, A.**, Barisa, A., Volkova, A., Lepiksaar, K., Laht, J. Local-Level Challenges in Sustainable Mobility: Survey Results from the Baltic Sea Region. *International Scientific Conference of Environmental and Climate Technologies CONECT2025*, Riga, Latvia, May 14–16, **2025**.

The results of the Doctoral Thesis are published in nine connected scientific publications, all indexed in Scopus.

1. Barisa, A., Kirsanovs, V., **Safronova, A.** Future Transport Policy Designs for Biomethane Promotion: A System Dynamics Model. *Journal of Environmental Management*, **2020**, Vol. 269, pp. 110842. <https://doi.org/10.1016/j.jenvman.2020.110842>.
2. Kirsanovs, V. Barisa, A., **Safronova, A.** Cost-Benefit Assessment of Electric Vehicles vs. Internal Combustion Engines in Latvia. *IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2020)*, **2020**, pp. 9316610. <https://doi.org/10.1109/RTUCON51174.2020.9316610>.
3. **Safronova, A.**, Barisa, A., Kirsanovs, V. Linking Sustainable Mobility Criteria to Policymaking: Results of Multi-Criteria Analysis. *EAI Endorsed Transactions on Energy Web*, **2022**, Vol. 9 (39): e7 <https://doi.org/10.4108/ew.v9i39.1549>.
4. Barisa, A., Kirsanovs, V., **Safronova, A.** Renewable Transport Challenge: A Comprehensive Policy Assessment Model. *Energy Proceedings*, **2021**, Vol. 20, paper id 858. <https://doi.org/10.46855/energy-proceedings-9315>.
5. **Safronova, A.**, Barisa, A., Kirsanovs, V. (2022). Incorporating User Behaviour into System Dynamics Modelling: A Case Study of Private vs Public Transport in Latvia. *Environmental and Climate Technologies*, **2022**, Vol. 26, pp. 294–305. <https://doi.org/10.2478/rtuct-2022-0022>.
6. **Safronova, A.**, Barisa, A. Hydrogen Horizons: A Bibliometric Review of Trends in Diverse Emission Sectors. *Sustainability*, **2023**, Vol. 15 (19), pp. 14355. <https://doi.org/10.3390/su151914355>.
7. **Safronova, A.**, Barisa, A. Realizing a Green Hydrogen Economy: An Examination of Influencing Factors. *Environmental and Climate Technologies*, **2023**, Vol. 27, pp. 928–949. <https://doi.org/10.2478/rtuct-2023-0068>.
8. **Safronova, A.**, Barisa, A., Volkova, A., Lepiksaar, K., Laht, J. Local-Level Challenges in Sustainable Mobility: Survey Results from the Baltic Sea Region. *Environmental and Climate Technologies*, **2025**, Vol. 29 (1), pp. 987–1004. <https://doi.org/10.2478/rtuct-2025-0066>.
9. **Safronova, A.**, & Barisa, A. Climate Neutrality through Scenario Analysis: A Local Authority Perspective. *Journal of Environmental Management*, **2025**, Vol. 383, p. 125365. <https://doi.org/10.1016/j.jenvman.2025.125365>

Other publications

1. Kirsanovs, V., Romagnoli, F., Piščika, A., **Safronova, A.**, Feofilovs, M. Transportation Biofuels in Latvia: A Life Cycle Thinking Approach. *Environmental and Climate Technologies*, **2023**, Vol. 27, pp. 40–55. <https://doi.org/10.2478/rtuct-2023-0004>

In addition, one scientific monograph was prepared within the framework of the Doctoral Thesis.

1. D. Blumberga, J. Pubule, D. Lauka, V. Kosteviča, A. Kubule, I. Vamža, I. Luksta, Ģ. Bohvalovs, A. Safronova, A. Blumberga, K. Laktuka, D. Paule, R. Freimanis, and K. Rošā, *Klimatneitralitātes dimensijas*. Rīga, Latvija: RTU Izdevniecība, 2026. doi: 10.7250/9789934372681

Structure of the Thesis

The Doctoral Thesis focuses on road passenger transport, which is strongly influenced by challenges outlined in the introduction: the prevalence of private vehicles, an ageing vehicle fleet, and reliance on fossil fuels. This research investigates the potential solutions to these challenges by examining the decarbonisation of road passenger transport across three interconnected dimensions: technology transition, behavioural change, and policy measures. Together, these dimensions contribute to the assessment and are designed to mitigate GHG emissions in the transport sector.

Figure 1 illustrates the analytical framework of the PhD thesis. The middle of the picture represents the primary subject of the study – road passenger transport. The surrounding dimensions define the primary aspects of decarbonisation analysis: technological transition, behavioural change, and policy interventions, all contributing to the reduction of GHG emissions.

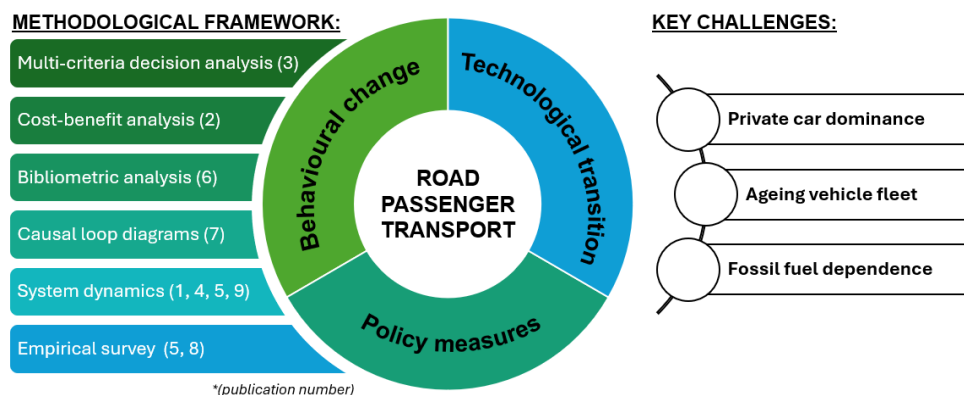


Fig. 1. Analytical framework for assessing road passenger transport decarbonisation (developed by the author).

The research methods used in the study are listed on the left side of the figure, with corresponding publication numbers indicating where these approaches are utilised. The methodologies encompass multi-criteria decision analysis, cost-benefit analysis, bibliometric analysis, causal loop diagrams, system dynamics modelling, and empirical surveys. The

publication numbers in brackets correspond to those in the approbation section, thereby linking the structure of the Thesis with the applied methods and scientific outputs. Overall, the figure shows how the Doctoral Thesis connects the challenges of decarbonising road passenger transport, the main analytical dimensions, and the research methods used.

The Doctoral Thesis is based on nine thematically connected publications. It consists of an introduction and five chapters:

- Literature review;
- Methodology;
- Results;
- Conclusions;
- Recommendations.

The introduction justifies the topicality and the aim of the Doctoral Thesis. The literature review provides insights on the concept of climate neutrality in the transport sector, current objectives in the transport sector of the EU and Latvia, the avoid-shift-improve framework, technological solutions for climate-neutral transport, the role of municipalities and citizen behaviour in decarbonisation. Additionally, it presents a literature analysis on the scenario analysis approach.

The methodology part summarises all the methods and indicators used to conduct the research. The methodology section discusses the study approaches, data gathering and analysis methods, and model creation and validation processes. It justifies the approaches used and describes how they help to achieve the Thesis' aims. The results section summarises the study's main findings and organises them by topic areas. It demonstrates how the findings address the research topics and help to provide better knowledge of effective emission reduction measures in the road passenger transport sector.

1. LITERATURE REVIEW

The literature review summarises the theoretical and policy context that forms the basis for research on the decarbonisation of passenger road transport. It examines the main aspects of climate neutrality in transport, sustainable mobility approaches, technological solutions, the role of local governments, citizen behaviour, and the importance of multi-level governance in implementing emission reduction measures.

The concept and importance of climate neutrality in the transport sector

The concept of climate neutrality assumes that the total amount of GHGs emitted by an entity (country, city, company, or individual) is balanced by the amount removed from the atmosphere, resulting in a net-zero impact on the climate [23]. This includes both reducing emissions generated and using carbon sinks, which allow the absorption of remaining emissions.

The transport sector is the second-largest final energy-consuming sector and a major source of emissions, accounting for more than 23 % of total global energy-related CO₂ emissions [1]. Road transport is the largest polluter in the transport sector, which together – cars, trucks, buses and two- and three-wheeled vehicles – accounts for almost three-quarters of global transport CO₂ emissions [6].

The European Climate Law sets the intermediate goal of lowering net GHG emissions by at least 55 % by 2030 in comparison to 1990 levels, while the European Green Deal seeks to reduce emissions by 90 % by 2050 by providing a smart, competitive, safe, accessible, and affordable transport system [24], [25]. The latest targets include increasing the use of renewable energy in transport to 29 % of final energy consumption in the transport sector by 2030 [26].

Transport decarbonisation is highly relevant for Latvia, as it faces several structural barriers. According to data from 2023, road transport accounts for 97 % of total transport sector emissions in Latvia [12]. The high share of emissions is associated with an ageing fossil-fuel-powered car fleet, high private car dependence and the low share of RES [27]. Thus, the problem lies not only in the high emission levels but also in the inertia of the existing structure, which hinders the decarbonisation of the sector. Overall, the Latvian case demonstrates the need for an approach that allows for assessing which measures can make a real contribution to emission reduction, considering both the conditions for implementing technologies and the development of mobility alternatives.

Avoid-shift-improve framework

The avoid-shift-improve (ASI) framework is widely used to structure policies aimed at reducing transportation-related emissions and developing sustainable transport. It emphasises three key strategies: avoiding unnecessary travel, encouraging a shift to more environmentally friendly modes of transport, and improving the effectiveness of current transport systems. Studies have shown that combining all of the mentioned strategies enhances their effectiveness [28], [29]. Furthermore, research highlights that effective policy design must consider the local context.

Although all three strategies are important, current energy and transport policies frequently fail to properly represent "avoid" policies, despite their potential [30], due to implementation complexities, societal resistance, and limited municipal control over land-use planning [31]. The goal of "avoid" policies is to reduce travel demand. They include changes in urban planning that make cities more compact and with more services close to home. The literature suggests that e-services and remote work, as well as other "avoid" policies, should be seen as complementary measures rather than separate solutions for decarbonising transport.

The following are examples of "shift"-type policies aimed at shifting commuters to more sustainable transport alternatives and include promotion of active mobility and wider public transport usage. This approach is significant because it cuts emissions not by fully eliminating travel, as "avoid" policies suggest, but by changing how daily needs are satisfied. The effectiveness of these policies, however, is determined by the local environment, which includes distances, population density, weather conditions, the quality of infrastructure maintenance, and residents' sense of safety [32]. Literature analysis also revealed that active mobility and micromobility initiatives are more effective when combined with modernised public transport and the creation of multimodal links, rather than as standalone solutions.

This highlights modernisation of public transport as a key component of transport decarbonisation, as it combines both technological improvements and a shift towards more sustainable modes of transport [33], [34]. Modernisation of public transport should therefore not be seen only as replacing the fleet. It also includes improving service quality, optimising routes and timetables, increasing accessibility, creating multimodal connections and using digital solutions [35]. However, the impact of such measures on reducing emissions depends not only on the technology used but also on the quality of service, the availability of infrastructure, the stability of financing, and the willingness of residents to change their travel habits.

Since it is impossible to completely abandon motorised vehicles, technological solutions are an essential component of the "improve" strategy in achieving climate neutrality in transport [28]. However, it is important to note that the effectiveness of technological solutions also depends largely on integration with policy and behavioural changes [36]. Without policy support, the market is unable to introduce new technologies on a significant scale [36]. At the same time, without behavioural changes, which include people's willingness to change habits and support innovations, even the best technologies cannot achieve the intended effect [37].

Technological solutions are an essential part of the decarbonisation of transport; however, each alternative energy type has a different role and suitability. Electric transport has significant potential to reduce transport emissions, but it is not a sufficient solution on its own, as its impact depends on the electricity generation structure, the availability of charging infrastructure, vehicle costs and policy support [38], [39]. In turn, the potential of hydrogen in Latvia at the current stage of development is mainly associated with those transport segments where direct electrification is more difficult, such as public transport, heavy transport, port or railway applications [40], [41]. Biomethane and other advanced renewable fuels can be considered as transitional solutions, as they allow for reducing GHG emissions and using existing

infrastructure while wider electrification and the use of green hydrogen are developed [42], [43].

The transition to alternative fuels is vital for achieving climate neutrality in the transport sector; however, according to the ASI approach, it is equally important to work on demand reduction, which in turn reduces the need for any type of fuel. Digitalisation and other smart mobility solutions can also help to optimise existing processes, thus improving efficiency and reducing emissions. In addition, such solutions can encourage behavioural change.

Municipal implementation and citizen behaviour in transport decarbonisation

Most research on decarbonising the transport sector focuses either on the national level, where general strategies and technology developments are studied, or on individual policies or technology development opportunities [36], [44], [45]. However, in reality, very important work is carried out at the municipal level, because it is at this level that decisions are made about infrastructure, changing mobility habits, as well as other support mechanisms for residents. Municipalities have a distinct advantage in being able to promptly address the issue of reducing GHG emissions, since they have significant control over decisions on land use, buildings, local transport, and waste management at the local level [46].

A sustainable transport system is one that minimises its negative effects on the environment and promotes social and economic well-being while offering basic access to transport and running in a fair, safe, and economical manner [47], [48]. This suggests that policymakers should consider economic, environmental, and social factors when developing policy frameworks. The potential of local governments suggests that to achieve climate neutrality goals, a two-pronged approach is required: top-down, where goals are set at the national level and support instruments are developed, and bottom-up, where local governments ensure the practical implementation of these goals through their actions and local solutions. Such an approach can ensure policy coherence between the national and local levels by identifying synergies and gaps between levels, resulting in increased efficiency.

Since there is no one-size-fits-all answer and policies must be customised to local needs to produce positive outcomes, it is crucial to account for unique local characteristics such as geography, demographics, and socioeconomic conditions [49], [50]. The effectiveness of a sustainable mobility policy is determined not only by the chosen measure but also by the local context in which it is implemented. In practice, these differences often manifest themselves in differences between urban, suburban and rural areas in terms of population density, access to services, transport infrastructure and mobility needs. These findings are particularly relevant in Latvia, where rural-urban disparities have a similar influence on the adoption of sustainable mobility alternatives.

Several barriers can limit the ability of municipalities to implement sustainable mobility measures. Financial resources have a significant impact on the decisions made by municipalities, while national funding often does not provide sufficient support for regional-level sustainable transport projects [51]. Cultural and political barriers can also exist, especially in cases where certain groups in society resist the introduction of new policy measures [52]. Therefore, coordination between stakeholders, inhabitants, and various decision-making levels,

sectors, and public sector agencies is crucial when creating and implementing sustainable urban transport strategies [53]. Institutional capacity and competence are also important barriers. A lack of a framework for carrying out long-term quantitative environmental evaluations and a lack of proficiency in identifying and characterising actions and objectives are two significant obstacles [54], [52]. It is frequently difficult to establish baselines, model the impact of potential policies, and track progress because municipalities lack accurate, detailed data on energy consumption, emissions, and local conditions [55]. This issue is also present in Latvian municipalities, characterised by limited data availability and insufficient technical capacity.

Besides knowledge, there are several other factors that need to be considered to change current behaviour patterns. Transport mode choice is influenced by costs, travel time, traffic jams, distance, comfort, availability, health and fitness, weather and season, safety, environmental awareness, and government policy and initiatives [56].

Overall, local governments play a key role in linking national climate goals with practical implementation at the local level. However, the contribution of local governments to transport decarbonisation depends on local circumstances, available financial resources, institutional capacity, data availability, stakeholder cooperation and public support. This justifies the need for local-level scenario assessment tools that allow comparing different policy combinations and identifying the most appropriate transport decarbonisation development directions for local conditions.

Stakeholder roles and multi-level interaction in transport decarbonisation

Decarbonising transport is a multi-level governance challenge that requires coordinated action by multiple stakeholders. The triple helix approach provides a useful starting point for analysing the interactions between government, industry, and academia, while its later extensions also highlight the importance of society and sustainability-oriented innovation [57]–[59]. In the context of decarbonising passenger road transport, the national level provides strategic direction, regulation, and support instruments; municipalities adapt and implement these measures at the local level, society determines their acceptability and practical implementation through everyday mobility choices, and industry and research provide the technologies, services, data, and knowledge needed for implementation [60]–[62].

2. METHODOLOGY

To test the hypothesis that an integrated analytical approach incorporating technological, behavioural and multi-level policy implementation factors provides a more comprehensive and realistic assessment of road passenger transport decarbonisation pathways than a technology-only assessment, the Thesis employed a combination of research methods. The methodological framework combines policy and technology prioritisation, economic assessment, bibliometric and system-based analysis, system dynamics modelling, municipal scenario modelling and an empirical citizen survey. The research framework was designed as an integrated multi-level approach, in which the decarbonisation of passenger road transport is analysed by linking national-level policies, municipal implementation capacity and citizens' mobility behaviour. Figure 2.1. describes the workflow of the study.

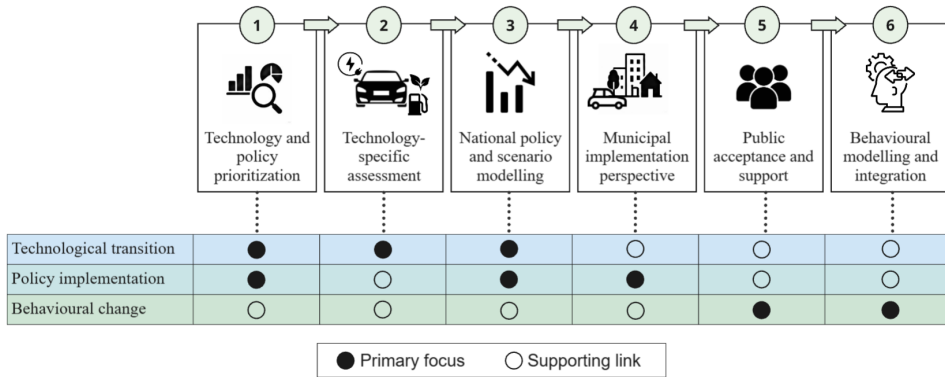


Fig. 2.1. Methodological structure of the integrated assessment framework.

The methods used were chosen to allow assessing of interrelated transition dimensions: technological development, policy effectiveness, local-level implementation and public acceptability. The research process was structured in six consecutive stages. In the first stage, transport decarbonisation policy and technology priorities were identified using multi-criteria decision analysis. In the second stage, individual technologies were evaluated in depth using cost-benefit analysis, bibliometric analysis and causal loop diagrams. In the third stage, national-level policy scenarios were analysed using a system dynamics model. In the fourth stage, the analysis was extended to the municipal level by developing a scenario-based transport emissions assessment model. In the fifth stage, mobility habits and support for transport policy measures were analysed using an international population survey. Finally, behavioural factors were integrated into system dynamics modelling to assess how changes in travel time and cost may affect the shift from private car to public transport.

2.1. Multi-criteria decision analysis

Multi-criteria analysis (MCDA) was used to prioritise transport policy instruments and alternative fuel technology analyses, considering economic, environmental, technological and social criteria. The TOPSIS method was chosen because it allows ranking alternatives based on their relative proximity to the ideal solution, both in terms of benefits and costs [63], [64]. This approach has also been widely used in transport research to assess sustainability, operational efficiency and policy alternatives [65]–[67].

The analysis was based on a survey of 19 experts representing research institutions, public administration, local governments, industry, associations and non-governmental organisations. The experts assessed 24 transport policy instruments and five alternative fuel or vehicle technologies important to Latvia: electric vehicles, natural gas vehicles, biomethane vehicles, biofuel vehicles, and hydrogen vehicles.

The policy instruments were selected based on a literature review and the experience of other countries. Countries with a high share of renewable energy resources in transport were analysed, including Sweden, Norway, Finland, the Netherlands and Austria, as well as the experience of the Baltic States and planned measures in Latvia. For the purpose of this Thesis, the selected policy measures were grouped into six categories: (1) support for rail and public transport; (2) support for biofuels and biomethane; (3) support for alternative fuel infrastructure; (4) support for the purchase of low- or zero-emission vehicles; (5) tax measures based on the polluter-pays principle; and (6) urban mobility measures that provide additional support for low- or zero-emission vehicles. The policy instruments were evaluated according to four criteria: the required investments, the complexity of monitoring, the potential to promote renewable energy resources, and public support. The necessary investments and the complexity of monitoring were defined as cost criteria, whereas the potential for promoting renewable energy resources and public support were defined as benefit criteria. Fuel and technology alternatives were evaluated according to social, environmental, technological and economic aspects. For the fuel/technology assessment, social benefit and technological maturity aspects were treated as benefit criteria, while environmental impact and economic cost were treated as cost criteria. Experts also determined the weights for the criteria, as well as for the assessment of policy instruments and fuels/technologies. The sum of criteria weights was equal to 1, and these weights were used to weight the decision matrix.

TOPSIS calculation was performed in MS Excel. First, a decision matrix was created from the experts' average ratings. Then the matrix was normalised, the expert-defined criteria weights were applied to it, ideal and negative-ideal solutions were determined, and the distance of each alternative to these solutions was calculated. Finally, the relative proximity of the alternatives was determined, according to which they were ranked.

The uncertainty of the expert assessments was addressed by analysing only the specified criteria, changing the main criteria weights, and proportionally recalculating the remaining criteria weights so they summed to 1. In addition, the dispersion of expert opinions was analysed, and the 95 % confidence interval was calculated, where a wider interval indicates

greater differences in expert assessments. The results of the MCDA/TOPSIS analysis are presented in Section 3.1.

2.2. Cost-benefit analysis

This study employed cost-benefit analysis to compare electric vehicles and internal combustion engine vehicles in Latvia from an economic and socio-environmental perspective. The method was chosen because it allows the assessment to include not only direct economic costs but also external costs, such as air pollution, GHG emissions and noise [68], [69]. At the time of the study, such a comparison was particularly relevant, given the growing policy interest in vehicle fleet electrification and the lack of Latvia-specific assessments that analysed the costs of vehicle use together with external environmental and social impacts.

The analysis compared both new and five-year-old petrol, diesel and electric vehicles. The study aimed to establish which vehicle type is most favourable from an economic and socio-environmental standpoint. The system boundary included the vehicle's production, purchase, operation and end-of-life or disposal. To ensure comparability, Volkswagen models of a similar class, comfort level and engine power were studied.

The following cost categories were included in the analysis: vehicle purchase price, fuel or electricity costs, maintenance and servicing costs, operating and registration taxes, parking costs, vehicle production emissions costs, end-of-life emissions costs, as well as external costs related to air pollution, climate change and noise. The cumulative costs were calculated for a 10-year operation period, assuming an annual vehicle mileage of 13 000 km.

The cost assessment included direct and external costs. Direct costs included car purchase, maintenance, fuel or electricity expenses, taxes, and fees. External costs included air pollution, GHG emissions, and noise. These costs were monetised using emission factors, vehicle activity data and external cost values for air pollution, and climate change impacts and noise. Although electric vehicles do not produce direct exhaust emissions during operation, emissions associated with electricity generation were included in the assessment.

Sensitivity analysis was conducted to assess how changes in annual mileage, fuel and electricity prices, and CO₂ price affect the total cumulative costs of the analysed vehicles.

Results of this study are presented in Subsection 3.2.1.

2.3. Bibliometric analysis

When studying any innovation technology, it is useful to understand the existing research trends in the area. It helps to identify knowledge gaps, avoid duplication of research that has already been done and increases understanding of what topics are gaining attention in the field. One approach that helps to examine large volumes of scientific publications to map research activity, collaboration networks, influential authors, and emerging themes is bibliometric analysis.

A bibliometric analysis of hydrogen technology development was used to provide a broader understanding of the dynamics of innovation and research directions that form the basis for the

decarbonisation options of the transport sector. The method was selected because it allows large volumes of scientific publications to be analysed to identify publication dynamics, thematic clusters and emerging research directions [70], [71].

The study aimed to determine, how the use of hydrogen in different sectors is linked to the achievement of the sustainable development goals (SDGs) and how sustainability is discussed in different sectors. The Scopus database was used for the analysis. Data selection was performed on 15 August 2023. Articles, review articles, and conference papers in English only were analysed, and the initial overall search covered publications from 1975 to 2023. Data were analysed using bibliometric performance indicators (publication dynamics, citations) and thematic mapping with VOSviewer software [72], [73].

The study considered hydrogen-related publications in six application sectors, namely energy, industry, transport, agriculture, commercial sector and residential sector. The publications were manually classified according to application sectors, and the frequency of hydrogen research linked to sustainable development goals and concepts such as green hydrogen, circular economy and climate neutrality was assessed. Comparison with other sectors was used to characterise the thematic focus and development maturity of hydrogen transport research, while the Doctoral Thesis focused on the transport sector.

The bibliometric analysis served as a background assessment for the development of hydrogen technologies and was complementary to a wider assessment of hydrogen as one of possible solutions for transport decarbonisation. The results of this study are given in Subsection 3.2.3.

2.4. Causal loop diagram

Causal loop diagrams are visual tools for depicting and examining the feedback structure of complex systems [74]. The primary goal of CLDs is to map out cause-and-effect linkages between system variables, emphasising how feedback loops influence system behaviour over time. CLDs use variables linked by arrows, incorporating polarities and delays, to create feedback loops that illustrate complex cause-and-effect relationships. Each connection signifies a direct causal relationship between variables, which may be positive (reinforcing) or negative (balancing). This method allows for a better understanding of complex systems and the interactions between their parameters, as well as assessing the impact of multiple variables on the system over time, which typical linear models sometimes overlook [75]–[77].

In this study, the CLD approach was employed to understand dynamic, multi-factor interactions and feedback loops of the hydrogen economy as well as to identify opportunities and risks to later guide successful technology adaptation. The methodology consisted of several parts. First, a literature analysis and desk research on hydrogen economy development factors were conducted. During the literature analysis, factors were identified that have been repeatedly mentioned in the literature as enabling or hindering the introduction of hydrogen, such as technology costs, infrastructure availability, intensity of policy support, investments, public acceptability, research and development activity, and demand for green hydrogen.

Five main factor groups were identified, including (1) hydrogen demand, (2) policy initiatives, (3) research and development, (4) economic factors, and (5) social component. Such grouping allowed structuring the development of the hydrogen economy as the interaction of several interconnected subsystems. In the first part, the stakeholders engaged in the hydrogen value chain development process, and their perceived barriers and needs were also identified. The literature selection ranged from 2003 to 2023; however, more than 66 % of the materials were published in the last five years, indicating that research in this field is becoming increasingly relevant.

Next, causal relationships were defined between the identified factors. The developed causal loop diagram is not a quantitative system dynamics model but a conceptual model that shows the main feedback mechanisms that influence the development of the green hydrogen economy. This method provided a comprehensive vision of how to improve hydrogen's position in the energy transition. The link between two variables was included in the diagram only if there was reason to believe in the literature or policy documents that changes in one factor affect changes in the other factor. Each link was assigned a polarity. A positive link meant that an increase in one variable causes an increase in the other variable, or in the case of a decrease, a decrease. A negative link meant that an increase in one variable causes a decrease in the other variable and vice versa.

In the third stage, the created causal structure was analysed to identify reinforcing and balancing feedback loops. Reinforcing loops were interpreted as mechanisms that can accelerate the development of the hydrogen economy, such as the interaction of demand, investment, installed capacity and cost reduction. In turn, balancing loops were interpreted as mechanisms that can limit or stabilise the development of the system, such as the interaction of policy pressure, implementation difficulties and public resistance.

In the last stage, the developed causal loop diagram was assessed from the point of view of logical consistency, assessing whether the links between the variables correspond to the relationships described in the literature and whether the identified loops can be interpreted in the context of the development of the hydrogen economy. Since the developed CLD is a conceptual model, it was not calibrated with quantitative data. Its main task was to reveal systemic interactions, possible development drivers and risks to be considered when planning the introduction of hydrogen technologies. Results of this study are presented in Subsection 3.2.3.

2.5. System dynamics modelling

System dynamics (SD) is a scientific approach where computer-based modelling and simulation are used to go beyond the system's structure and study how and why complex systems develop over time [78]. The structure of the model is intended to reflect a consistent description of the real system. Each closed chain of causality defines a feedback loop; numerous such links interact to form patterns of SD [79].

The system's structure and causal relationships are represented through variables, stocks and flows. Stocks represent the accumulation of some material or information, such as

emissions or population, over time, while flows describe how stocks change. System dynamics modelling is closely related to the causal loop diagram approach, since CLD allows identification of initial system interactions, which can later be translated into SD models for simulation and analysis of diverse industries and processes [80].

The transport sector is a common focus of SD research as this method allows long-term policy effects, technology diffusion, transport demand and emission changes to be analysed dynamically [81]–[84]. Within the Thesis framework, system dynamics was used in four separate studies, each focusing on a specific aspect of the problem: biomethane development potential, national-level policy scenarios, behavioural factors influencing transport mode choice, and municipal-level transport emission scenarios. The methodological Subsections 2.5.1–2.5.4 provide detailed descriptions of each of these applications.

2.5.1 ASSESSMENT OF THE POTENTIAL OF A BIOMETHANE APPLICATION

During the research phase, a SD model was created to examine the impact of transport policy on the promotion of biomethane use in the transport sector. Although biomethane has been used in transport for a long time in Europe, the technology has not been widely adopted in Latvia. When the study was published in 2020, Latvia had no use of biomethane in transport, and natural gas was also very limited. This was explained by political regulations regulating the use of biogas in electricity generation, a lack of demand, and technological constraints. The country lacked a comprehensive assessment of its biogas potential and of policy instruments aimed at increasing biomethane production and use in transport. Therefore, this study addressed the need to assess biogas potential and evaluate policy instruments aimed at increasing biomethane production and use in transport.

The research methodology is based on SD modelling principles and included transport fuel market evolution, subsidy policy scenarios, and emission targets. The model included several interrelated components: development of biomethane production capacity; dynamics of transport fuel demand (fossil fuels vs biomethane); the impact of subsidies and prices on market development; and modelling of CO₂ emission reduction.

The model was developed applying emission calculation methods, secondary data from Latvian statistics, and other modelling initiatives. The model was created using the Powersim Studio 10 modelling tool, using a one-year modelling time step.

The dynamic hypothesis of the presented model is that policies influence the profitability of biogas utilisation pathways and may redirect biogas toward biomethane use in transport. The model was based on three main sectors: resource supply, biogas and biomethane production, and transport demand. Feedstocks from agriculture, waste management and wastewater treatment were considered, while feedstock availability was treated as a limiting factor for biogas and biomethane production. The model also included capital costs, operational costs, feedstock costs and support mechanisms that could impact the economic attractiveness of different biogas utilisation options.

The biogas and biomethane production sector consisted of three possible biogas utilisation routes: biogas utilisation for combined heat and power production, biogas utilisation for direct heat production and biogas upgrading to biomethane. The choice between these alternatives

was modelled using a logit function based on the perceived profitability of each alternative. Changes in costs, revenues, and support schemes affected the distribution of investments, installed capacity and the amount of heat, electricity and biomethane produced. The comparison of biomethane supply and demand in the transport sector was performed using empirical equations based on historical data and GDP forecasts from the Ministry of Finance of the Republic of Latvia [85].

The model was validated by comparing market development projections with historical patterns and emission estimates with data from Latvia's National Inventory Document. After validation, a series of policy instruments and their combined effects were tested. Applied policies and modelling results are presented in Subsection 3.2.2.

2.5.2 NATIONAL POLICY ASSESSMENT MODEL

During this phase of the research, a comprehensive system dynamics model was created to evaluate the influence of various policy combinations on the adoption of renewable fuels in the transport sector. The model was developed based on a previously developed DTRem-LV model (Dynamic TRansport emission Model for Latvia) that projects carbon dioxide emission trends in the Latvian transport sector until 2030 and evaluates the emission-saving potential of a broad set of policy measures [86].

The new model was created using the Stella Architect simulation solution and consists of multiple interconnected sub-models, including those for fuel demand, renewable fuel generation, technological diffusion, and GHG emissions. The study's dynamic hypothesis is that a combined avoid-shift-improve policy approach can result in greater emission reductions because it reduces transport demand while also encouraging a shift to more sustainable modes of transport and increasing the share of alternative fuels and more efficient technologies than when the policy measures are implemented separately.

The research approach was divided into three stages. First, policy instruments for transport decarbonisation at the Latvian and EU levels were collated and classified by their type (regulatory, economic, informational) and purpose. Second, cause-and-effect diagrams and model structure were developed, using literature, expert assessments and available statistical data. The model considered the available volume of biofuels based on domestic feedstock potential, differentiated passenger and freight transport demand and evaluated the potential use of seven fuels: diesel, petrol, LPG, natural gas, biofuels, electricity and hydrogen. Third, 10 individual policy scenarios and policy combinations were assessed using the model to evaluate their effectiveness and mutual synergy in meeting the EU and Latvia's climate targets by 2030. Three main CO₂ reduction directions were considered in scenario runs following the “avoid-shift-improve” sustainable mobility concept.

The policy scenarios were structured as ten policy instruments: P1 – alternative fuel charging policy; P2 – alternative fuel vehicle purchase policy; P3 – alternative fuel information campaign policy; P4 – rail electrification policy; P5 – mode shift policy (passengers); P6 – mode shift policy (freight); P7 – biogas production and upgrading support policy; P8 – remote work and services policy; P9 – old vehicle scrappage scheme policy; P10 – fossil fuels tax policy. These policy instruments were used in the model as scenario assumptions in three avoid-

shift-improve policy directions. Each policy direction affected specific model parameters: transport demand, modal split, fleet technological structure, use of renewable fuels and vehicle energy efficiency.

The “avoid” policy package (P8, P10) included the development of remote working and e-services, as well as fossil fuel cost policies. The “shift” direction (P5, P6) included changes in the modal split of passenger and freight transport. In the case of passenger transport (P5), the scenario was interpreted as increasing the share of public transport from 21 % to 53 % of passenger-kilometres and increasing the share of cycling from 1 % to 5 %. In the case of freight transport (P6), a shift from road to rail was modelled. The “improve” direction of vehicle and fuel efficiency included policies P1, P2, P3, P4, P7, P9. This package was modelled mainly by increasing the share of alternative-fuel vehicles in the fleet to around 10 % and improving fuel economy by around 1 % per year. In the case of railway electrification and efficiency improvements, increasing the share of electric trains and improving the energy efficiency of rolling stock were tested, while fleet renewal measures were modelled by increasing the share of new vehicles in first-time registrations. The results were interpreted at the level of policy packages in the further analysis. The results Subsection 3.3.1 describes the policy scenarios studied and the simulation results.

2.5.3 USER BEHAVIOUR MODELLING VIA SYSTEM DYNAMICS

During this research phase, a system dynamics model was built that incorporates characteristics of individual behaviour in the choice of transport between private and public modes. The national policy assessment model represented residents’ behaviour in a simplified way, without detailed insight into the factors that directly affect changes in transport mode choice. Thus, the behaviour modelling module was developed to extend the existing DTRem-LV model with parameterised decision logic.

The dynamic hypothesis of the developed model is that mode shift from private cars to public transport does not depend on a single factor; isolated effects may overestimate the actual shift potential. The research consisted of three phases.

In the first (preparation) phase, a literature analysis focused on determining factors that affect transport choice was performed, and the initial concept of the SD model was developed. Eleven factors were identified: prestige of the transport mode, environmental concerns, the car is necessary for work duties, driving speed, safety, costs, possibility to carry passengers and luggage, infrastructure availability, ease of use, travel comfort, and travel time. The identified factors were used as a basis for developing survey questions and defining behavioural variables that could later be represented in a system dynamics model.

In the second (test) phase, a survey was prepared, and 350 respondents were surveyed in April – May 2021 to determine the weight of each of the eleven previously mentioned factors. The survey was distributed online on social networks and was available in Latvian and Russian to reach both Latvian- and Russian-speaking respondents. The aim of the survey was to obtain information from drivers about their willingness to switch to public transport. The survey included several thematic blocks: current travel habits, factors influencing transport mode

choice, time spent on the road, travel costs, public transport comfort, infrastructure availability, social and environmental attitudes, and socio-demographic characteristics of the respondents.

In the third (integration) phase, the obtained results were interpreted, and a new behaviour modelling module was created, which was later integrated into the whole transport system model for Latvia DTRem-LV [86]. The developed model further examined two of the five main factors influencing mode choice identified by the research, namely, travel time and cost. To better represent behavioural trends of different populations, the weights of the time and price factors were studied in three income groups: up to EUR 750 per household member; EUR 750–1500 per household member; and above EUR 1500 per household member. Additionally, trends by place of residence were incorporated, modelling responses from respondents in rural and urban areas independently.

The survey results were used not only as descriptive information but also as an empirical basis for developing model assumptions, including the creation of graphical functions characterising the impact of travel time and travel costs on the potential switch from private cars to public transport. Since the survey was distributed online and was not designed as a statistically representative sample of the Latvian population, its results should be interpreted as empirically based modelling assumptions, not as a representative assessment of the entire Latvian society.

The results of modelling are described in Subsection 3.4.2.

2.5.4 DEVELOPMENT OF A SCENARIO-BASED MUNICIPAL EMISSIONS MODEL USING SYSTEM DYNAMICS PRINCIPLES

One of the novelties of the Doctoral Thesis is an attempt to look at the potential for GHG emission reduction in the transport sector from the perspective of local planning. For this purpose, a new calculation and analysis model for scenario modelling based on system dynamics principles and a stock-flow structure was developed. The model was developed in *Stella Architect* software and was designed to assess the role of transport in the overall municipal GHG emissions balance, compare policy scenarios and support decision-making up to 2050. The transport model is part of a larger tool for estimating municipal emissions (including energy use in buildings, transport and public infrastructure; waste and wastewater management; local energy production).

In the initial phase of model development, a dynamic hypothesis was formulated, stating that emissions in the municipal transport sector are determined by the interaction of several linked factors: transport demand, changes in population and mobility habits, vehicle fleet structure, energy consumption, and the pace of policy implementation. Individual policy instruments were assumed to reduce emissions; however, their effectiveness varies over time and depends on whether they reduce travel demand, promote a shift to more sustainable transport modes, or improve vehicle and energy efficiency. As a result, the municipal emission reduction potential was assessed as a dynamic development trajectory until 2050, influenced by both initial input data and policy scenario combinations.

The model creation process is described in Fig. 2.2. It shows how the analysis of literature and policy instruments, assessment of municipal data availability, model formulation,

development of emission calculation logic, scenario building and case study testing were linked to feedback from target groups.

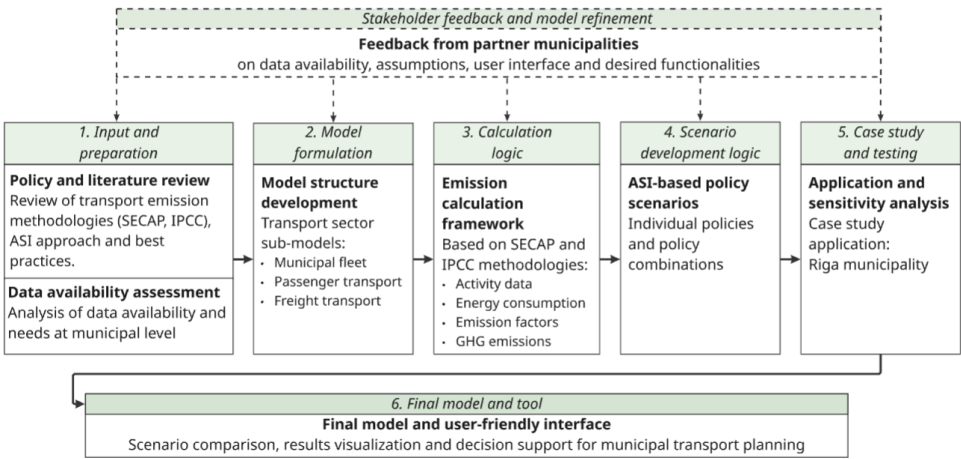


Fig. 2.2. Model development process for the municipal transport emission scenario modelling tool.

Target groups were involved in the formulation and refinement of the model. The municipalities involved in the study were Cēsis and Riga in Latvia, Palecznica and Raciechowice in Poland, and the Association of Lapland Municipalities in Sweden, representing the municipalities of Gällivare, Kiruna, Jokkmokk and Pajala. Municipal representatives provided comments on input data availability, model assumptions, user interface, desired functionalities and the way of displaying the results. This feedback was used to refine the model structure and, where possible, simplify the input data requirements.

The first phase of the model development involved a broad review of existing transport emissions and policy tools to determine the necessary system boundaries, parameters and their interactions. To evaluate the input data structure available to local governments, representatives from municipalities were consulted, and open data was analysed. This stage was crucial, as the model was intended to be a practical tool that could be adjusted to the actual data availability of local governments. Next, the model was developed in accordance with the specified requirements of local governments, with three distinct transport groups identified: (1) municipal fleet – where the municipality may provide more precise statistics on mileage, fuel consumption, and fleet structure; (2) passenger transport – which is dependent on population travel patterns, mobility demand, and vehicle option distribution; (3) freight transport – predicted with greater uncertainty due to low data availability but included to provide a more comprehensive emissions inventory.

The calculations included in the decision-support model are based on SECAP and Intergovernmental Panel on Climate Change (IPCC) methodologies, which are adapted to the input data of the municipalities. Transport emissions were calculated by linking transport activity and fuel or energy consumption with appropriate emission factors. Emission factors, energy content and fuel density were treated as calculation parameters rather than mandatory

municipal input data. If local values were unavailable, default values based on IPCC, SECAP or national GHG inventory methodologies could be used.

Then, policy effectiveness can be assessed using the ASI approach. Several policies were selected and defined (described in detail in Subsection 3.3.2), including “avoid” (A) strategies that promote remote work and e-services, optimising the municipal car fleet; “shift” (S) strategies that determined optimistic and moderately ambitious rates of replacement of private cars with public or active mobility; and “improve” (I) strategies that encouraged switching to more efficient vehicles, increased the use of renewable energy sources, and banned internal combustion engines. Several scenarios were developed (one for each ASI approach group, and a combined scenario) and their impact on emissions was assessed.

The model was designed as a general municipal-level scenario analysis tool, whereas Riga municipality data were used to test the model's application. Model calculations were based on demographic and migration data from the Riga municipality. A sensitivity analysis was also undertaken to determine the effect of specific input parameters (e.g., mobility intensity, migration changes, and number of passengers in cars) on the modelled emission results.

2.6. Methodology of the citizen survey on mobility behaviour and policy support

The survey was used in this study to include a citizen perspective in the analysis of transport policy and to assess how mobility habits, perceptions of municipal action, and policy acceptability can influence the implementation of sustainable transport solutions.

An international survey was carried out in four countries: Latvia, Estonia, Poland, and Sweden. The survey covered both national and municipal levels. In Latvia, the survey was conducted in Riga and Cēsis at the national level; in Estonia at the national level; in Sweden in four municipalities; and in Poland in the Pałecznicza municipality. In total, 1151 responses were received: 258 from Sweden, 500 from Estonia, 308 from Latvia, and 85 from Poland. The survey was conducted from December 2023 to January 2024.

The aim of the survey was to determine the current assessment of local authorities in the transport sector by residents, their travelling habits and the main factors influencing their choices. In addition, the level of support for various policies that correspond with the avoid-shift-improve (ASI) approach was also determined, setting priority directions.

The survey was distributed both online and in print. It had several sections, of which the first three were used in the analysis: (1) socio-demographic data, (2) mobility patterns, and (3) assessment of the municipality's actions in the transport sector and policy evaluation. The survey used several types of questions: single-choice questions, multiple-choice questions, rating scale questions, and open-ended questions.

Descriptive statistics were used to analyse the survey data. The analysis included calculation of the share distribution of responses for each question and comparison across countries, age groups, and types of residence. The analysis included travel habits, factors affecting the choice of transport mode, evaluation of the local transport policy and residents' support for various policy instruments. For policy support questions, each policy measure was classified according

to the ASI approach, and the share of respondents who supported the specific measure was calculated.

The results were not considered statistically representative for each country due to the uneven territorial coverage, various survey distribution channels, and a relatively small number of respondents in some areas. Instead, they offer a comparative perspective on the mobility patterns of the inhabitants of the chosen regions, their evaluation of the municipality's efforts, and the public's support for different transport policy initiatives. The full survey structure and more descriptive results are provided in the population survey report [87]. The results of the survey analysis are described in Subsection 3.4.1.

3. RESULTS

The stages of research development, as shown in Fig. 2.1, ensured a logical progression in the choice and application of methods. The results obtained in this Thesis are structured into thematic groups to emphasise the contribution of each publication to the study of a particular problem, rather than being based on the chronology of their creation.

3.1. Integrated assessment of policy and technology priorities

This section describes the research reported in the article “Linking Sustainable Mobility Criteria to Policymaking: Results of Multi-Criteria Analysis” (3), the methodology of which is described in Section 2.1. The MCDA study serves as a first step in prioritising future directions of action. It helps to understand which policy instruments and technologies are perceived by experts as most promising for further in-depth analysis.

3.1.1 ASSESSMENT OF POLICY INSTRUMENTS

24 policies were selected through a literature review and good practice examples from eight different countries. For the Thesis, these instruments were grouped into six thematic categories to support interpretation of the MCDA results. Table 3.1. summarises the policy instruments assessed in the study and their division into thematic groups.

Table 3.1

Grouping of Policy Instruments	
Policy group	Policy instrument
Tax incentives and exemptions	1A. Exemption from registration tax for zero-emission and low-emission vehicles.
	1B. Increase in registration tax for fossil fuel vehicles.
	2A. Exemption from operating tax for zero-emission and low-emission vehicles.
	2B. Increasing the operating tax on fossil fuel vehicles.
	3A. Reduction of excise duty on alternative fuels.
	3B. Increase in excise duty on fossil fuels.
	4. Tax incentives for zero-emission and low-emission vehicles owned by companies.
Purchase support	5A. Aid for the purchase of new zero-emission and low-emission vehicles.
	5B. Aid for the purchase of used (up to 8 years) zero-emission and low-emission vehicles.
	5C. Aid for the purchase of low-emission and zero-emission vehicles in public procurement.
Infrastructure support	6. Establishment of alternative fuel filling/charging station infrastructure.
	7. Support for the technical adaptation of vehicles to use alternative fuels.
	8. Development of bicycle infrastructure.
	9. Increasing the mandatory biofuel blend.
Biofuel/biomethane support	10A. Subsidisation of biofuel production, including biomethane.
	10B. Subsidising the capital costs of biofuel plants, including biomethane.
	10C. Facilitated conditions for biomethane injection into the natural gas grid.

Table 3.1 continued

	10D. Proofs of origin for biomethane.
	11A. Free parking for zero-emission and low-emission vehicles.
Urban mobility measures	11B. Permitting the use of public transport lanes for zero-emission and low-emission vehicles.
	12. Introduction of low-emission zones in cities to reduce car traffic.
	13. Electrification of the railway network.
Public transport and rail measures	14A. Renewal of the public transport fleet.
	14B. Reduction of the public transport ticket price.

Four criteria with expert weights were used in the assessment of policy instruments: required investment – 0.33, RES promotion potential – 0.25, public support – 0.23, and complexity of the monitoring mechanism – 0.19. Thus, the result reflects not only the potential of the measure to promote the use of RES in transport but also its costs, complexity of implementation and monitoring, and expected public support. Fig. 3.1 shows the results of relative closeness to the ideal solution for all policy instruments.

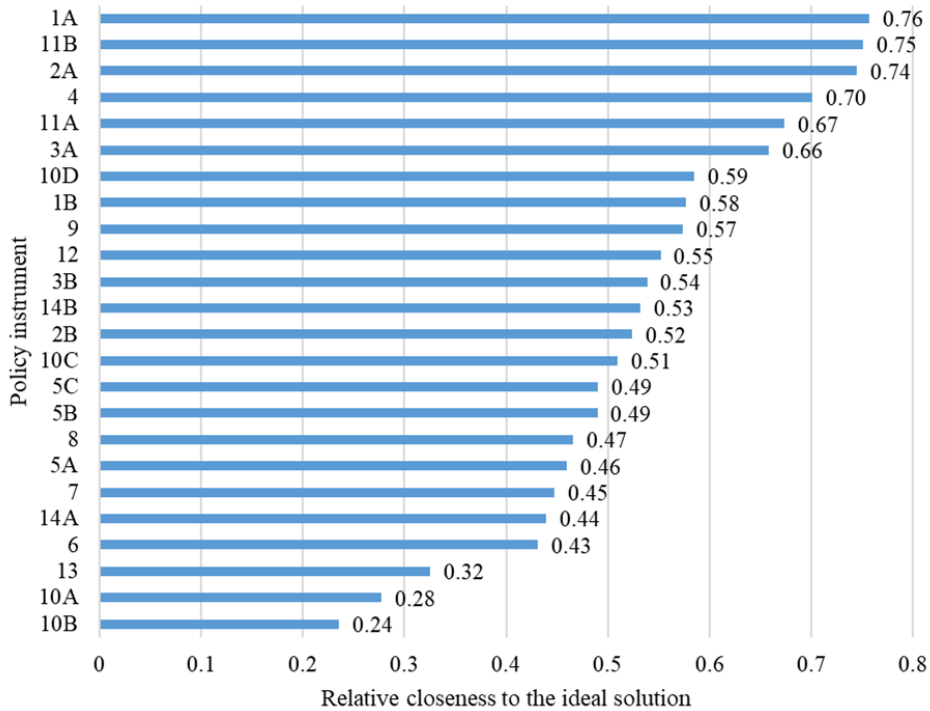


Fig. 3.1. Relative closeness to the ideal solution of policy instruments.

The highest TOPSIS proximity scores were obtained by exemption from registration tax for low- and zero-emission vehicles (1A; 0.76), permission to use public transport lanes for low- and zero-emission vehicles (11B; 0.75), exemption from operating tax for low- and zero-emission vehicles (2A; 0.74), tax incentives for company-owned low- and zero-emission

vehicles (4; 0.70), free parking for low- and zero-emission vehicles (11A; 0.67), and reduction of excise duty on alternative fuels (3A; 0.66).

The highest-rated policy instruments mainly fall into the tax incentives and urban mobility measures groups. This result is explained by the fact that these policies provide direct benefits to users of low- or zero-emission vehicles. The implementation of such measures also requires less investment than infrastructure development, modernisation of public transport or support for large-scale fuel production. Therefore, the highest score in the TOPSIS analysis should not be interpreted as a direct assessment of the emission reduction potential but rather as a combined indicator of the feasibility, acceptability and cost-effectiveness of the measures.

The group-level comparison confirms that the highest average TOPSIS proximity score was obtained for urban mobility measures and tax incentive measures. Lower average scores were obtained for the groups of purchase support, infrastructure support, biofuels and biomethane support, and public transport and rail measures. However, these results do not mean that the lower-ranked groups are less relevant for the decarbonisation of transport. Rather, their lower score reflects higher investment needs, more complex implementation or a higher monitoring burden.

The sensitivity analysis showed that the ratings of the policies vary significantly depending on the assigned weights. When the importance of required investments increased, policy instruments with lower implementation costs, such as tax incentives and urban mobility measures, became more favourable. In contrast, when greater importance was assigned to RES promotion potential, measures related to vehicle purchase support, infrastructure development and fuel-related support gained relative importance. Thus, it was noticed that some criteria have the opposite effect on the ranking of policy instruments. As a result, the findings should not be interpreted as a fixed hierarchy of policy importance but rather as a structured evaluation of the performance of various policy instruments based on expert-defined criteria.

Additionally, the dispersion of the weights assigned to the criteria by the experts was also analysed using 95 % confidence intervals. Wider confidence intervals indicate greater differences in expert opinions on the importance of the respective criterion. The highest weight was assigned to required investments, while the highest dispersion was observed for the monitoring mechanism criterion. This once again confirms that the obtained results should be interpreted as an expert-based prioritisation tool and not as an absolute assessment of policy effectiveness. Thus, the results show a trade-off between environmental potential, investment needs, monitoring feasibility and public support. Policy prioritisation in this case is not simply a question of which measure has the highest theoretical emission reduction potential but rather which measures are simultaneously feasible, socially acceptable and effective enough to be forwarded for further in-depth analysis.

3.1.2 ASSESSMENT OF FUEL AND TECHNOLOGY OPTIONS

After assessing policy instruments, the second part of the MCDA analysed alternative fuel and vehicle technologies to determine which technological directions, in the opinion of experts, are the most promising in the context of decarbonising Latvia's transport. The same experts had to evaluate five alternative fuels and vehicle technologies (hydrogen (H₂), biofuels (BIO),

biomethane (CBG), natural gas (CNG), electricity (EV)), evaluating each of the five proposed fuels according to social, environmental, economic and technological aspects. Four criteria with expert weights were used in the assessment of alternative fuels and vehicle technologies: social (impact on employment, welfare, health) – 0.22; economic (total costs) – 0.31; environmental (environmental impact) – 0.25; and technological (technology development potential) – 0.21. The experts' assessment is presented in Fig. 3.2.

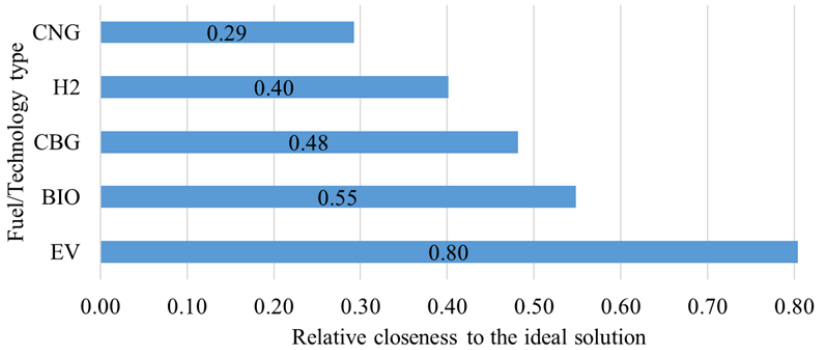


Fig. 3.2. Relative closeness to the ideal solution of each selected fuel type.

Electric vehicles received the highest ratings across all the options, particularly in terms of economic and environmental benefits. Biofuels and biomethane came next, with natural gas receiving the lowest grade, owing to its negative environmental impact. At the same time, the hydrogen assessment should be interpreted with caution. In the expert assessment, hydrogen received a relatively favourable score for the economic aspect. Such an assessment seems to contradict the market situation, where hydrogen technologies are usually characterised by high costs and limited infrastructure. This may indicate differences in how experts interpreted the economic criterion, possibly reflecting expectations about future cost reductions rather than current market conditions.

Sensitivity analysis revealed that the evaluation of technologies depends on the emphasis put on each criterion. When increasing the importance of environmental and technological criteria, electric vehicles kept a high rating, whereas hydrogen gained in favour. The change in the weight of the economic criterion also shifted the relative positions of individual alternatives, showing that cost assumptions were significant in the evaluation of technologies. However, the general trend was preserved – electric vehicles got the highest rating and natural gas stayed the lowest.

Additionally, the dispersion of the weights assigned to the criteria by the experts was also analysed using 95 % confidence intervals. Wider confidence intervals indicate greater differences in expert opinions on the importance of the respective criterion. The highest weight was assigned to the economic aspect, while the highest dispersion was observed for the social and technological aspects. Thus, the technology assessment shows that there is no one-size-fits-all solution for decarbonising transport. Electric vehicles were ranked as the most promising in the experts' view, but biofuels, biomethane and potentially hydrogen may play a role in specific segments or transition stages. At the same time, the results obtained should be interpreted as

expert-based prioritisation and not as a complete assessment of the economic or climate effectiveness of technologies.

3.2. Assessment of technological transition in transport decarbonisation

This section further describes the research related to the implementation of new technologies at the national level, i.e., Subsection 3.2.1 describes the results of the EV cost-benefit analysis; Subsection 3.2.2 describes the biomethane potential in Latvia determined using the SD model, and Subsection 3.2.3 describes the results related to the bibliometric study of hydrogen and the related causal loop diagram.

3.2.1 COST ASSESSMENT OF ELECTRIC VEHICLES

This subsection describes the research reported in the article “Cost-benefit assessment of electric vehicle vs internal combustion engine in Latvia” (2), the methodology of which is described in Section 2.2.

Although the development of the electric vehicle (EV) industry has been identified as one of the priority directions for the decarbonisation of the transport sector, despite its rapid development, at the time of the study there was still uncertainty about the true economic benefits of such vehicles if the full life cycle is considered. The cost-benefit analysis conducted looked at the costs of both new and used EVs and compared their costs with internal combustion engine (ICE) vehicles, considering not only economic but also social and environmental aspects.

For all vehicles analysed, the purchase cost accounted for a significant portion of the total cost; however, the differences between EV and ICE vehicles were most noticeable during the operational phase. Electric vehicles had significantly lower operational costs due to lower energy costs, taxes, and parking fees, as well as lower social and environmental costs. A comparison of operating costs revealed a significant difference between EVs and ICE vehicles. The annual operating costs of a new EV were around EUR 669, while those of a new diesel and petrol car were around EUR 1874 and EUR 2147, respectively. A similar pattern was observed for five-year-old vehicles: annual operating costs of an EV were around EUR 747, while diesel and petrol vehicles were around EUR 2154 and EUR 2289, respectively. As a result, the main advantage of an EV was identified during the operational phase rather than during the initial purchase.

At the same time, the findings indicate that the EV advantage is not linked to lower initial costs. In contrast, the purchase price of a new EV and the monetised emissions costs associated with production and disposal were higher than for ICE vehicles. This means that the cost advantage of EVs is only realised after a longer period of use, when lower operating costs compensate for the higher initial purchase price and higher production/disposal costs. This is also proven by the cumulative results over 10 years presented in Fig. 3.3.

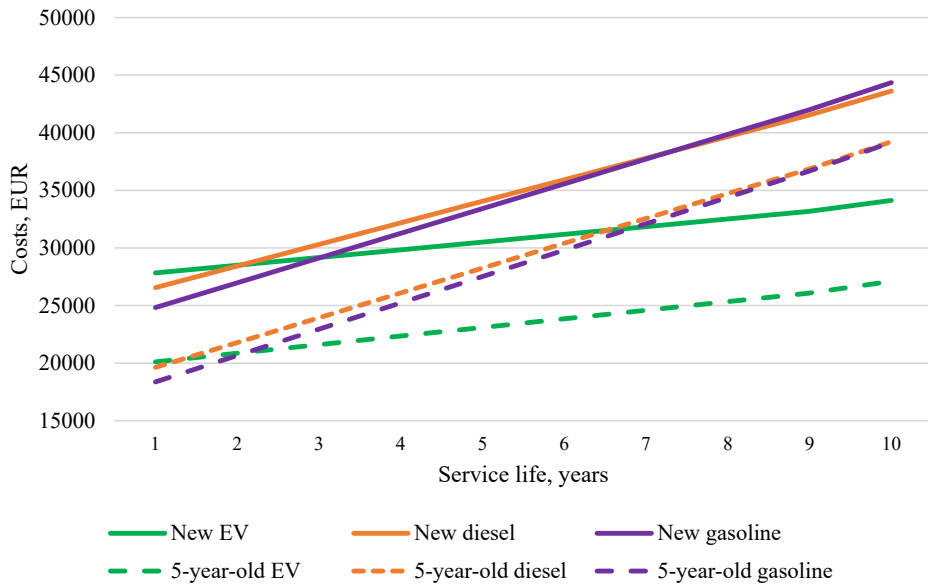


Fig. 3.3. Comparison of total calculated cumulative costs of different technologies.

Although the costs of both new and 5-year-old vehicles show that EVs are initially more expensive, calculations show that this changes over time. Overall, the costs of EVs were lower over the entire life cycle, even considering significantly higher disposal costs. Thus, a 5-year-old EV costs 22.3 % less than a 5-year-old diesel and 19.2 % less than a 5-year-old gasoline vehicle. Meanwhile, over 10 years, a new EV costs 27.8 % less than a new diesel car and 30 % less than a new gasoline car. This confirms that the higher purchase price of an EV is compensated for in the operating phase.

The sensitivity analysis examined the impact of changes in parameters such as mileage, fuel price and CO₂ price on the results. In all cases, increasing the importance of this parameter contributed to an increase in the total cost, but annual mileage was found to be the most sensitive factor influencing final cost. It was determined that the advantage of EVs over internal combustion engine vehicles increased with mileage. Meanwhile, rising fuel and CO₂ costs affect ICE vehicles more than EVs, so the relative advantage of EVs increases in such scenarios. Thus, as fossil fuel and CO₂ costs increased, the overall cost of ICE vehicles increased faster than the cost of EVs. This makes EVs even more advantageous in scenarios with higher fuel or carbon costs.

Overall, the obtained results are consistent with the literature analysis and create a foundation for integrated policy evaluation models. They not only indicate the potential and viability of EV use in the transport sector but also indicate the need to disseminate the obtained results to break stereotypes in the population that EVs are an expensive solution. It is necessary to highlight both the cost difference and other benefits of electric vehicles, such as lower noise and air emissions.

These results also complement the MCDA results, which assessed electric vehicles as the most promising technological direction. The CBA shows that the advantage of EVs is not only related to environmental considerations but can also be justified economically if operating costs and external costs are considered over a longer period. Therefore, EV support measures, such as purchase subsidies, tax breaks and the development of charging infrastructure, can be justified as transitional policy instruments that help overcome the high initial purchase costs.

3.2.2 BIOMETHANE PRODUCTION POTENTIAL AND TRANSPORT USE MODELLING

This subsection describes the research reported in the article “Future transport policy designs for biomethane promotion: A system Dynamics model” (1), the methodology of which is described in Subsection 2.5.1.

The baseline scenario reflects the development of the biogas sector if no further policy measures are implemented to promote biomethane production. The alternative scenarios were defined to answer the question of which policy measures are the most effective for increasing biogas use for upgrading. The model projects the speed of the shift from biogas use in CHPs (current situation) to biogas upgrading (desired situation) until 2030 under the proposed policy measures.

Policy instruments were grouped into three sub-categories: policies affecting biogas production costs (A); policies affecting biomethane production price (B); and policies affecting the final price of biomethane or natural gas (C), see Fig. 3.4. Each of the policy measures was tested individually and in combination with other instruments to evaluate its effect on the biomethane production price and the final market price of the biomethane.

A: Biogas promotion	B: Biomethane promotion	C: Fuel price
A1: Capital cost subsidy for biogas plants A1-1: at 20 % rate A1-2: at 40 % rate A2: Feedstock “subsidy” A2-1: at 20 % rate A2-2: at 40 % rate	B1: Capital cost subsidy for biomethane plants B1-1: at 20 % rate B1-2: at 40 % rate B2: Refueling infrastructure subsidy B2-1: at 20 % rate B2-2: at 40 % rate B3: Feed-in premium tariff B3-1: 15 EUR/MWh B3-2: 30 EUR/MWh	C1: 10 % annual excise tax increase for CNG C2: 100 % excise tax reduction for biomethane C3: VAT reduction for biomethane from 21 % to 12 %

Fig. 3.4. Summary of policy instruments tested in the model.

In addition to the policies described in Fig. 3.4, the F-EL (interruption of feed-in tariff for electricity) policy was also tested. Modelling results show that different trajectories are potentially achievable using different policy instrument combinations (Fig. 3.5).

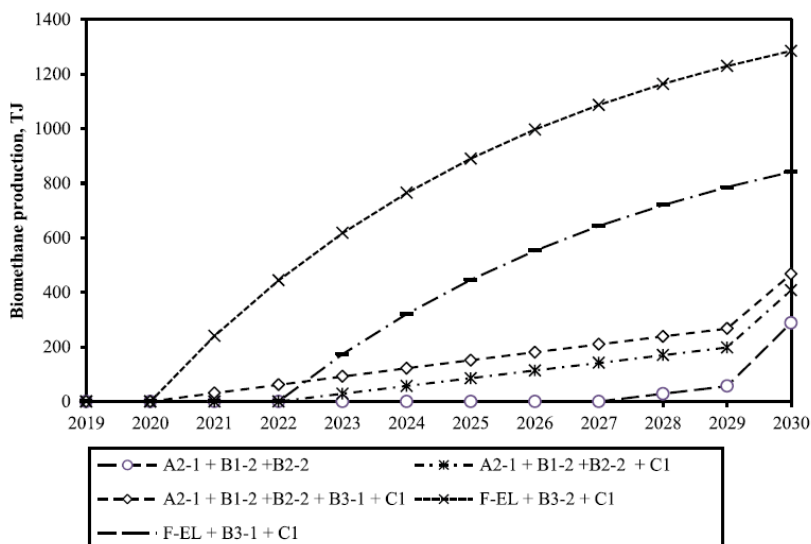


Fig. 3.5. The effect of a selection of combined policies on biomethane production.
(A breakdown of the policy instruments is available in Fig. 3.4).

One of the model's scenarios, F-EL + B3-1 + C1, envisages the simultaneous development of biomethane production technologies and the introduction of targeted support instruments, including the termination of the electricity purchase tariff, the establishment of a surcharge for biomethane, and an increased excise duty on natural gas. This scenario allows for a large rise in the use of advanced biofuels and biogas in the transport sector's energy consumption. Considering that such biofuels are double-counted towards the objective, the model's scenario F-EL + B3-1 + C1 would allow Latvia to satisfy its RED II obligations while simultaneously reducing GHG emissions and boosting biomethane market competitiveness.

The findings also indicate that the availability of bioresources exceeds current demand; thus, it is possible to increase the biomethane production capacity if new biogas plants are installed, and it is possible to produce around 250 mil. m³ of biogas with the existing availability of bioresources. Support mechanisms play an important role in the biomethane development, directly influencing its price competitiveness with fossil fuels. The biomethane market has limited potential without major legislative backing. Price subsidies enable biomethane to become competitive by about 2030 if fossil fuel costs remain steady. By combining price subsidies and an emission tax, we may achieve a quicker increase in biomethane penetration while significantly reducing emissions by 2030.

Overall, the modelling results show that the development of biomethane use in transport is limited not only by bioresource availability but mainly depends on policy design, market competitiveness and the combination of support instruments.

3.2.3 HYDROGEN DEVELOPMENT OPPORTUNITIES, BARRIERS AND RESEARCH TRENDS

This subsection presents the results of two publications that examined the potential of hydrogen. The EU identified hydrogen as an important solution for the decarbonisation of the EU transport sector, particularly in transport sectors that are often considered difficult to decarbonise, such as aviation and heavy road transport.

The hydrogen research trends reported in the article titled “Hydrogen Horizons: A Bibliometric Review of Trends in Diverse Emission Sectors” (6), follow the methodology described in Subsection 2.3. Bibliometric analysis showed a rapid increase in scientific interest in hydrogen sustainability. The number of publications increased more than 12-fold from 2011 to 2022, while over the past five years it increased from 54 publications in 2019 to 213 publications in 2022. This confirms that hydrogen is increasingly seen as one of the directions for decarbonising energy and transport.

Of all articles, the energy sector (such as hydrogen production, storage and grid integration) accounted for the largest share of research (57 %), followed by the industrial sector (17 %) and the transport sector (13 %), including hydrogen vehicles, shipping, aviation and other related fields. The transport sector had a higher citation rate, indicating innovation and significance, but having a smaller quantity share. Time trend analysis showed that recent research directions are increasingly related to decarbonisation, energy transition, green hydrogen and hydrogen storage. This is relevant in the context of transport decarbonisation, as the use of hydrogen in transport is closely dependent on the availability of renewable hydrogen, storage options and infrastructure development.

To gain insight into the stage of hydrogen development in the transport sector, the transport-specific co-occurrence analysis was performed. In the transport sector cluster, 221 publications were identified. The co-occurrence analysis of transport sector keywords showed that hydrogen research in transport is concentrated around several interconnected themes (see Fig. 3.6). The clusters not only include transport-specific keywords such as “fuel cells”, “vehicles”, “transportation”, and “alternative fuels”, but also broader system themes such as “hydrogen production”, “hydrogen storage”, “renewable energies”, “energy policy”, “costs”, “life cycle”, and “carbon dioxide”. This confirms that hydrogen in the transport sector is not studied in isolation as a separate vehicle technology but as part of a broader energy, infrastructure and policy system.

Additionally, sustainability is often discussed in hydrogen research, but the direct link to the SDGs is weak. The data showed that SDGs 7 (Affordable and Clean Energy), 13 (Climate Action), and 9 (Industry, Innovation, and Infrastructure) were most associated with publications, but SDGs 11 (Sustainable Cities) and 3 (Health and Well-Being) were less often referenced. This indicates that although hydrogen is often associated with sustainable development, its contribution to achieving specific SDGs in the transport sector has not yet been systematically assessed.

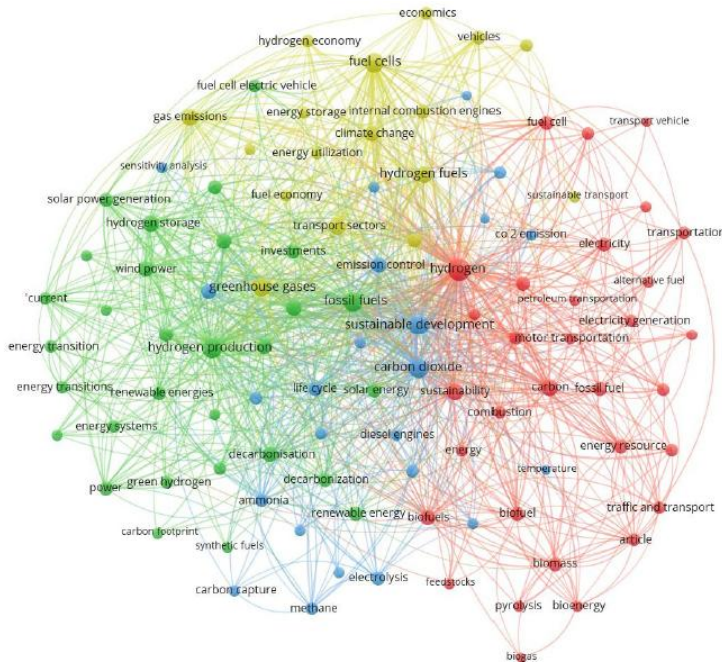


Fig. 3.6. Co-occurrence network generated by VOSviewer.

Overall, the bibliometric results show that hydrogen should be interpreted as a potential complementary solution for specific transport applications rather than as a universal solution for decarbonising road passenger transport. This result justifies the need to evaluate hydrogen not only in terms of its potential to reduce transport emissions but also in terms of system readiness. Namely, the availability of renewable hydrogen, storage options, refuelling infrastructure, costs, and coordinated policy support should also be assessed. Therefore, hydrogen is interpreted in this Thesis as a potential complementary solution for specific transport segments, rather than as a universal alternative for the decarbonisation of road passenger transport.

Further, the results reported in the article titled “Realising a Green Hydrogen Economy: An Examination of Influencing Factors” (7), the methodology of which is described in Section 2.4, revealed both the primary constraints to green hydrogen development and the main drivers. The research highlighted several aspects that influence the development of the hydrogen economy, including cost competitiveness, policy strength, R&D impact, and social acceptance.

The literature analysis showed that one of the most significant factors limiting the development of the hydrogen economy is cost competitiveness. The cost of green hydrogen is affected not only by the cost of production technologies but also by the price of electricity, capital investments in electrolyzers, storage and transportation costs, infrastructure availability, and competition with fossil hydrogen and other low-emission technologies [88], [89]. Therefore, the use of green hydrogen in many sectors is not yet economically competitive without policy support or targeted financial instruments [90].

The second important factor is the strength of the policy and the long-term policy framework. The literature emphasises that the implementation of hydrogen technologies requires clear national goals, strategies, standards, certification systems, infrastructure development mechanisms and support for demand generation [91], [92]. A stable policy framework reduces investor uncertainty and helps to create a market for technologies that are not yet competitive with existing solutions in the initial development stage [93], [94].

The third factor is the impact of research and development. R&D investments are essential for increasing technological maturity, reducing costs, implementing pilot projects, preparing human resources and building cooperation between the academic sector, businesses and public institutions [95], [96]. This factor is particularly important because the development of a hydrogen economy depends not only on a single technology but on a set of solutions along the entire value chain – production, storage, transportation, infrastructure and end-use technologies [97].

The fourth important factor is social acceptability. The adoption of hydrogen technologies can be hindered by public awareness, safety concerns, lack of trust and resistance to policy measures whose purpose or benefits are not sufficiently clear [95], [98], [99]. Therefore, the literature emphasises the importance of information campaigns, risk communication, safety standards and public engagement to promote trust in hydrogen technologies and reduce potential public resistance [100]–[102]. The literature review showed that the development of a green hydrogen economy is not determined by one dominant obstacle but by a set of several interrelated factors. Cost reduction, a stable policy framework, R&D support, and promotion of social acceptability are mutually reinforcing conditions that together can promote the development and deployment of hydrogen technologies.

Based on the literature review, a causal loop diagram was developed. The developed causal loop diagram depicts the drivers and inhibitors of hydrogen demand across five sectors: economy, policy, society, R&D, and demand (Fig. 3.7). The diagram also emphasises the importance of public policy as a driving factor in the system, impacting both cost reduction (e.g., through tax breaks) and societal acceptability.

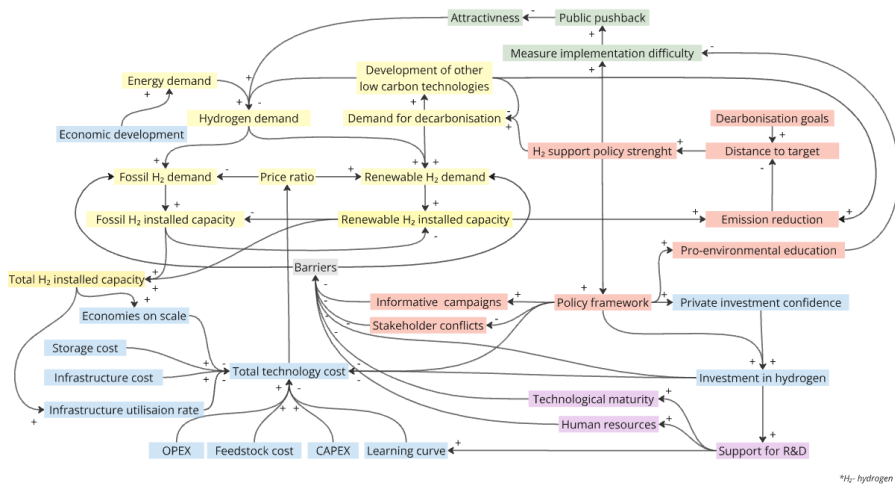


Fig. 3.7. Causal loop diagram of simplified system dynamics model structure.

(The parameters in the yellow, red, purple, blue, and green boxes are linked to hydrogen demand, policy, R&D, the economy, and the social component, respectively).

During the literature review, several feedback loops were identified. The capacity, economies of scale and cost reduction loop shows that increasing renewable hydrogen demand can promote installed capacity, economies of scale and cost reduction, thereby further increasing demand. The policy support, investment and cost reduction loop shows that stronger policy support can encourage investment, R&D and cost reduction, while emission reductions reduce the distance to decarbonisation targets and therefore the need for additional policy pressure. The public acceptance and policy feedback loop illustrates the risk that strong policy pressure can backfire if the implementation of measures is perceived as too difficult by the public or market participants. In turn, the public acceptance and education loop shows that information and environmental education can reduce public resistance and increase the attractiveness of hydrogen technologies.

In the causal loop diagram study, the impact of infrastructure availability on the development of the hydrogen economy was also examined. On the one hand, higher installed hydrogen capacity can improve infrastructure utilisation and support economies of scale, reducing total technology costs. On the other hand, the need for additional storage, distribution and refuelling infrastructure can increase infrastructure costs and slow down deployment if demand remains insufficient.

Furthermore, the results showed that the development of hydrogen is constrained by competition from other low-carbon technologies. In road passenger transport, this mainly concerns electric vehicles, which may be cheaper, more mature, and easier to deploy than hydrogen technologies. Therefore, hydrogen is more likely to play a role in specific niches or hard-to-electrify segments rather than as a universal transport decarbonisation solution.

Overall, the findings confirm that addressing the issues of technological immaturity and economic viability necessitates increased policy support, particularly through targeted national strategies, R&D investments, and cross-sectoral collaboration among the private, academic, and

public sectors. Thus, the constructed model serves as a foundation for future SD modelling and decision-making support in the implementation of hydrogen policy.

3.3. Transport emission scenario modelling at national and municipal levels

3.3.1 NATIONAL-LEVEL POLICY SCENARIO MODELLING IN LATVIA

This subsection describes the research reported in the article “Renewable Transport Challenge: A Comprehensive Policy Assessment Model” (4), the methodology of which is described in Subsection 2.5.2.

In this part of the research, a novel SD model for evaluating the impact of national transport and energy policy, with a focus on the incorporation of renewable energy, was created and verified. The model contains ten policy instruments that reflect the ASI approach, meaning three major strategies: travel reduction, modal shift, and efficiency improvement. After formulating and validating the baseline scenario with historical data, three policy packages were examined. The results of the policy modelling are described in Table 3.2.

Table 3.2

Modelling Results of Annual CO ₂ Saving Potential Compared to the Baseline		
Approach	CO ₂ savings, % compared to the baseline scenario	Policy measures
Reduce travel	5–8 %	P8, P10
Mode shift	Increased public transport share: < 5 %	P5, P6
	Increased cycling share: < 2 %	
	Mode shift in freight transport: 2–4 %	
Improve efficiency	Increased alternative fuel share up to 10 % of stock: 5–8 %	P1, P2, P3, P4, P7, P9
	Improved energy efficiency: 6 %	

Each policy was evaluated individually and in combination with other policies from the same strategy. The results obtained revealed that in the case of Latvia, the “avoid” strategies (P8, P10), which reduce the need to travel, result in CO₂ emissions savings of up to 8 % compared to the baseline scenario. The “improve” strategies (P1–P4, P7, P9), aimed at improving the energy efficiency of transport, achieve a similar result. In comparison, the “shift” strategies (P5, P6), which aim at shifting to more environmentally friendly modes of transport, result in smaller CO₂ emissions reductions compared to the “avoid” strategies, namely up to 5 % (compared to the baseline scenario). Then, an impact assessment of several strategy combinations was carried out, which showed that it is possible to achieve up to a 30 % decrease in emissions relative to the baseline scenario for 2030.

The developed model not only identifies possible emission reductions from the implementation of different policies but also enhances the existing knowledge base with innovations. Its “white-box” design ensures transparency and the discovery of feedback systems, allowing modelling of behavioural aspects (such as modal shift), estimating the net social costs and benefits of different measures, and identifying synergies and trade-offs among policy measures. The proposed model not only combines technological solutions with

regulatory provisions, which aim to reduce costs and increase the reduction of CO₂ emissions, but also integrates behavioural aspects into technological and economic modelling.

3.3.2 MUNICIPAL-LEVEL IMPLEMENTATION AND RIGA CASE STUDY

This Subsection describes the research reported in the article “Climate Neutrality through Scenario Analysis: A Local Authority Perspective” (9), the methodology of which is described in Subsection 2.5.4.

Within the framework of this study, a mathematical tool was developed for calculating transport emissions in municipalities. To validate the developed tool, a Riga city case study was conducted. Initially, all necessary data were collected for defining the baseline scenario. The obtained baseline scenario data are shown in Fig. 3.8.

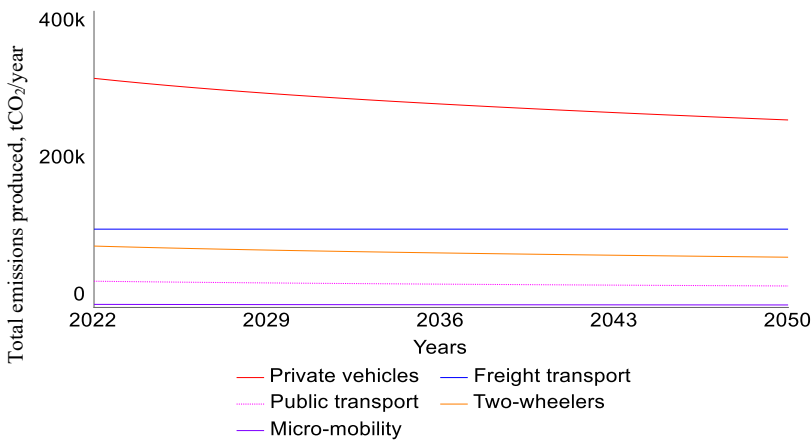


Fig. 3.8. Distribution of generated emissions by mode of transport in the baseline scenario (tCO₂/year).

The baseline scenario indicates the emission reduction by 2050. It was determined that the reduction in emissions achieved by the tool by 2050 is realised only through demographic changes (population reduction), rather than effective policy implementation. Throughout the modelling period, the private transport sector continues to emit the most emissions. This confirms that without additional policy measures, demographic change alone is not sufficient to substantially reduce municipal transport emissions.

As described in the literature analysis section, municipalities struggle with low capacity and a lack of data. Therefore, it was decided to perform a sensitivity analysis to reveal the influence of changes in key variables. Results showed that modest changes in key variables (for example, the number of trips, migration intensity, or the number of passengers in cars) might have a considerable impact on the final conclusions, underlining the need for higher-quality data at the municipal level.

Since freight is not the focus of the analysis, the Riga case study assumes that cargo transport emissions will stay constant in the baseline scenario due to historical stability, limited forecast data, and the need to simplify the model for easier comparison with policy scenarios.

The sensitivity analysis also showed that changes in freight transport demand, migration assumptions, travel intensity and car occupancy can significantly affect the modelled emission results. It revealed that the parameters under consideration can have a significant impact on the final results, emphasising the importance of collecting more precise data and making corrections when newer data becomes available.

To determine the impact on road passenger transport emissions, a total of 12 individual policy analysis simulations and 5 policy combination simulations were conducted. The analysed policies are described in Table 3.3.

Table 3.3

Description of Analysed Policies				
	Policies	Policy description	Policy type*	Policy start (S) / end (E)* year
Horizontal policies	H1	Internal combustion engine ban	I	S – 2035
	H2	Increasing the share of renewable fuels	I	S – 2030
	H3	Moderate mode shift policy	S	E – 2050
	H4	Optimistic mode shift policy	S	E – 2050
Municipality transport	M1	Moderate reduction of municipal transport mileage (by 10 %)	A	S – 2027
	M2	Optimistic reduction of municipal transport mileage (by 20 %)	A	S – 2027
Public transport	PU 1	Transition to more efficient vehicles	I	S – 2022
Private vehicles	PR 1	Transition to more efficient vehicles	I	S – 2022
	PR 2	Increase of average car occupancy rate by 2030	S	E – 2050
	PR 3	Increase of average car occupancy rate by 2050	S	E – 2050
Transport demand policies	TD1	Work-from-home policy	A	E – 2050
	TD2	E-services policy	A	E – 2050

*A – avoid; S – shift; I – improve.

**S (start year) – the year when the model starts using the described value; E (end year) – the year when the value has reached the described target value.

Only the emissions resulting from passenger transport are detailed in the baseline scenario, since it is assumed that the demand for freight transport stays constant and that specific policies that directly affect freight transport are not addressed. Figure 3.9 displays the outcomes for each policy.

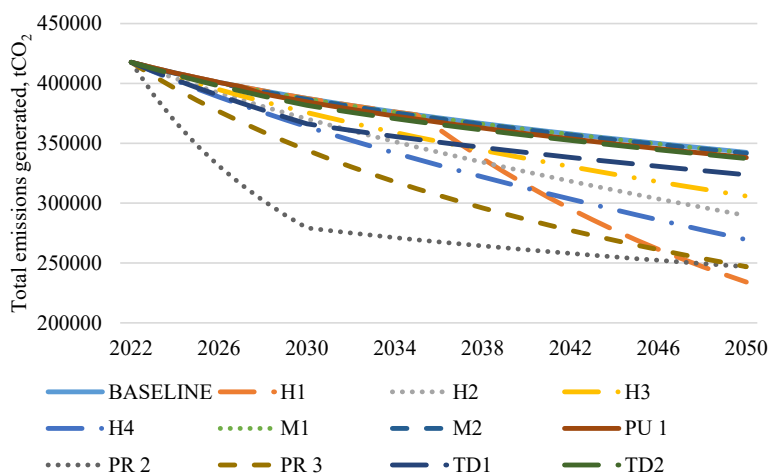


Fig. 3.9. Comparison of the impact of the developed policies on the amount of generated emissions (a transcript of the policy instruments is available in Table 3.3).

According to the analysis, the work-from-home policy (TD1), the decrease in municipal transport mileage (M1 and M2), and the switch to more efficient public transport vehicles (PU1) have the least impact. This is explained by the fact that only a small percentage of the emissions from the transport sector are addressed by these measures. Increasing the proportion of renewable fuels (H2), banning internal combustion engines (H1), and implementing an optimistic mode shift policy (H4) that applied to all mechanical transport modes were found to have the highest potential for reducing emissions. Since private vehicles are responsible for over half of all emissions in the baseline scenario, increased average car occupancy (PR2, PR3) also led to notable emission reductions.

To compare the impact of policies based on the ASI approach, four additional scenarios were established: avoid (TD1, TD2, M2); shift-moderate (H3, PR3); shift-optimistic (H4, PR2); improve (H1, H2, PU1, PR1). A hybrid of all policies was also investigated, which contained a combination of all policies (“avoid”, “shift (optimistic)”, “improve”).

The results of policy combinations are shown in Fig. 3.10.

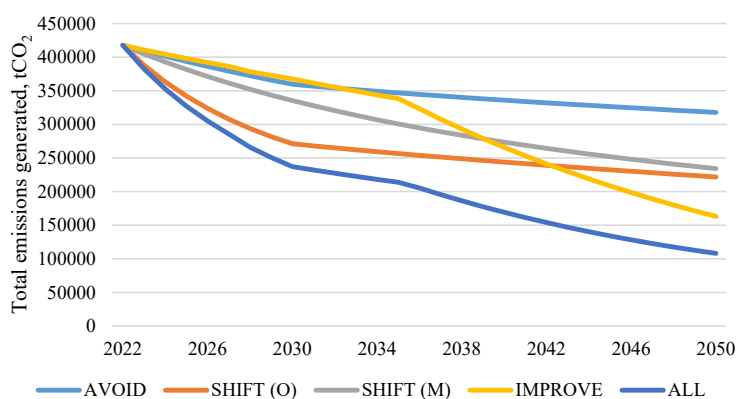


Fig. 3.10. Comparison of the impact of the developed policy combinations on the amount of generated emissions.

The obtained results indicate that “avoid” policies result in the lowest emissions reduction outcomes when compared to other policy combinations. This is explained by the fact that, while avoiding travel does not generate emissions in the transport sector, reducing travel demand is difficult to achieve in practice. “Shift” policies produced better emissions reductions, suggesting that even though the 2050 results in the optimistic and moderate scenarios are almost the same, accelerating the phase-out of private transport can result in larger cumulative emissions savings by that year. The ban on internal combustion engine vehicles in 2035 was the main factor behind the notable emission reductions due to “improve” policies.

The combined (all ASI approaches) scenario produces the best outcomes, with emissions reduced by up to 68 % relative to 2022. This is consistent with the literature review's conclusions and implies that to achieve the best outcomes, decision-makers need to implement a wide range of policies. However, the achieved emission reduction is insufficient to reach full climate neutrality by 2050, especially when freight transport is factored in.

Overall, the Riga case study shows that the decarbonisation of municipal transport requires a mix of “avoid”, “shift” and “improve” measures, and the largest reductions are achieved when technology-oriented policies are combined with measures influencing mobility behaviour. At the same time, the results indicate that scenario modelling at the municipal level is heavily dependent on data quality, particularly for assumptions regarding travel demand, migration, vehicle occupancy and freight transport.

3.4. Public acceptance and behavioural factors in transport decarbonisation

3.4.1 SURVEY RESULTS: PUBLIC ACCEPTANCE AND LOCAL-LEVEL MOBILITY PREFERENCES

This subsection describes the research reported in the article “Local-Level Challenges in Sustainable Mobility: Survey Results from the Baltic Sea Region” (8), the methodology of which is described in Subsection 2.6.

An international study was undertaken in four Baltic Sea countries – Latvia, Estonia, Sweden, and Poland – to analyse public behaviour, mobility patterns, and support for various sustainable mobility initiatives. The survey was carried out with 1151 respondents, and its findings showed several noteworthy conclusions.

Regarding existing travel patterns, it was discovered that private cars continue to be the most common transport mode in all countries, and that public transport is used less frequently in rural areas. This can be explained by the lower population density and the associated higher costs per user, which lead to the reduction of supply. Respondents also identified travel time, distance, comfort, and availability of infrastructure as the main factors impacting transport mode choice. Meanwhile, the impact on the environment and government policies were rated as insignificant influencing factors. This indicates that everyday practical considerations remain more important for residents' mobility choices than climate-related arguments alone.

Evaluation of local government activities in the transport sector found that residents' ratings were average. The greatest average rating was achieved in Estonia and Latvia (3.97 and 3.96 out of 7, respectively) and the lowest in Sweden (2.83). Urban residents rate the work of their local governments significantly higher than rural residents on average 4.17 versus 3.31.

Criticism of municipalities focused mainly on a deficient public transport system, inadequate pedestrian and bicycle infrastructure, and speed limit infractions. Residents from several rural areas showed worse ratings, which also highlights the lack of convenient private car alternatives in these regions.

To determine what could be done to improve the situation, residents were asked to choose their 3 most preferred transport policies. The policies that received the most support across all countries were: improving public transport (34 %); developing bike infrastructure (26 %); pedestrian-friendly urban planning (20 %); and promoting remote work opportunities (20 %).

When the proposed policies were divided according to the ASI framework, it was discovered that “shift” strategies (improving public transport and cycling infrastructure) received the most support across all countries. “Avoid”-type initiatives (remote work, pedestrian-friendly urban development) received widespread support, while “improve” policies (smart traffic management, emission zones, and levies) received significantly less support.

Overall, the results show that citizens are more supportive of the measures that improve access to services and mobility options than restrictive policy instruments. Younger respondents prefer digital and flexible solutions, while older respondents prefer accessibility, safety and ease of movement. The survey results were combined with a literature review to conclude that when implementing transport decarbonisation policies, it is important to consider citizens' perceptions, explain the benefits of the proposed measures and avoid overly strict restrictions without public support, as this can foster social resistance and hinder the achievement of transport decarbonisation goals.

3.4.2 BEHAVIOURAL FACTORS IN TRANSPORT MODE CHOICE MODELLING

This subsection describes the research reported in the article “Incorporating User Behaviour into System Dynamics Modelling: A Case Study of Private vs Public Transport in Latvia” (5), the methodology of which is described in Subsection 2.5.3.

To explore the attitude of private car users towards public transport in Latvia, a preference survey was carried out, which included 350 respondents. Results from the public survey performed in this research show that, similarly to previous studies, costs of the transport mode are considered important; however, many factors are rated higher, such as travel time and comfort, ease of use, infrastructure availability and the possibility to carry passengers and luggage. For the integration into the SD model, factors influencing travel mode choice from the survey were grouped, creating five major groups: (1) travel time, (2) cost, (3) infrastructure availability, (4) comfort, and (5) prestige.

To investigate the effect of the most popular factor (travel time) on mode shift from private cars to public transport, the effects of time and travel cost on mode shift from private cars to public transport were modelled in an SD model based on responses collected from the survey. The results showed that both time and cost factors would lead to an increase in public transport usage if considered separately. If travel cost was the only factor influencing transport mode choice, the public transport share would be much higher, increasing by 57.3 %. If only travel time was important, public transport usage would increase by 6.1 %. However, when both factors were modelled simultaneously, their combined effect was significantly lower, resulting in only a 0.6 % increase from the baseline scenario.

According to modelling results for the baseline scenario, it would be possible to achieve a public transport share of 75.3 % by 2030 with existing expenses if travel costs were the only significant factor. This highlights that the existing costs are acceptable to the majority, but people are not switching because of other reasons. In contrast, if travel time remained the same but was the only significant factor, the public transport share would rise to 24.1 % in 2030. When travel time and travel costs were considered simultaneously, modelling results showed that the share of people who are satisfied with both travel time and travel cost would be only 18.6 %, in the “both factors matter” scenario.

Then, scenarios with changes in travel time and cost were tested. In the case of travel time, the first scenario showed that if travel time was the only aspect that would be important, then getting travel time for public transport to be the same as private transport travel time would lead to an increase in public transport share for up to 76.8 % while 98.1 % of public transport share could be achieved by decreasing public transport’s travel time by half in comparison to private cars. However, such a scenario should be interpreted as a theoretical sensitivity test, not a practically directly achievable result, as the choice of mode of transport is influenced not only by travel time but also by cost, availability, comfort, habits and other factors.

More modest results were obtained when the “both factors matter” scenario was studied. The findings indicate that if travel time and costs are considered, achieving the same travel time for public transport as private transport would only result in a 27.1 % increase in the share of public transport, whereas a 40.1 % increase could be attained by cutting the travel time of public transport in half when compared to private vehicles. Similarly, increasing the monthly cost of

private car use resulted in a much smaller shift when both factors were considered than when the cost was analysed in isolation. Figure 3.11 shows the combined effect of travel time and cost on public transport share in 2030.

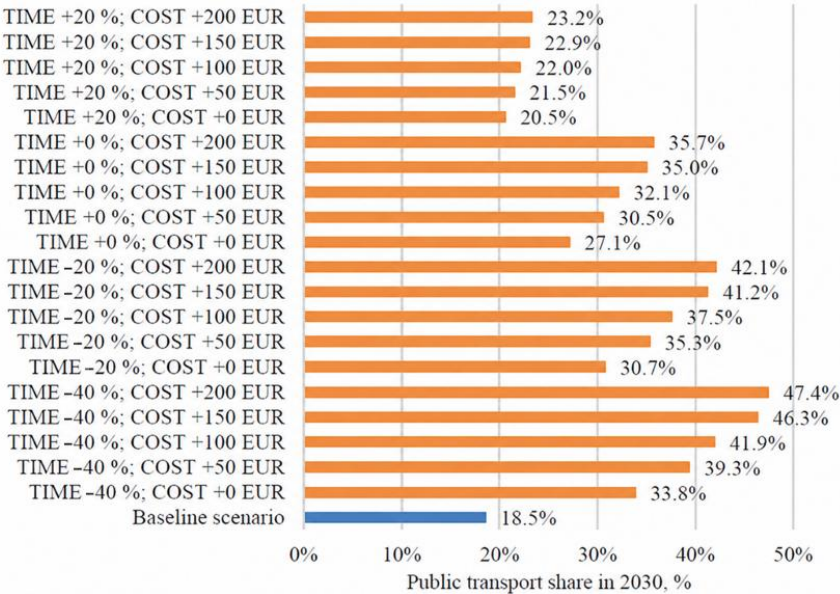


Fig. 3.11. The total effect on public transport share in 2030, “both factors matter” scenario.
 TIME – the difference in travel time between public and private transport. A positive value indicates that public transport is slower than private transport, whereas a negative value indicates that public transport becomes faster.
 COST – the increase in the cost of using a private passenger vehicle.

Testing of policy scenarios showed that similar results can be achieved with different policy combinations. For example, a reduction in public transport time and an increase in costs achieves a similar effect as cost increase alone. Such a multiplicity of results emphasises the need for a cost-effectiveness analysis to determine the optimal combination of policy measures.

Overall, the findings demonstrate that focusing policies on a single factor is incorrect, as the true benefit of policy implementation can only be obtained in the context of other influencing factors. This suggests that behaviour change is a multidimensional problem that needs to be approached with combined policies. The results also show that modelling behavioural change only through isolated assumptions may overestimate the potential shift from private cars to public transport.

CONCLUSIONS

The Doctoral Thesis confirms that the decarbonisation of road passenger transport cannot be reliably assessed by analysing technologies or policy measures in isolation. An integrated approach is needed that simultaneously considers technological transition, behavioural factors and coordinated policy implementation. The results of the Thesis can be summarised as follows.

1. The results showed that there is no single policy instrument that can achieve the decarbonisation of the road passenger transport sector. On the contrary, the Latvian case study showed that the best outcomes can be obtained using a combined ASI method. This indicated that achieving climate neutrality goals requires coordinated and mutually reinforcing policy packages that address demand reduction, modal shift, and improvement of trip efficiency.

2. The introduction of alternative fuels to the market largely depends on state commitment and regulatory support. The study showed that the biomethane market's growth is limited without extra political incentives, and that introducing hydrogen in the transport sector necessitates official backing for the country's broader hydrogen economy. Basing the development of alternative fuels solely on market mechanisms without additional support can significantly delay their introduction to the market.

3. Behavioural factors are very important and largely determine the effectiveness of policies. The empirical modelling results showed that fiscal mechanisms alone are insufficient to promote modal shift. They show that policymakers need to be aware of citizens' needs and ensure that the implementation of sustainable transport policies also considers other important factors influencing decision-making.

4. The Riga case study showed that local government initiatives can significantly reduce emissions. However, to achieve climate goals, these efforts might be insufficient without cooperation and national-level coordination.

5. The sensitivity analysis carried out in the Riga case study indicates that policy effectiveness largely depends on social factors. The study determined that changes in demographic and mobility indicators, such as migration intensity, trip frequency and vehicle occupancy, had a significant impact on the results. Such findings highlight the importance of data quality and inter-institutional coordination.

The study confirmed the proposed hypothesis that an integrated analytical approach incorporating technological, behavioural and multi-level policy implementation factors provides a more comprehensive and realistic assessment of road passenger transport decarbonisation pathways than a technology-only assessment. Applying this approach to transport sector planning shifts the perspective from a technology-availability focus to a system transformation perspective. In conclusion, the research demonstrated the importance of all levels in achieving sustainability in the transport sector: the national level is a key driver of innovation and the creator of the regulatory framework; the municipal level is an innovator and policy testing environment; and the social level is crucial for enabling behavioural innovation, which is just as important as technological innovation and requires trust and public participation in decision-making.

RECOMMENDATIONS

Based on the research conducted in this Doctoral Thesis and the results obtained, recommendations for policymakers were developed. They are presented below and are structured according to the three main dimensions – technological transition, behavioural change, and coordinated policy implementation – while considering cooperation needs between the national government, local government and individuals.

Recommendations for promoting technological transition

1. The development of electric transport should be supported as a medium-term priority, providing both support for vehicle acquisition and expansion of charging infrastructure. Although electric vehicles have higher initial costs, the results show that their use is economically justified over the long term.

2. The use of biomethane in transport should be promoted with long-term and predictable support mechanisms, including production support, tax breaks and investment subsidies. Support should be specifically directed at those transport segments that are more difficult to electrify, such as public transport, municipal fleets and logistics.

3. Hydrogen should be seen as a long-term complementary solution for specific transport segments, rather than as a universal alternative for the decarbonisation of passenger road transport. A national hydrogen development roadmap should be developed, setting out clear objectives, pilot projects, infrastructure priorities and support mechanisms.

4. Support for hydrogen development should include research and development funding, public-private partnerships and pilot projects. At the same time, public information activities are needed to reduce potential resistance and improve understanding of hydrogen technologies.

Recommendations for promoting behavioural change

5. Policies aimed at switching from private cars to public transport should not rely solely on price instruments. To promote a change in travel habits, public transport travel times, comfort, service quality, safety, accessibility, and infrastructure should be improved.

6. Measures that are of the “shift” type, such as improving public transport and cycling infrastructure, should be prioritised, as they have the greatest public support. At the same time, “avoid” type measures should also be promoted, including remote working and e-services, where they can reduce unnecessary travel demand.

7. Particular attention should be paid to rural areas where alternatives to the private car are more limited. In such areas, demand-driven public transport solutions and better connections to regional centres should be considered.

8. Restrictive or fiscal measures, such as low-emission zones, higher taxation of polluting vehicles or congestion charges, should be introduced gradually and only in combination with public consultations, information campaigns and practical alternatives to private car use.

Recommendations for a coordinated policy implementation

9. National and local transport policies need to be better aligned. National climate and transport targets should be translated into local investment priorities, while local authorities should be involved in the design of the measures they are expected to implement.

10. To avoid technological lock-in and adapt support instruments to changing market and technological conditions, dynamic policy evaluation should be used. Multi-criteria decision analysis or similar evaluation methods should be repeated every 3–5 years, involving state and local government representatives, industry, academia and society.

11. Public acceptability should be included in transport policy planning. Population surveys, stakeholder consultations and communication activities should be used to identify barriers, explain the benefits of the policy and reduce the risk of social resistance.

Recommendations for improving data, monitoring and further analysis

12. It is necessary to establish a unified transport data collection and monitoring system. It should include not only vehicle mileage and fuel consumption but also trip frequency, mobility habits, migration intensity, vehicle occupancy and public transport availability. Municipalities should regularly collect and update mobility data, and a national transport data platform could facilitate standardised data exchange and more reliable modelling.

REFERENCE LIST

- [1] S. Solaymani and J. Botero, 'Reducing Carbon Emissions from Transport Sector: Experience and Policy Design Considerations', *Sustainability*, vol. 17, no. 9, Art. no. 9, Jan. 2025, doi: 10.3390/su17093762.
- [2] European Commission, 'Final energy consumption in transport – detailed statistics'. Accessed: Oct. 19, 2025. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_transport_-_detailed_statistics.
- [3] European Environment Agency, 'Greenhouse gas emissions from transport in Europe'. Accessed: Aug. 12, 2025. [Online]. Available: <https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport>.
- [4] European Commission, *WHITE PAPER Roadmap to a Single European Transport Area – Towards a competitive and resource-efficient transport system*. 2011. Accessed: Oct. 19, 2025. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52011DC0144>
- [5] European Environment Agency, 'Share of energy from renewable sources'. Accessed: Sep. 28, 2025. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ren_custom_15120255/default/table?lang=en
- [6] I. Henke *et al.*, 'Fit for 2030? Possible scenarios of road transport demand, energy consumption and greenhouse gas emissions for Italy', *Transp. Policy*, vol. 159, pp. 67–82, Dec. 2024, doi: 10.1016/j.tranpol.2024.10.002.
- [7] N. Adamashvili and A. Thrassou, 'Towards Sustainable Decarbonization: Addressing Challenges in Electric Vehicle Adoption and Infrastructure Development', *Energies*, vol. 17, no. 21, Art. no. 21, Jan. 2024, doi: 10.3390/en17215443.
- [8] A. Jannesar Niri *et al.*, 'Sustainability challenges throughout the electric vehicle battery value chain', *Renew. Sustain. Energy Rev.*, vol. 191, p. 114176, Mar. 2024, doi: 10.1016/j.rser.2023.114176.
- [9] J. Li, L. Jin, H. Deng, and L. Yang, 'Review on Decarbonizing the Transportation Sector in China: Overview, Analysis, and Perspectives', Oct. 01, 2023, *arXiv*: arXiv:2310.00613. doi: 10.48550/arXiv.2310.00613.
- [10] N. V. Emodi, C. Okereke, F. I. Abam, O. E. Diemuodeke, K. Owebor, and U. A. Nnamani, 'Transport sector decarbonisation in the Global South: A systematic literature review', *Energy Strategy Rev.*, vol. 43, p. 100925, Sep. 2022, doi: 10.1016/j.esr.2022.100925.
- [11] S. Li, B. Wang, and H. Zhou, 'Decarbonizing passenger transportation in developing countries: Lessons and perspectives', *Reg. Sci. Urban Econ.*, vol. 107, p. 103977, Jul. 2024, doi: 10.1016/j.regsciurbeco.2024.103977.
- [12] Ministry for Climate and Energy of the Republic of Latvia, 'Latvia's National Inventory Document under the UNFCCC and Paris Agreement', Riga, 2025. [Online]. Available: <https://videscentrs.lv/gmc.lv/lapas/information-on-ghg-emissions-in-latvia>.
- [13] J. Savickis, L. Zemite, N. Zeltins, I. Bode, L. Jansons, 'Natural Gas and Biomethane in the European Road Transport: The Latvian Perspective', *Latv. J. Phys. Tech. Sci.*, vol. 57, no. 3, pp. 57–72, May 2020, doi: 10.2478/lpts-2020-0016.
- [14] I. Kulušić, L. Jukić, I. Smajla, and D. Karasalihović Sedlar, 'The Role of Natural Gas in the Socio-Technical Transition to a Carbon-Neutral Society and a Review of the European Union's Framework', *Sustainability*, vol. 16, no. 9, p. 3791, Jan. 2024, doi: 10.3390/su16093791.
- [15] A. Scedrovs and M. Feofilovs, 'Selection of Criteria for Load Analysis on Electrical Grid in the Context of Transport Electrification in Latvia', *CONNECT Int. Sci. Conf. Environ. Clim. Technol.*, pp. 55–55, May 2025, doi: 10.7250/CONNECT.2025.027.
- [16] L. Rozentale, G. B. Mo, A. Gravelins, C. Rochas, J. Pubule, and D. Blumberga, 'System Dynamics Modelling of Railway Electrification in Latvia', *Environ. Clim. Technol.*, vol. 24, no. 2, pp. 247–257, Sep. 2020, doi: 10.2478/rtuect-2020-0070.
- [17] T. Teoh, O. Kunze, C.-C. Teo, and Y. D. Wong, 'Decarbonisation of Urban Freight Transport Using Electric Vehicles and Opportunity Charging', *Sustainability*, vol. 10, no. 9, p. 3258, Sep. 2018, doi: 10.3390/su10093258.
- [18] J. Brizga, M. Jurušs, and B. Šmite-Roķe, 'Impact of the environmental taxes on reduction of emission from transport in Latvia', *Post-Communist Econ.*, vol. 34, no. 5, pp. 666–683, Jul. 2022, doi: 10.1080/14631377.2021.1965358.
- [19] A. Barisa and M. Rosa, 'Scenario analysis of CO2 emission reduction potential in road transport sector in Latvia', *Energy Procedia*, vol. 147, pp. 86–95, Aug. 2018, doi: 10.1016/j.egypro.2018.07.036.

- [20] G. Valdmānis, M. Drobins, and G. Bazbauers, 'Use of Synthetic Fuels Derived from Green Hydrogen and CO₂ in Heavy-duty and Long-range Transport: the Case of Latvia', *CONNECT Int. Sci. Conf. Environ. Clim. Technol.*, pp. 74–74, May 2023, doi: 10.7250/CONNECT.2023.053.
- [21] A. Backurs, L. Zemīte, A. Laizans, I. Bode, A. Starikovs, L. Vempere, 'Towards Sustainable Transport: Evaluating Potential of Hydrogen Fuel Cell Buses and Trucks in Latvia'. Accessed: Oct. 19, 2025. [Online]. Available: <https://ieeexplore.ieee.org/document/10412884>
- [22] J. Kleperis *et al.*, 'Analysis of the Role of the Latvian Natural Gas Network for the use of Future Energy Systems: Hydrogen from Res', *Latv. J. Phys. Tech. Sci.*, vol. 58, no. 3, pp. 214–226, Jun. 2021, doi: 10.2478/lpts-2021-0027.
- [23] J. M. Chen, 'Carbon neutrality: Toward a sustainable future', *The Innovation*, vol. 2, no. 3, p. 100127, Jun. 2021, doi: 10.1016/j.xinn.2021.100127.
- [24] European Commission, 'The European Green Deal'. Accessed: Nov. 03, 2023. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
- [25] European Parliament and the Council, *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')*, vol. 243. 2021. Accessed: Aug. 18, 2025. [Online]. Available: <http://data.europa.eu/eli/reg/2021/1119/oj/eng>
- [26] International Council on Clean Transportation, 'Provisions for transport fuels in the European Union's finalized "Fit for 55" package', Accessed: Sep. 28, 2025. [Online]. Available: <https://theicct.org/publication/fuels-fit-for-55-red-iii-jul23/>
- [27] Cabinet of Ministers of the Republic of Latvia, 'Aktualizētais Nacionālais enerģētikas un klimata plāns 2021.–2030. gadam', LIKUMI.LV. Accessed: Aug. 18, 2025. [Online]. Available: <https://likumi.lv/doc.php?id=353615>
- [28] R. Zhang and T. Hanaoka, 'Cross-cutting scenarios and strategies for designing decarbonization pathways in the transport sector toward carbon neutrality', *Nat. Commun.*, vol. 13, no. 1, p. 3629, Jun. 2022, doi: 10.1038/s41467-022-31354-9.
- [29] M. Arnz *et al.*, 'Avoid, Shift or Improve passenger transport? Impacts on the energy system', *Energy Strategy Rev.*, vol. 52, p. 101302, Mar. 2024, doi: 10.1016/j.esr.2024.101302.
- [30] M. Jarre, M. Noussan, and E. Campisi, 'Avoid–Shift–Improve: Are Demand Reduction Strategies Under-Represented in Current Energy Policies?', *Energies*, vol. 17, no. 19, Art. no. 19, Jan. 2024, doi: 10.3390/en17194955.
- [31] C. Holz-Rau and J. Scheiner, 'Land-use and transport planning – A field of complex cause-impact relationships. Thoughts on transport growth, greenhouse gas emissions and the built environment', *Transp. Policy*, vol. 74, pp. 127–137, Feb. 2019, doi: 10.1016/j.tranpol.2018.12.004.
- [32] D. Ton, D. C. Duives, O. Cats, S. Hoogendoorn-Lanser, and S. P. Hoogendoorn, 'Cycling or walking? Determinants of mode choice in the Netherlands', *Transp. Res. Part Policy Pract.*, vol. 123, pp. 7–23, May 2019, doi: 10.1016/j.tra.2018.08.023.
- [33] A. Vasconcelos, M. C. Coelho, and J. M. Bandeira, 'A Case Study on Peri-Urban Public Transport Optimisation From an Energy and Environmental Perspective', *IET Intell. Transp. Syst.*, vol. 19, no. 1, p. e70035, 2025, doi: 10.1049/itr2.70035.
- [34] N. Akram, W. Chen, K. Tariq, H. Linjun, and L. Zhaosheng, 'Role of Public Transportation in Reducing Traffic Congestion, Enhancing Connectivity, And Promoting Sustainable Urban Development in Manchester And Shenzhen', *Int. J. Soc. Sci. Humanit. Invent.*, vol. 12, no. 01, pp. 8401–8408, Jan. 2025, doi: 10.18535/ijsshi/v12i01.01.
- [35] E. Sogbe, S. Susilawati, and T. C. Pin, 'Scaling up public transport usage: a systematic literature review of service quality, satisfaction and attitude towards bus transport systems in developing countries', *Public Transp.*, vol. 17, no. 1, pp. 1–44, Mar. 2025, doi: 10.1007/s12469-024-00367-6.
- [36] S. Speizer *et al.*, 'Integrated assessment modeling of a zero-emissions global transportation sector', *Nat. Commun.*, vol. 15, no. 1, p. 4439, May 2024, doi: 10.1038/s41467-024-48424-9.
- [37] A. Dugan, J. Mayer, A. Thaller, G. Bachner, and K. W. Steininger, 'Developing policy packages for low-carbon passenger transport: A mixed methods analysis of trade-offs and synergies', *Ecol. Econ.*, vol. 193, p. 107304, Mar. 2022, doi: 10.1016/j.ecolecon.2021.107304.
- [38] R. Zaino, V. Ahmed, A. M. Alhammadi, and M. Alghoush, 'Electric Vehicle Adoption: A Comprehensive Systematic Review of Technological, Environmental, Organizational and Policy Impacts', *World Electr. Veh. J.*, vol. 15, no. 8, p. 375, Aug. 2024, doi: 10.3390/wevj15080375.
- [39] J. A. Fuinhas *et al.*, 'Effect of Battery Electric Vehicles on Greenhouse Gas Emissions in 29 European Union Countries', *Sustainability*, vol. 13, no. 24, p. 13611, Jan. 2021, doi: 10.3390/su132413611.
- [40] W. Loengbudnark, K. Khalilpour, G. Bharathy, F. Taghikhah, and A. Voinov, 'Battery and hydrogen-based electric vehicle adoption: A survey of Australian consumers' perspective', *Case Stud. Transp. Policy*, vol. 10, no. 4, pp. 2451–2463, Dec. 2022, doi: 10.1016/j.cstp.2022.11.007.

- [41] D. De Wolf and Y. Smeers, 'Comparison of Battery Electric Vehicles and Fuel Cell Vehicles', *World Electr. Veh. J.*, vol. 14, no. 9, p. 262, Sep. 2023, doi: 10.3390/wevj14090262.
- [42] M. Repele, L. Udrene, and G. Bazbauers, 'Support Mechanisms for Biomethane Production and Supply', *Energy Procedia*, vol. 113, pp. 304–310, May 2017, doi: 10.1016/j.egypro.2017.04.070.
- [43] E. S. Maté, C. Garcia, P. M. Ramos, and E. M. Calvo, 'Natural Gas as a Gateway for Renewable Gas in Transport', in *Sustainable Mobility*, IntechOpen, 2020. doi: 10.5772/intechopen.91344.
- [44] Y. Briand *et al.*, 'Passenger transport decarbonization in emerging economies: policy lessons from modelling long-term deep decarbonization pathways', *Clim. Policy*, vol. 0, no. 0, pp. 1–21, doi: 10.1080/14693062.2023.2194859.
- [45] J. Lefèvre *et al.*, 'A pathway design framework for sectoral deep decarbonization: the case of passenger transportation', *Clim. Policy*, vol. 21, no. 1, pp. 93–106, Jan. 2021, doi: 10.1080/14693062.2020.1804817.
- [46] Ocean WISE Research Institute, 'Ocean Watch Howe Sound Edition 2020 Executive Summary: Overview and Future Directions'. [Online]. Available: <https://oceanorg.blob.core.windows.net/oceanorg/2023/08/Ocean-Watch-Howe-Sound-Edition-2020.pdf>
- [47] D. Bamwesigye and P. Hlavackova, 'Analysis of Sustainable Transport for Smart Cities', *Sustainability*, vol. 11, no. 7, Art. no. 7, Jan. 2019, doi: 10.3390/su11072140.
- [48] F. Jelti, Allouhi, Amine, and Aoul, Kheira Anissa Tabet, 'Transition Paths towards a Sustainable Transportation System: A Literature Review', *Sustainability*, vol. 15, no. 21, p. 15457, 2023, doi: <https://doi.org/10.3390/su152115457>.
- [49] T. Bon, M. Bruno, and N. van Oort, 'Three-dimensional transport poverty and its socio-demographic and urban density predictors: Spatial regression analyses of neighborhoods in the Amsterdam metropolitan area', *Transp. Res. Interdiscip. Perspect.*, vol. 29, p. 101340, Jan. 2025, doi: 10.1016/j.trip.2025.101340.
- [50] M. Thondoo, O. Marquet, S. Márquez, and M. J. Nieuwenhuisen, 'Small cities, big needs: Urban transport planning in cities of developing countries', *J. Transp. Health*, vol. 19, p. 100944, Dec. 2020, doi: 10.1016/j.jth.2020.100944.
- [51] X. Liu, M. Dijk, and C. Colombo, 'Improving multilevel policy mixes for sustainable urban mobility transition', *Environ. Innov. Soc. Transit.*, vol. 50, p. 100808, Mar. 2024, doi: 10.1016/j.eist.2023.100808.
- [52] D. M. Papadakis, A. Savvides, A. Michael, and A. Michopoulos, 'Advancing sustainable urban mobility: insights from best practices and case studies', *Fuel Commun.*, vol. 20, p. 100125, Sep. 2024, doi: 10.1016/j.fuenco.2024.100125.
- [53] J. Carvalho, J. P. de Sousa, and R. Macário, 'Sustainable urban mobility planning at the metropolitan scale: a review of current practices and narratives', *Transp. Res. Procedia*, vol. 72, pp. 4175–4182, Jan. 2023, doi: 10.1016/j.trpro.2023.11.357.
- [54] J. Baltazar, G. Bouillass, F. Vallet, J. Puchinger, and N. Perry, 'Integrating environmental issues into the design of mobility plans: Insights from French practices', *Transp. Policy*, vol. 155, pp. 1–14, Sep. 2024, doi: 10.1016/j.tranpol.2024.06.019.
- [55] D. Di Battista *et al.*, 'The Reporting of Sustainable Energy Action Plans of Municipalities: Methodology and Results of Case Studies from the Abruzzo Region', *Energies*, vol. 14, no. 18, p. 5932, Jan. 2021, doi: 10.3390/en14185932.
- [56] A. Javaid, F. Creutzig, and S. Bamberg, 'Determinants of low-carbon transport mode adoption: systematic review of reviews', *Environ. Res. Lett.*, vol. 15, no. 10, p. 103002, Sep. 2020, doi: 10.1088/1748-9326/aba032.
- [57] H. Etzkowitz, 'The Triple Helix of University–Industry–Government', 2002, [Online]. Available: https://www.donorth.co/appurtenancy/pdfs/etzkowitz_triple_helix.pdf
- [58] S. Cvetanović, A. A. Panić, and S. Vukadinovic, 'Media and culture-based public in the quadruple helix innovation model', *BizInfo Blace*, vol. 16, no. 1, pp. 115–122, Apr. 2025, doi: 10.71159/bizinfo250013C.
- [59] E. G. Carayannis, T. D. Barth, and D. F. Campbell, 'The Quintuple Helix innovation model: global warming as a challenge and driver for innovation', *J. Innov. Entrep.*, vol. 1, no. 1, p. 2, Aug. 2012, doi: 10.1186/2192-5372-1-2.
- [60] L. V. Lerman, W. Gerstlberger, M. Ferreira Lima, and A. G. Frank, 'How governments, universities, and companies contribute to renewable energy development? A municipal innovation policy perspective of the triple helix', *Energy Res. Soc. Sci.*, vol. 71, p. 101854, Jan. 2021, doi: 10.1016/j.erss.2020.101854.
- [61] E. Eneqvist, J. Algehed, C. Jensen, and A. Karvonen, 'Legitimacy in municipal experimental governance: questioning the public good in urban innovation practices', *Eur. Plan. Stud.*, vol. 30, no. 8, pp. 1596–1614, Aug. 2022, doi: 10.1080/09654313.2021.2015749.
- [62] S. James, Z. Liu, G. R. T. White, and A. Samuel, 'Introducing ethical theory to the triple helix model: Supererogatory acts in crisis innovation', *Technovation*, vol. 126, p. 102832, Aug. 2023, doi: 10.1016/j.technovation.2023.102832.
- [63] Bystrzanowska, M. and Tobiszewski, M., 'How can analysts use multicriteria decision analysis?', vol. 105, 2018, doi: 10.1016/j.trac.2018.05.003.

- [64] C.-L. Hwang and K. Yoon, *Multiple Attribute Decision Making: Methods and Applications : a State-of-the-art Survey*. Springer-Verlag, 1981.
- [65] B. Djordjević and E. Krmac, 'Evaluation of Energy-Environment Efficiency of European Transport Sectors: Non-Radial DEA and TOPSIS Approach', *Energies*, vol. 12, no. 15, p. 2907, Jan. 2019, doi: 10.3390/en12152907.
- [66] I. Siksnyte-Butkiene and D. Streimikiene, 'Sustainable Development of Road Transport in the EU: Multi-Criteria Analysis of Countries' Achievements', *Energies*, vol. 15, no. 21, p. 8291, Jan. 2022, doi: 10.3390/en15218291.
- [67] S. Goyal, S. Agarwal, N. S. S. Singh, T. Mathur, and N. Mathur, 'Analysis of Hybrid MCDM Methods for the Performance Assessment and Ranking Public Transport Sector: A Case Study', *Sustainability*, vol. 14, no. 22, p. 15110, Jan. 2022, doi: 10.3390/su142215110.
- [68] A. Chaianong, C. Pharino, S. Langkau, P. Limthongkul, and N. Kunanusont, 'Pathways for enhancing sustainable mobility in emerging markets: Cost-benefit analysis and policy recommendations for recycling of electric-vehicle batteries in Thailand', *Sustain. Prod. Consum.*, vol. 47, pp. 1–16, Jun. 2024, doi: 10.1016/j.spc.2024.03.025.
- [69] Q. Qiao *et al.*, 'Life cycle cost and GHG emission benefits of electric vehicles in China', *Transp. Res. Part Transp. Environ.*, vol. 86, p. 102418, Sep. 2020, doi: 10.1016/j.trd.2020.102418.
- [70] P. Kut, K. Pietrucha-Urbanik, and M. Zelenáková, 'Assessing the Role of Hydrogen in Sustainable Energy Futures: A Comprehensive Bibliometric Analysis of Research and International Collaborations in Energy and Environmental Engineering', *Energies*, vol. 17, no. 8, p. 1862, Jan. 2024, doi: 10.3390/en17081862.
- [71] A. del Bosque, P. Fernández-Arias, and D. Vergara, 'Advancements in Hydrogen Storage Vessels: A Bibliometric Analysis', *Sci*, vol. 7, no. 1, p. 21, Mar. 2025, doi: 10.3390/sci7010021.
- [72] N. J. Van Eck and L. Waltman, 'Bibliometric mapping of the computational intelligence field', *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.*, vol. 15, no. 05, pp. 625–645, Oct. 2007, doi: 10.1142/S02184885070004911.
- [73] N. J. van Eck, L. Waltman, E. C. M. Noyons, and R. K. Buter, 'Automatic term identification for bibliometric mapping', *Scientometrics*, vol. 82, no. 3, pp. 581–596, Mar. 2010, doi: 10.1007/s11192-010-0173-0.
- [74] M. Schaffernicht, 'Causal loop diagrams between structure and behaviour: A critical analysis of the relationship between polarity, behaviour and events', *Syst. Res. Behav. Sci.*, vol. 27, no. 6, pp. 653–666, 2010, doi: 10.1002/sres.1018.
- [75] J. F. Uleman, K. Stronks, H. Rutter, O. A. Arah, and N. H. Rod, 'Mapping complex public health problems with causal loop diagrams', *Int. J. Epidemiol.*, vol. 53, no. 4, p. dyae091, Aug. 2024, doi: 10.1093/ije/dyae091.
- [76] H. Roubik, J. Mazancová, J. Rydval, and R. Kvasnička, 'Uncovering the dynamic complexity of the development of small-scale biogas technology through causal loops', *Renew. Energy*, vol. 149, pp. 235–243, Apr. 2020, doi: 10.1016/j.renene.2019.12.019.
- [77] F. C. Rust, L. R. Sampson, A. A. Cachia, B. M. Verhaeghe, H. S. Fourie, and M. A. Smit, 'Use of causal loop diagrams to assess future drivers and trends in South African transport', *J. Transp. Supply Chain Manag.*, vol. 17, p. 13, Nov. 2023, doi: 10.4102/jtscm.v17i0.958.
- [78] A. Blumberga, *Sistēmdinamika vides inženierzinātņu studentiem*. Rīga: RTU Vides aizsardzības un siltuma sistēmu institūts, 2010.
- [79] J. Randers, 'Elements of the System Dynamics Method', *J. Oper. Res. Soc.*, Nov. 1997, doi: 10.1057/PALGRAVE.JORS.2600456.
- [80] Thomas Binder, A. Vox, S. Belyazid, and H. V. Haraldsson, 'Developing System Dynamics Models From Causal Loop Diagrams', Proceedings of the 22nd International Conference of the System Dynamics Society. Accessed: Aug. 03, 2025. [Online]. Available: https://proceedings.systemdynamics.org/2004/SDS_2004/PAPERS/249BINDE.pdf
- [81] A. Watabe, J. Leaver, H. Ishida, and E. Shafiei, 'Impact of low emissions vehicles on reducing greenhouse gas emissions in Japan', *Energy Policy*, vol. 130, pp. 227–242, Jul. 2019, doi: 10.1016/j.enpol.2019.03.057.
- [82] J. J. Gómez Vilchez and P. Jochem, 'Simulating vehicle fleet composition: A review of system dynamics models', *Renew. Sustain. Energy Rev.*, vol. 115, p. 109367, Nov. 2019, doi: 10.1016/j.rser.2019.109367.
- [83] D. Keles, M. Wietschel, D. Möst, and O. Rentz, 'Market penetration of fuel cell vehicles – Analysis based on agent behaviour', *Int. J. Hydrog. Energy*, vol. 33, no. 16, pp. 4444–4455, Aug. 2008, doi: 10.1016/j.ijhydene.2008.04.061.
- [84] G. Pasaoglu, G. Harrison, L. Jones, A. Hill, A. Beaudet, and C. Thiel, 'A system dynamics based market agent model simulating future powertrain technology transition: Scenarios in the EU light duty vehicle road transport sector', *Technol. Forecast. Soc. Change*, vol. 104, pp. 133–146, Mar. 2016, doi: 10.1016/j.techfore.2015.11.028.

- [85] Ministry of Finance of the Republic of Latvia, 'Tautsaimniecības un budžeta izpildes analīze | Finanšu ministrija'. Accessed: Nov. 04, 2025. [Online]. Available: <https://www.fm.gov.lv/tautsaimniecibas-un-budzeta-izpildes-analize>
- [86] A. Barisa and M. Rosa, 'A system dynamics model for CO2 emission mitigation policy design in road transport sector', *Energy Procedia*, vol. 147, pp. 419–427, Aug. 2018, doi: 10.1016/j.egypro.2018.07.112.
- [87] Riga Technical University, Institute of Energy Systems and Environment, 'CommitClimate Citizen Survey', Interreg Baltic Sea Region Programme project CommitClimate – Towards Energy Transition and Climate Neutrality in the BSR Municipalities, 2024. [Online]. Available: https://br-commitclimate.rtu.lv/wp-content/uploads/CITIZEN_survey_report-1-1.pdf
- [88] J. A. Gordon, N. Balta-Ozkan, and S. A. Nabavi, 'Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions', *Appl. Energy*, vol. 336, p. 120850, Apr. 2023, doi: 10.1016/j.apenergy.2023.120850.
- [89] P. Halder *et al.*, 'Advancements in hydrogen production, storage, distribution and refuelling for a sustainable transport sector: Hydrogen fuel cell vehicles', *Int. J. Hydrog. Energy*, Aug. 2023, doi: 10.1016/j.ijhydene.2023.07.204.
- [90] Dr Ad van Wijk, 'Green Hydrogen for a European Green Deal: A 2x40 GW Initiative'. [Online]. Available: https://hydrogeneurope.eu/wp-content/uploads/2021/11/Hydrogen-Europe_2x40-GW-Green-H2-Initiative-Paper.pdf
- [91] IEA, 'Global Hydrogen Review 2023'. Accessed: Oct. 30, 2023. [Online]. Available: <https://iea.blob.core.windows.net/assets/8d434960-a85c-4c02-ad96-77794aa175d/GlobalHydrogenReview2023.pdf>
- [92] European Commission, *A hydrogen strategy for a climate-neutral Europe*. 2020. Accessed: Oct. 26, 2025. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301>
- [93] C. Li, L. Zhang, Z. Ou, and J. Ma, 'Using system dynamics to evaluate the impact of subsidy policies on green hydrogen industry in China', *Energy Policy*, vol. 165, p. 112981, Jun. 2022, doi: 10.1016/j.enpol.2022.112981.
- [94] M. Menes, 'Program initiatives of public authorities in the field of hydrogenation of the economy in a global perspective, as of the end of 2020', *Combust. Engines*, vol. 189, no. 2, pp. 18–29, Apr. 2022, doi: 10.19206/CE-142170.
- [95] C. Chantre *et al.*, 'Hydrogen economy development in Brazil: An analysis of stakeholders' perception', *Sustain. Prod. Consum.*, vol. 34, pp. 26–41, Nov. 2022, doi: 10.1016/j.spc.2022.08.028.
- [96] S. Yoo and S. Park, 'South Korea's national pursuit for fuel cell electric vehicle development: The role of government R&D programs over 30 years (1989–2021)', *Int. J. Hydrog. Energy*, vol. 48, no. 26, pp. 9540–9550, Mar. 2023, doi: 10.1016/j.ijhydene.2022.12.136.
- [97] J. Cader, R. Koneczna, and P. Olczak, 'The Impact of Economic, Energy, and Environmental Factors on the Development of the Hydrogen Economy', *Energies*, vol. 14, no. 16, Art. no. 16, Jan. 2021, doi: 10.3390/en14164811.
- [98] D. Astiaso Garcia, 'Analysis of non-economic barriers for the deployment of hydrogen technologies and infrastructures in European countries', *Int. J. Hydrog. Energy*, vol. 42, no. 10, pp. 6435–6447, Mar. 2017, doi: 10.1016/j.ijhydene.2017.01.201.
- [99] K. Ono, E. Kato, and K. Tsunemi, 'Does risk information change the acceptance of hydrogen refueling stations in the general Japanese population?', *Int. J. Hydrog. Energy*, vol. 44, no. 31, pp. 16038–16047, Jun. 2019, doi: 10.1016/j.ijhydene.2019.04.257.
- [100] W. McDowall and M. Eames, 'Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature', *Energy Policy*, vol. 34, no. 11, pp. 1236–1250, Jul. 2006, doi: 10.1016/j.enpol.2005.12.006.
- [101] R. Freeman, 'Modelling the socio-political feasibility of energy transition with system dynamics', *Environ. Innov. Soc. Transit.*, vol. 40, pp. 486–500, Sep. 2021, doi: 10.1016/j.eist.2021.10.005.
- [102] D. L. Edmondson, F. Kern, and K. S. Rogge, 'The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions', *Res. Policy*, vol. 48, no. 10, p. 103555, Dec. 2019, doi: 10.1016/j.respol.2018.03.010.



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