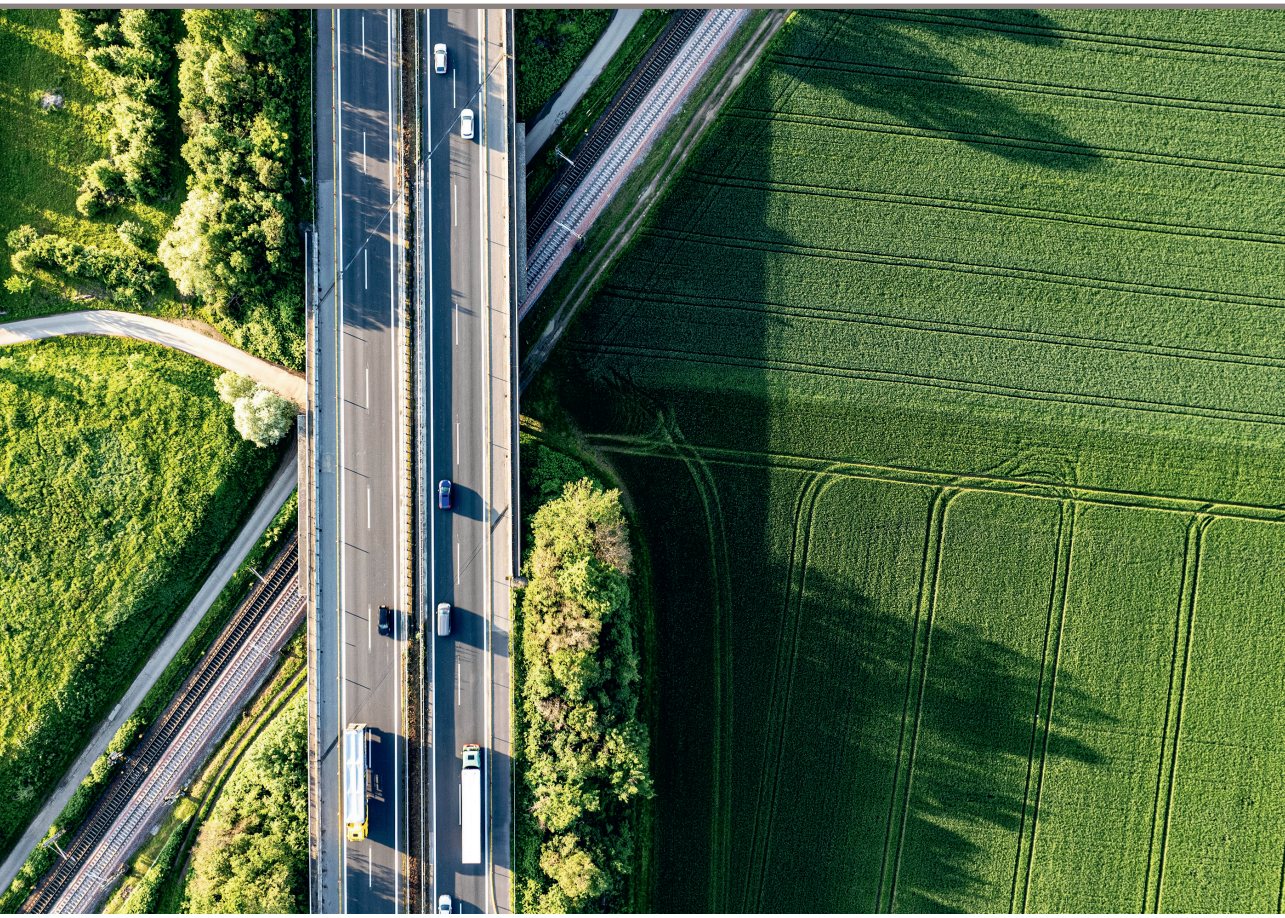
RIGA TECHNICAL UNIVERSITY

Alīna Safronova

AN INTEGRATED APPROACH TO ASSESSING ROAD PASSENGER TRANSPORT DECARBONISATION PATHWAYS

Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
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AN INTEGRATED APPROACH TO ASSESSING ROAD PASSENGER TRANSPORT DECARBONISATION PATHWAYS

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ANNOTATION

Human-caused climate change has highlighted the necessity for effective decarbonisation strategies in all sectors of the economy. The European Union has committed to becoming climate neutral by 2050 to reduce the negative impact of climate change. While other sectors are seeing reductions in emissions, the transport sector remains one of the most difficult sectors to decarbonise, both globally and in Latvia. In Latvia, the transport sector is also very important in achieving climate goals, as it generates over 30 % of the total national emissions. The decarbonisation of this sector is hindered by the dominance of private road transport in passenger transport, as well as an outdated car fleet that mostly relies on fossil fuels. The work further focuses on the decarbonisation of road passenger transport, as a significant source of emissions in the Latvian transport sector.

Avoid-shift-improve (ASI) approach states that emission reduction in the transport sector depends not only on improvements in vehicle efficiency and introduction of low-emission vehicles. Equally important is the transition to sustainable mobility modes such as walking, cycling, public transport. The potential for such changes is closely linked to the willingness of residents to change their behaviour, which in turn is closely linked to the availability of infrastructure and services, as well as the political framework that makes this change possible. This indicates that for technology implementation and behavioural change, a supportive policy framework is needed.

This need is particularly evident in the Latvian context. Latvia's National Energy and Climate Plan (NECP) set a goal of reducing transport sector emissions by 21.2% by 2030 compared to the 2005 baseline, while projecting a reduction in emissions of only 2.3% compared to 2005. This difference indicates a significant implementation gap between strategic objectives and the realistically expected impact of the policy. Therefore, the political framework must link strategic and regulatory conditions with practical implementation capacity and citizen feedback.

The aim of the work is to develop and apply an integrated approach to assessing the decarbonisation potential of road passenger transport, analysing technological transition, behavioural change and coordinated policy implementation as interrelated elements. The work investigated the interaction of technological improvement, policy implementation, and behavioural change in the context of decarbonisation of road passenger transport, considering the role of the state, local governments, and individual levels in implementing these changes. The work evaluates transport policy and technological solutions (such as biomethane, electric vehicles, hydrogen) for reducing CO_2 emissions using literature analysis, multi-criteria decision analysis, bibliometric analysis, cost-benefit analysis, causality diagrams and system dynamics methods. Factors influencing human behaviour were studied using empirical surveys and system dynamics modelling. Recognizing the role of municipalities, a mathematical model with a user-friendly interface was developed for policy evaluation and tested with the Riga case study to support their long-term planning documents. Finally, the findings were structured according to six research phases, covering technology and policy prioritisation, technology-

specific assessment, national-level scenario modelling, municipal implementation perspective, public acceptance, and integration of behavioural factors.

The doctoral thesis is structured as a set of publications based on 9 thematic unified scientific publications developed in the period from 2020-2025. The work consists of an introduction and five chapters: (1) literature review, (2) research methodology, (3) results and discussion, (4) conclusions, and (5) recommendations. The introduction presents the aim and hypothesis of the work, describes the relevance, novelty, practical significance, and structure of the research. The first chapter summarises the literature on the challenges of decarbonisation of the transport sector, the ASI approach, and technological solutions, as well as analyses the role of municipalities and residents in mobility changes. The second chapter describes the structural approach of the study and the research methods used. The third chapter includes a description of the results and discussion, which describes a comprehensive approach to the assessment of policies and potential technologies, the impact of behavioural factors, and the possibilities of municipalities to reduce transport-related emissions. The work concludes with a summary of the main conclusions and recommendations of the study.

This doctoral thesis is written in English, consists of 252 pages, including appendices, contains 37 figures, 12 tables, 18 equations and 252 references.

ANOTĀCIJA

Cilvēku darbības izraisītās klimata pārmaiņas ir izcēlušas nepieciešamību pēc efektīvām dekarbonizācijas stratēģijām visās ekonomikas nozarēs. Eiropas Savienība ir apņēmusies līdz 2050. gadam kļūt klimatneitrāla, lai mazinātu klimata pārmaiņu negatīvo ietekmi. Lai gan citās nozarēs emisijas samazinās, transporta nozare joprojām ir viena no grūtāk dekarbonizējamajām nozarēm gan pasaulē, gan Latvijā. Arī Latvijā transporta nozare ir ļoti svarīga klimata mērķu sasniegšanā, jo tā rada vairāk nekā 30 % no kopējām valsts emisijām. Šīs nozares dekarbonizāciju kavē privātā autotransporta dominance pasažieru pārvadājumos, kā arī novecojis autoparks, kas galvenokārt izmanto fosilo kurināmo. Darbs tālāk koncentrējas uz pasažieru autotransporta dekarbonizāciju kā nozīmīgu emisiju avotu Latvijas transporta nozarē. Izvairīties–pārorientēties–uzlabot (*Avoid-Shift-Improve* (ASI)) pieeja nosaka, ka ilgtspējīgu pārvietošanās veidu attīstība (piemēram, ar kājām, divriteņiem, sabiedrisko transportu), kā arī izmantoto transportlīdzekļu efektivitātes uzlabošana ir nepieciešama, lai samazinātu transporta sektora radītās emisijas. Jauno tehnoloģiju ieviešana pati par sevi neizraisa emisiju samazinājumu – līdztekus ar tehnoloģiju pieejamību pārmaiņām sektorā ir nepieciešama cilvēku paradumu maiņa. Abu komponentu īstenošanai nepieciešams atbilstošs politikas ietvars dažādos plānošanas līmeņos, ietverot gan augšupēju (*bottom-up*), gan lejupēju (*top-down*) pieeju.

Šī nepieciešamība ir īpaši izteikta Latvijas kontekstā. Latvijas Nacionālais enerģētikas un klimata plāns (NEKP) nosaka mērķi līdz 2030. gadam samazināt transporta sektora emisijas par 21,2% salīdzinājumā ar 2005. gada bāzes līmeni, taču NEKP prognozē emisiju samazinājumu tikai par 2,3% salīdzinājumā ar 2005. gadu. Šī atšķirība norāda uz būtisku īstenošanas plaisu starp stratēģiskajiem mērķiem un reāli paredzamo politikas ietekmi. Tāpēc politiskajam ietvaram ir jāsaista stratēģiskie un normatīvie nosacījumi ar praktisko īstenošanas spēju un iedzīvotāju vajadzībām.

Darba mērķis ir izstrādāt un pielietot integrētu pieeju pasažieru autotransporta dekarbonizācijas potenciāla novērtēšanai, analizējot tehnoloģisko pāreju, uzvedības maiņu un koordinētu politikas īstenošanu kā savstarpēji saistītus elementus. Darbā tika pētīta tehnoloģisko uzlabojumu, politikas ieviešanas un uzvedības maiņas mijiedarbība pasažieru autotransporta dekarbonizācijas kontekstā, ņemot vērā valsts, pašvaldību un individuālā līmeņa lomu šo izmaiņu ieviešanā. Darbā, izmantojot literatūras analīzi, daudzkritēriju lēmumu analīzi, bibliometrisko analīzi, izmaksu un ieguvumu analīzi, cēloņsakarību diagrammas un sistēmdinamikas modelēšanas metodes, tiek izvērtēta transporta politika un tehnoloģiskie risinājumi (piemēram, biometāns, elektrotransportlīdzekļi, ūdeņradis) CO_2 emisiju samazināšanai. Izmantojot empīriskas aptaujas un sistēmdinamikas modelēšanu, tika pētīti cilvēku uzvedību ietekmējošie faktori. Atzīstot pašvaldību lomu, politikas novērtēšanai tika izstrādāts sistēmdinamikas modelis ar lietotājam draudzīgu saskarni un pārbaudīts ar Rīgas gadījuma izpēti, lai atbalstītu to ilgtermiņa plānošanas dokumentus. Visbeidzot, secinājumi tika strukturēti atbilstoši sešiem pētījuma posmiem, aptverot tehnoloģiju un politikas prioritāšu

noteikšanu, tehnoloģiju specifisku novērtējumu, nacionālā līmeņa scenāriju modelēšanu, pašvaldību ieviešanas perspektīvu, sabiedrības pieņemšanu un uzvedības faktoru integrāciju.

Doktora disertācija ir strukturēta kā publikāciju kopums, kas balstīts uz 9 tematiskām vienotām zinātniskām publikācijām, kas izstrādātas laika posmā no 2020. līdz 2025. gadam. Darbs sastāv no ievada un piecām nodaļām: (1) literatūras apskata, (2) pētījuma metodoloģijas, (3) rezultātiem un diskusijas, (4) secinājumiem un (5) ieteikumiem. Ievadā ir izklāstīts darba mērķis un hipotēze, aprakstīta pētījuma atbilstība, novitāte, praktiskā nozīme un struktūra. Pirmajā nodaļā ir apkopota literatūra par transporta sektora dekarbonizācijas izaicinājumiem, ASI pieeju un tehnoloģiskajiem risinājumiem, kā arī analizēta pašvaldību un iedzīvotāju loma mobilitātes izmaiņās. Otrajā nodaļā ir aprakstīta pētījuma strukturālā pieeja un izmantotās pētījuma metodes. Trešajā nodaļā ir ietverts rezultātu apraksts un diskusija, kurā aprakstīta visaptveroša pieeja politikas un potenciālo tehnoloģiju novērtēšanai, uzvedības faktoru ietekmei un pašvaldību iespējām samazināt ar transportu saistītās emisijas. Darbs noslēdzas ar pētījuma galveno secinājumu un ieteikumu kopsavilkumu.

Šis promocijas darbs ir izstrādāts angļu valodā, tas sastāv no 252 lappusēm, iekļaujot pielikumus, ietver 37 attēlus, 12 tabulas, 18 vienādojumus un 252 atsauces.

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ABBREVIATIONS

AFIR		The Alternative Fuels Infrastructure Regulation
AI	-	Artificial Intelligence
ASI	-	Avoid-Shift-Improve
BEV	-	Battery Electric Vehicles
CBA	-	Cost-benefit analysis
CH4	-	Methane
CHP	-	Combined Heat and Power
CLD	-	Causal Loop Diagram
CO_2	-	Carbon Dioxide
EU	-	European Union
EUR	-	Euro
EV	-	Electric Vehicles
FCEV	-	Fuel Cell Electric Vehicles
GHG	-	Greenhouse Gas
HDV	-	Heavy-Duty Vehicles
ICE	-	Internal Combustion Engine
IEA	-	International Energy Agency
IoT	-	Internet of Things
IPCC	-	Intergovernmental Panel on Climate Change
LDV	-	Light-Duty Vehicles
MaaS	-	Mobility-as-a-Service
MCDA	-	Multi-Criteria Decision Analysis
NECP	-	National Energy and Climate Plan
NID	-	National Inventory Document
PHEV	-	Plug-in Hybrid Electric Vehicles
RED III	-	Renewable Energy Directive
RES	-	Renewable energy resources
RFNBO	-	Renewable Fuel of Non-Biological Origin
SD	-	System Dynamics
SUMP	-	Sustainable Urban Mobility Plan
TEN-T	-	Trans-European Transport Network
TOPSIS	-	Technique of Order Preference Similarity to the Ideal Solution
USD	-	United States Dollar
V2G	-	Vehicles-To-Grid

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 CO_2 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 (CO_2) 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 (CONECT2022)*, 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 (CONECT2023),* 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, p. 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**, p. 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. 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/rtuect-2022-0022
6. **Safronova, A.,** Barisa, A. Hydrogen Horizons: A Bibliometric Review of Trends in Diverse Emission Sectors. *Sustainability*, **2023,** Vol. 15(19), p. 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/rtuect-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/rtuect-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/rtuect-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.

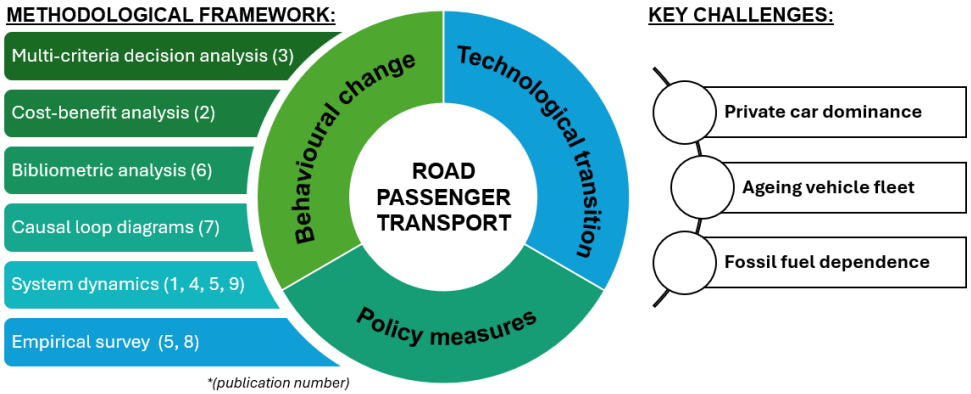


Fig. 1. Analytical framework for assessing road passenger transport decarbonisation (developed by the author).

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.

1.1. The concept and importance of climate neutrality in the transport sector

The Industrial Revolution, which took place in the second half of the eighteenth century, contributed to the development of humanity, replacing manual labour with various mechanisms. The increased use of fossil fuels led to higher atmospheric concentrations of carbon dioxide and other GHGs, contributing to an increase in the Earth's average temperature [1]. Although the increase in temperature on Earth has been observed before, it is important to consider the rate of change. From the 1920s to the 1940s, temperatures rose by about 0.1°C per decade, while the 2020 anomaly of the 21st century is in the range of 1.23°C to 1.31°C, compared to pre-industrial levels [4], [5]. If atmospheric GHG concentrations continue to increase at current rates in the coming years and no effective adaptation and mitigation measures are implemented, the impacts of climate change are expected to intensify, leading to environmental, economic and social consequences [2]. Humanity will face increasing challenges such as rising sea levels, more intense rainfall, and heat waves that endanger human health [8] . Extreme events like forest fires, floods, and droughts endanger food and water supplies [7]. At the same time, biodiversity loss and air pollution can further amplify these risks. 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. This concept is the foundation of the Paris Agreement, which seeks to achieve deep reductions in GHG emissions in the second half of this century [24]. The Paris Agreement is defined as a global accord aimed at combating climate change by limiting global warming to well below 2°C above preindustrial levels, with a goal of pursuing efforts to limit it to 1.5°C. It emphasises cooperation among nations through nationally determined contributions and seeks to enhance financial support for climate actions, particularly in developing countries [25]. The Paris Agreement does not impose binding emission limits on any party but does state that developed country parties shall undertake economy-wide absolute emission reduction targets and that developing countries should continue enhancing their mitigation efforts and move over time toward economy-wide emission reduction or limitation targets. The Paris Agreement also adopts monitoring and reporting requirements that are largely the same for developed and

developing countries, including transparency requirements for domestic monitoring, reporting, and verification [25].

1.1.1. IMPACT OF THE TRANSPORT SECTOR ON CLIMATE CHANGE

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 CO_2 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 CO_2 emissions [9]. Statistical data shows that as the production and use of vehicles increased, as well as emissions from the transport sector also increased. CO_2 emissions raised from 4.6 giga tonnes in 1990 to nearly 8 Giga tonnes of carbon dioxide in 2022 [26]. The exception is in 2020, when, due to measures to stop the COVID-19 pandemic and the resulting crisis emissions from the transport sector decreased [11].

The most important challenges in the transport sector are the growing demand for energy, which increased by 28% in Europe between 1990 and 2017 [12], as well as the low rates of energy efficiency and renewable energy deployment. Renewable energy reached about 3.7% of transport fuel demand in 2018, with a consumption of about 4 exajoules. The majority, or 93%, of all renewable energy was provided by biofuels, while the remainder was provided by renewable electricity [13]. The EU benchmark for the use of renewable energy in the transport sector was set in 2009 by the Renewable Energy Directive [14]. Collectively, EU Member States achieved this target – the share of energy from renewable sources in transport in the EU reached 10.2% in 2020 – although most Member States failed to meet this target [15]. In other countries, like China, United States of America, India, Japan, Canada, Australia and others the transport sector is also among the most difficult to decarbonize [16] – [18].

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 [27], [28]. The latest targets include increasing the use of renewable energy in transport to 29% in final energy consumption in the transport sector by 2030 [29].

The data described above show that pollution from transport is a significant problem both in Latvia, EU, and around the world. The negative impacts of the transport sector include GHG emissions, poor air quality, congestion, traffic accidents and other negative health impacts caused by car-dependent lifestyles [25]. However, not only transport affects climate change, but climate change also has a negative impact on the transport sector.

Climate trends affect the design of transport infrastructure, which is expensive and designed for a long life (typically 50 to 100 years) [26]. The consequences of climate change are extreme weather conditions and events – hurricanes/cyclones and floods. These can disrupt transport routes both inland and on the coast. As climate conditions change, these parts of the infrastructure will be increasingly exposed to climatic conditions, which will reduce the reliability and capacity of transport systems. Transport engineers usually refer to historical climate records, especially extreme weather conditions, when designing transport systems. For example, bridges are often designed to withstand storms that are likely to occur only once or

twice in 100 years. However, climate change has made historical climate an unreliable predictor of future risk.

Climate change is projected to increase the frequency and intensity of some extreme weather events. Heat waves are likely to be more intense, rising sea levels may increase storm surges in coastal areas, and rainfall is likely to be more intense. These changes can increase the risk of delays, disruptions, damage, and failures in our land, air, and maritime transport systems. Much of the transport infrastructure currently under construction is expected to last 50 years or more. Coastal transport infrastructure, particularly seaports, will be affected by rising sea levels, which will exacerbate coastal flooding during extreme storms. Road and rail infrastructure, inland waterways and airports, which are already vulnerable to flooding, may face more frequent inland flooding and deeper flooding under climate change. Infrastructure damage, disruptions and delays are possible across global supply chains, with potentially large economic impacts [27]. Transport systems are also vulnerable to fuel and power outages, as well as communication disruptions, which are also subject to climate stress. For example, power outages caused by Hurricane Katrina shut down three major oil pipelines for two days and left systems operating at reduced capacity for two weeks [30].

Climate change will have a direct impact on transport systems through damage to infrastructure, and indirectly through changes in trade flows, agriculture, energy use and payment patterns. It is already clear that we will face challenges in adapting transport systems to climate change in the future, especially given the projected growth of the transport sector. It is therefore important to understand how future climate could affect these investments in the coming decades [28].

1.1.2. INTERNATIONAL OBJECTIVES

Recognizing the challenges related to the sustainability of the transport sector, the EU has developed a European Strategy for Low-Emission Mobility [31]. The strategy states that transport emissions must be reduced rapidly so that by 2050, GHG emissions from transport are at least 60 % lower than in 1990 [31]. The strategy provides for high support for innovation and will also facilitate Europe's transition to a low-carbon economy, as well as support employment and growth. The strategy also links low-emission mobility with wider set of co-benefits, including lower air and noise pollution, reduced congestion, improved safety and better quality of life in cities. It is expected that vehicles will consume less energy, which will be produced from renewable energy sources [31]. The movement of citizens will also be facilitated by more stable route connections, including reducing delays and facilitating more convenient vehicle transfers, by introducing digital technology solutions [31].

The main elements of the strategy are increasing the efficiency of the transport system, introducing alternative energy in transport, as well as moving towards zero-emission vehicles. Increasing efficiency provides for more convenient movement of residents and clarity about costs and/or refuelling options and/or route lists, etc [31]. Low-emission alternative energy sources, the introduction of which is planned to be popularised by the middle of the century, include modern biofuels, renewable electricity, hydrogen and renewable synthetic fuels. It is

also important to remove obstacles to the creation of appropriate transport infrastructure to accelerate the transition to low- or zero-emission vehicles [31].

Cities and local governments will play a key role in implementing the policy by promoting the production of alternative fuels, the development of zero- and low-emission cars, and the necessary infrastructure [31]. Increasing the appeal of public transport and encouraging active travel (cycling and walking) will also be important. To reduce congestion and pollution, specific efforts will need to be made to share solutions and create multimodality, which entails building schemes to connect different types of vehicles, making them easier to combine and utilize.

The last century's experience has shown that an increasing number of people are relocating to cities, which adds to urban expansion and raises demand for energy consumption, notably in the transport sector. The increased number of vehicles has contributed to traffic bottlenecks, in which individuals not only waste time but also generate noise and air pollution. To address this additional pressure from urbanisation, many urban planners began to expand road infrastructure; however, experience has shown that increased road capacity can generate additional vehicle traffic and may not provide long-term congestion relief [32], [33]. As a result, transport planning increasingly needs to focus not only on vehicle technologies, but also on demand management, public transport, active mobility and multimodal solutions[34].

1.1.3. LATVIA'S CASE STUDY

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]. Energy consumption trends show that, in comparison to 1990, demand for diesel fuel is increasing in all major road transport categories. Notably, demand for light-duty vehicles (LDVs) is increasing as their total number and CO_2 equivalent emissions have increased fourfold [12].

The road transport category includes private cars, which account for 52% of total road transport CO_2 emissions, as well as buses, commercial transport, cargo transport, and L-category vehicles. 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 [35]. In this way, 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.

The EU is implementing the updated renewable energy regulation 2023/2413 (RED III), which went into effect in 2023, to cut emissions in the transport sector [36]. Like the other Member States, Latvia has the right to decide its contribution within the framework of integrated national energy and climate strategies, as per RED III [36]. The Latvian National Energy and Climate Plan 2021–2030 (NECP) outlines Latvia's objectives for the integration of renewable energy sources (RES) in the energy sector [35]. The following are the primary goals of Latvia's NECP in the transport sector [35].

- Reduction of GHG emissions intensity in transport – to achieve a 14.5% reduction by 2030 (based on 2022 baseline)
- Share of renewable energy in transport – to increase to 29% by 2030 (compared to approximately 3.1% baseline in 2022)

- Share of advanced biofuels/biogas in transport – to increase to 5.5% by 2030 (from approximately 0.9% in 2022)
- RFNBO (renewable fuel of non-biological origin) – to ensure a 1% share of RFNBO in transport by 2030

These quantitative targets mainly concern the energy and fuel mix. Some of the issues relevant to road passenger transport in the NECP are formulated more as action lines than as measurable targets. These include lowering the average age of the vehicle fleet, increasing the use of renewable energy in transport, accelerating EV adoption, reducing reliance on private cars, and promoting public transport and active mobility. This highlights that policy measures should focus not only on increasing the use of renewable and low-emission technologies, but also on a shift to public transport and active mobility.

An important problem is also the gap between targets and actions – Latvia's updated NECP states that in 2030 the transport sector will achieve a reduction of approximately 2.3% in the baseline scenario compared to 2005, while the target pathway required a 21.2% reduction. This gap highlights the need to evaluate alternative policy scenarios and different combinations of measures.

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.

1.2. 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 [37], [38].

Each policy group has both advantages and disadvantages [39] – [41]. For example, "improve" policies can provide relatively rapid emission reductions and may generate economic co-benefits but can be costly and may lead to rebound effects (increased travel), where efficiency gains are partly offset by increased travel demand [39]. "Shift" policies on the one hand promote active transport and improve social equity by promoting more accessible public transport, but on the other hand these policies need significant infrastructure investment and may be less effective without supportive urban design [40], [41]. "Avoid" policies can directly reduce emissions and congestion and be cost-effective, however they may face public resistance and thus require strong planning [40].

Although all three strategies are important, current energy and transport policies frequently fail to properly represent "avoid" policies, despite their potential [42] due to implementation complexities, societal resistance, and limited municipal control over land-use planning [43]. The proposed entities are less inclined to support purely financial or high-tech solutions and rather give the opportunity to cost-effective technical and regulatory ones. The literature has

indicated the main obstacles in these situations, such as demand for infrastructure, fair access and cooperation between many parties. Furthermore, research highlights that effective policy design must consider the local context.

1.2.1. AVOID MEASURES

This section briefly reviews policies that reduce travel demand. These policies include changes in urban planning that make cities more compact and with more services close to home.

The "15-minute city" concept envisages urban planning that creates cities with self-sufficient neighbourhoods, providing their residents with all the basic functions they need: housing, work, commerce, health, education and entertainment [44]. In this way, the 15-minute city approach supports "avoid" policies by reducing the need for long daily trips. The advantage of the approach is that it is based on principles such as proximity, density, diversity, mixed-use, human-scale design, connectivity and digitalisation, which promote economic and environmental sustainability. However, when implementing this concept, it is also necessary to be aware of the practical limitations, including the needs of different social groups. Furthermore, since the simple assurance of physical closeness does not ensure a change in mobility habits, it is crucial to be aware of the tendency to overestimate the effectiveness of physical planning in addressing the mobility issue [45].

Another group of avoid policies is based on the development of e-services and remote work, which also reduce the need to physically travel to workplaces, public institutions, and service centres [46]. However, the effectiveness of such measures depends on the type of work or service, digital accessibility, the availability of appropriate infrastructure and the extent to which reduced commuting is not replaced by other non-work-related trips [47]. Therefore, e-services and remote work as well as other "avoid" policies should be seen as complementary measures, rather than separate solutions for decarbonising transport.

1.2.2. SHIFT MEASURES

The following are examples of "shift"-type policies aimed at shifting commuters to more sustainable transport alternatives. 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. In this way, the importance of travel, as a value, is also recognised when people prefer to travel for subjective reasons.

ACTIVE MOBILITY AND MICROMOBILITY

Active mobility, such as walking and cycling, as well as micromobility solutions like electric scooters and shared bikes, can help reduce dependence on private road transport, especially for short and medium distances [48]. To make these transport modes an attractive alternative to daily car trips, it is necessary to develop infrastructure that is safe and convenient, such as cycle lanes, pedestrian sidewalks, safe crossings, bicycle parking, and connectivity to public transport. The introduction of "Park&Ride" parking lots can also encourage, for example, residents from rural or suburban areas to use public transport more widely, since in such cases the car is used only as a means of first/last mile transportation [49]. The advantage

of these solutions is that they reduce transportation-related emissions while also improving public health, reducing congestion, and promoting a more accessible urban environment. 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 [50]. Active mobility and micromobility initiatives are thus most effective when combined with modernised public transport and the creation of multimodal links, rather than as standalone solutions.

MODERNISATION OF PUBLIC TRANSPORT

Modernisation of public transport is a key component of transport decarbonisation, as it combines both technological improvements and a shift towards more sustainable modes of transport [51], [52]. On the one hand, replacing ageing fossil fuel vehicles with electric buses, hydrogen, biomethane or other low-emission vehicles can reduce direct emissions and air pollution. On the other hand, modern, reliable and easily accessible public transport can reduce dependence on private cars if it becomes a competitive alternative for everyday travel.

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 [53]. Smart ticketing systems, real-time information for passengers, vehicle monitoring and demand data analysis can improve the efficiency of public transport and the user experience [54]. Such solutions allow for better integration of public transport with walking, cycling, micromobility, rail and Park & Ride systems.

From a social perspective, modernisation of public transport is important as it can improve mobility access for residents who do not own a private car, as well as reduce transport costs and mobility inequalities [55]. 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. Behavioural aspects related to the transition from private cars to public transport are discussed in more detail in Chapter 1.4.3.

1.2.3. IMPROVE MEASURES

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 [37]. However, it is important to note that the effectiveness of technological solutions also depends largely on integration with policy and behavioural changes [56]. Without policy support, the market is unable to introduce new technologies on a significant scale [56]. 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 [57]. This chapter will review the available technological solutions, their advantages and disadvantages, as well as the existing level of integration and political support, while social acceptance will be discussed in Chapter 1.4.

DEVELOPMENT OF ELECTRIC TRANSPORT

Electric vehicles are vehicles that are powered by an electric motor using electricity stored in batteries or generated on board by fuel cells. They can be further divided into Battery Electric Vehicles (BEVs), which are powered solely by batteries and produce zero tailpipe emissions; and Plug-in Hybrid Electric Vehicles (PHEVs) which combine batteries with a conventional engine, allowing them to run on electricity for short distances. Separately, Fuel Cell Electric Vehicles (FCEVs) which use hydrogen to generate electricity on board are also considered and they are described in 1.3.2. section.

The main advantage of BEVs is that they produce no tailpipe GHG or air pollutant emissions during vehicle operation, while PHEVs can reduce tailpipe emissions when operated in electric mode [58], [59]. However, their life cycle GHG emissions depend on electricity mix, vehicle manufacturing and end-of-life treatment [60]. Therefore, the highest climate benefits are achieved when EVs are charged with electricity that was produced from renewable energy sources [58], [59]. These vehicles also have fewer moving parts which lowers operating and maintenance costs as well as improves energy efficiency, reducing energy consumption. According to the study [61], these variables result in 27.8-30 % lower life cycle costs compared to ICE. Importantly, these costs fall as the vehicle's mileage rises.

EV uptake in Latvia has been supported through user benefits and tax incentives. The EVs receive a special blue licence plate that permits them to use public transport lanes as well as free parking and entry into Jurmala, a Latvian resort city. However, such measures are early implementation incentives that will have to be removed as the number of EVs increases. An initiative to end free parking for EVs is already being considered in Latvia's capital; on the one hand, Riga is experiencing a shortage of parking places in the city centre, but the Electric Car Association believes the decision to abolish free parking is premature [62]. People invest in vehicles as a long-term solution, and the sudden elimination of free parking may cause frustration and distrust in the municipality.

In Latvia, legislators follow the "polluter pays" approach, increasing expenses for more powerful vehicles that operate on fossil fuels while lowering rates for less polluting vehicles. If emitting less than 50 g CO2/km, all vehicles, including cars, goods vehicles, buses, and motorcycles, are exempt from payment of the Vehicle Operation Tax and Registration tax [35], [63]. Companies receive similar benefits in terms of tax rates for light automobiles. In 2021, Latvia started an EV entry support programme with a total budget of 10 million euros. The program offered a purchase subsidy of up to EUR 4,500 for households and up to EUR 9,000 for electric vans for households with multiple children for disposing of an old fossil fuel-powered vehicle and purchasing a new EV [63], [64]. The new program that was adapted in 2026 April provides 40 million EUR in financing for individuals to purchase electric cars, externally rechargeable hybrid cars and hydrogen cars [65]. The support is provided until the funding is used up, but no longer than until December 31, 2029. The amount of support is from 3,000 to 9,000 euros, depending on the type of vehicle and the applicant's status, and it is possible to receive an additional 2,000 euros for writing off an old internal combustion engine car or transferring it to the Ukrainian Armed Forces.

Thus, EV policy in Latvia is not limited to individual user benefits, such as tax breaks, free parking or the use of public transport lanes, but is gradually being linked to a broader support system for vehicle purchase and infrastructure accessibility.

The number of EVs in Latvia has increased over the years, and more than 11,000 EVs are now registered in Latvia, accounting for less than 1.2% of all registered vehicles in 2025. In terms of new vehicle registrations, EVs are playing an increasingly important role in Latvia, with a 7.5% share at the beginning of 2025 [66].

The continued EV growth, together with clean energy and aiding policies, is crucial for achieving climate neutrality targets. This not only helps to decarbonize a difficult-to-decarbonize sector like transport, but it also allows for sector-coupling through technologies such as vehicle-to-grid. Overall, EVs are important, but not sufficient alone: their effect depends on electricity mix, charging infrastructure, affordability and policy support.

HYDROGEN AS ALTERNATIVE FUEL TYPE FOR VEHICLES

Hydrogen is a promising energy carrier with several advantages, including high gravimetric energy density and the potential to store surplus renewable electricity, thus contributing to the flexibility of the energy system [67]. Another environmental benefit is that the hydrogen combustion process as well as electrochemical conversion in a fuel cell produces water vapor, which results in zero tailpipe emissions in FCEVs. The greater integration of hydrogen technologies also not only contributes to energy security but also has an impact on economic development [68]. It is also very promising in the transport sector, as it is highly versatile and can be used in cars, buses, heavy-duty vehicles, trains, and even ships. Its application is also being actively researched in aviation [69]. The bibliometric analysis indicates a trend of increasing research on the feasibility of utilizing hydrogen in transport [70].

Like EVs, FCEVs have lower noise levels and the potential to reduce emissions when powered by renewable energy sources. However, they have faster and easier refuelling times than EVs and can go farther on a single charge, which eases range anxiety associated with EVs with smaller battery packs. FCEV engines are twice as efficient as ICE engines, but do not match the performance of electric vehicles [71]. The current integration of both technologies in the current vehicle market also differs - compared to BEVs, FCEV use is mostly limited to pilot projects or fleets in specific regions like Japan, Korea, California and Germany [72]. This is explained by the higher costs of FCEV technology, the lack of infrastructure, and a greater lack of knowledge and consumer familiarity [73], [74].

In most cases total cost of ownership for hydrogen transport is currently more expensive than diesel, owing to increased fuel and vehicle costs [75]. However, costs vary a lot by mode, distance, supply chain design, and future assumptions. The price of hydrogen in the gas pipeline is largely determined by the raw material cost and the technology used. According to various studies, the price ranges between 1 and 23 USD/kg [76]. It is noteworthy that the IEA predicts that by 2030, the price of renewable hydrogen could drop to 2–9 USD/kg [77].

To get hydrogen to the consumer, storage, transportation, and infrastructure costs must be considered. In the future, supply chain scale-up is expected to reduce the cost of hydrogen use for non-transport applications by 90 %, while manufacturing scale-up of end-use equipment

will account for up to 70 % of cost reductions in transportation applications [78]. Other studies have predicted that hydrogen fuel could be reduced by 60 % by 2030 as a result of future technological advances [79].

The EU recognises the potential of hydrogen and has developed the EU Hydrogen Strategy [80] and the REPower EU plan [81], which set targets of producing 10 million tonnes and importing 10 million tonnes by 2030. About 10 % of the EU's energy needs are expected to be met by renewable hydrogen by 2050, greatly reducing the carbon footprint of energy-intensive industrial processes and the transport sector. According to the EU Regulation 2023/1804 (AFIR) on the deployment of alternative fuels infrastructure, renewable hydrogen filling stations must be available on the TEN-T network at least every 200 kilometres [82]. In this way, minimum requirements were set to guide this sector. The objectives of the Renewable Energy Directive were also revised, not only increasing the existing objectives, but also setting a target of 1% of renewable fuels of non-biological origin (including hydrogen) in final transport consumption by 2030 [36].

In Latvia, hydrogen use in transport sector is still in its early stages of development. Practical experience of hydrogen vehicles in Latvia so far is mainly related to demonstration or pilot projects. Thus, the first filling station in Latvia was opened in 2019, and the first ten hydrogen-powered vehicles were purchased and put into operation at the beginning of 2020 to transport passengers in Riga, using hydrogen as a reserve fuel. It is worth noting that the filling station and production plant created supply grey hydrogen, which is produced from natural gas, is not considered renewable, and fails to meet AFIR standards.

In Latvia, the use of green hydrogen in transport is still at an early stage of development, and practical experience is mainly being built within the framework of pilot projects and demonstration initiatives. These projects explore the possibilities of using hydrogen in public transport, as well as in heavy vehicles, port operations, aviation and hard-to-electrify railway sections [83] – [87]. At the same time, technological standards, infrastructure requirements, cross-border interoperability, as well as opportunities to develop renewable hydrogen production and refuelling infrastructure are also being assessed. These projects allow for the accumulation of practical experience in the production, refuelling, and use of hydrogen in transport; however, they do not yet represent a full-fledged market-scale solution.

In addition to pilot projects, hydrogen vehicles are also included in the broader support instruments for the purchase of environmentally friendly cars for individuals [65]. However, this support should be interpreted as a technology-neutral incentive for the purchase of zero- and low-emission vehicles, and not as a separate hydrogen transport development program.

Concluding, current state of development shows that hydrogen's potential in Latvia is most likely related to transport segments where direct electrification is more difficult, such as public transport, heavy transport, port, or railway applications. To realise this potential, the state and municipalities must coordinate their actions, invest in renewable hydrogen production and refuelling infrastructure, and establish a clear linkage mechanism with the requirements of RED III and AFIR over the next decade.

BIOMETHANE AND ADVANCED BIOENERGY SOLUTIONS

To reduce emissions from the transport sector and to reduce reliance on fossil fuels, the EU has identified the development of biomethane and advanced fuel production as one of the solutions. These fuels are intended to be used in transport sectors that are particularly difficult to decarbonize, such as freight transport or aviation. The EU's objectives in this sector are also described in important legislative packages such as the Fit for 55 and in the Renewable Energy Directive. RED III requires EU member states to meet one of two binding targets by 2030, applicable to road, rail, maritime, and aviation transport: Achieve a 29% renewable energy share in the transport sector; or reduce the GHG intensity of transport fuels by 14.5% [36]. By 2030, advanced biofuels and RFNBOs must meet a combined minimum target of 5.5% in the transport sector with at least 1% of these must be RFNBOs.

Aside from that, the REPowerEU plan aims to increase biomethane production to 35 billion cubic meters per year by 2030, replacing fossil gas imports [81].

The main reason biomethane is so well-received is that biomethane can lower produced GHG emissions by 80–200 %, and depending on the feedstock, it can even create negative emissions [88]. This is possible if methane emissions from waste decomposition are minimised [89]. Biomethane can be produced from a variety of organic wastes, agricultural residues, and sewage, thus promoting circular economy principles and reducing reliance on fossil fuels. It is also one of the ways to manage organic waste and reduce waste generation. Biomethane, like other locally produced renewable fuels, helps to ensure energy security and generates local benefits [89].

Biomethane, like other advanced biofuels, has the potential to utilize existing fleets while requiring less investment than EV and hydrogen grid development [90]. As a result, biomethane and other advanced renewable fuels are viewed as transitional fuels because they provide an immediate way to reduce GHG emissions and leverage existing infrastructure while the longer-term transition to full electrification and green hydrogen is scaled up. They also have a high potential for use in vehicles that are more difficult to decarbonize, such as heavy-duty trucks, shipping, and aviation.

Among the drawbacks are biogas upgrading technologies, which frequently lack competitiveness in the absence of suitable state support [91]. While using waste as a raw material is beneficial and creates added value, it also draws attention to the logistical difficulties associated with transporting this material. In addition, certain knowledge and technological solutions are required for storage to stop frequent methane leaks [91]. Biomethane development, like other alternative fuels, is heavily reliant on supportive policies, incentives, and stable regulatory frameworks.

According to RED III, advanced biodiesel and biogas should account for 5.5% of final transport consumption in Latvia by 2030. Latvia has the potential to produce 250 million m^3 of biogas per year, with approximately 50 biogas plants and current raw material availability [92], [93]. The most significant barrier to biogas use is that most biogas plants in Latvia were originally designed for combined heat and power (CHP) generation rather than upgrading the gas to vehicle fuel. Other conditions also limit the use of transport vehicles powered by

biomethane. For example, Latvia has extensive natural gas infrastructure that could be used for biomethane transportation, but biomethane injection into the network has yet to be developed.

To promote the integration of renewable gaseous fuels, the regulation on the introduction of gaseous fuels into the natural gas transmission and distribution system has been updated. Cabinet Regulation No. 50, in force January 21, 2025, establishes the requirements for the introduction of regasified natural gas, gaseous fuels produced or obtained from renewable energy resources, and low-carbon gaseous fuels into the natural gas transmission and distribution system. This regulatory clarification is critical for biomethane development, as access to the gas network is one of the requirements for expanding biomethane production and use. Latvia's first publicly accessible biomethane injection point, located in Džūkste, was opened in the end of July 2025. This enables biomethane producers to inject biomethane into the natural gas system while receiving certificates of sustainable biomethane origin. In the future, at least two more centralised biomethane entry points will be established, increasing the availability of gas infrastructure for producers without a direct connection to the grid. However, the use of biomethane in transport is still limited by a lack of refuelling infrastructure. There are only a few CNG/CBG refuelling stations in Latvia, and most of them are concentrated in the Riga region, limiting the practical use of biomethane as a fuel for transport outside of the largest mobility centres.

To improve the availability of biofuel, guidelines were developed for the "Guidelines For The National Biogas Production Development Plan In Latvia", with proposals on how to advance the biogas industry: regulatory framework, use of waste raw materials, technology development [94]. In addition to the development guidelines, Latvia has also established a targeted support instrument for biomethane production and transportation. Cabinet Regulation No. 21 of 7 January 2025 determines the procedure for implementing the measure “Promotion of renewable energy sources – biomethane” of the EU Cohesion Policy Programme for 2021–2027 [95]. The support is intended for the purchase and installation of biomethane production equipment, the creation of the necessary infrastructure, including the construction of a connection, as well as the purchase of a biomethane transportation kit. Within the framework of one project, the maximum capital allowance can reach 4.2 million EUR [95]. The ALTUM programme provides for a combined financial instrument - a loan or guarantee with a capital allowance. Within the framework of the programme, support is provided both for the creation of biomethane production capacities and for biomethane transmission connections or transportation solutions. This is important, because biomethane producers do not always have a direct connection to the natural gas network, therefore, transportation and input infrastructure becomes an important prerequisite for the development of the biomethane market.

Thus, several important prerequisites have already been created for the development of biomethane in Latvia: updated regulation for the introduction of gaseous fuels into the natural gas system, the development of public biomethane entry points has begun, and investment support for biomethane production, transportation, and infrastructure has been introduced. However, the use of biomethane in transport is still limited due to the lack of widely available CNG/CBG refuelling infrastructure and stable long-term demand in the transport sector. Therefore, the full use of biomethane potential requires not only supporting production, but also

its integration into transport decarbonisation policy, ensuring a link between production, input into the network, guarantees of origin, refuelling infrastructure, and final consumption in transport [96], [97].

1.2.4. DIGITAL TECHNOLOGIES AND SMART MOBILITY

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 environmental mobility solutions can also help to optimise existing processes, thus improving efficiency and reducing emissions. In addition, digitalisation and environmental mobility solutions encourage behavioural change. The following are key digital solutions for transport sector's decarbonisation.

1. Internet of Things (IoT) – such solutions involve the widespread use of sensors in vehicles, infrastructure and logistic networks, with the aim of collecting real-time data on traffic, vehicle performance, air quality and travel behaviour. The obtained data is then processed with artificial intelligence (AI) tools with the aim of optimising routes, reducing congestion and improving public transport efficiency. These solutions include several, for example:

- Smart traffic management – this approach is based on systems that use real-time data to optimise traffic flow, reduce congestion and improve air quality. This can be implemented, for example, with adaptive traffic signals and AI-controlled systems that adjust the operation of traffic signals. In such cases, it is possible to save up to 25% of the total travel time, up to 40 % of the total waiting time and up to 20 % of the emissions generated in urban environments [98]. Other studies confirm the assumptions about the possible emission savings [99], [100]. The main obstacle to such technologies is the high cost and robust data management [98], [101].
- Digital twins – It is a powerful tool that provides dynamic, virtual replicas of physical transport assets, networks, or entire cities, continuously updated with real-world data via sensors and IoT devices. This allows scenario modelling and optimisation of existing operations, reducing emissions and improving resilience. It can be applied in several areas, such as in traffic management for real-time optimisation [102], public transport for adaptive planning [103], urban logistics for fleet emission management [104], [105] and infrastructure for predictive maintenance [106], [107].
- Autonomous vehicles – The use of such vehicle types demands the use of an automated driving system that makes decisions autonomously through communication with other vehicles and infrastructure. Such systems are heavily dependent on sensors and AI decisions made from information gathered on traffic, weather, and potential hazards, resulting in a more comprehensive understanding of the driving environment. The goal is to develop self-driving vehicles that can operate with little to no human intervention, not only making life easier but also

reducing the impact of the human factor on the road. Studies show that the wider implementation of such vehicles would optimise vehicle flow and reduce the amount of emissions generated [108], [109]. In particular, significant impacts arise when combining these technologies with electrification and shared-mobility promoting solutions [110].

- Smart charging and vehicles-to-grid (V2G) – This technology uses EV batteries to provide distributed energy storage, allowing for flexible demand and supply balancing. Smart charging technologies reduce overall system costs and emissions by enabling electric vehicles to be charged during times of high renewable energy production, while eliminating the need for stationary batteries and peak power plants [111], [112]. Studies show that in urban and national energy frameworks, the integration of EVs can reduce energy storage requirements by as much as 35% and lower system expenses by 4–8% [111].

2. Mobility-as-a-Service (MaaS) – While IoT is a technological platform for data collection and exchange between devices, MaaS is a service concept that incorporates IoT together with data analysis, GPS, payment systems, and so on [113]. This concept anticipates the creation of platforms that combine various modes of transport into a single digital application, making it easier for users to plan, reserve, and pay for trips. The various modes of transport include both public and alternative modes of transport, such as shared mobility and micromobility. The main impact of MaaS is to change residents' habits, making the transition to these modes of transport easier and more understandable [113]. Several studies suggest various scenarios for the impact of MaaS implementation. Thus, Pim Labee et al. determined that it is possible to achieve a 3-4% reduction in emissions in conservative scenarios, while this value increases to 43-54% in optimistic scenarios [114]. Other researchers found a similar range of emission savings of 4–41% [115].

1.3. Municipal implementation and citizen behaviour in transport decarbonisation

Scenario development is a useful tool for making informed decisions because it encourages a better understanding of the future and the development of long-term strategies. It enables decision-makers to be "smart before the event," rather than "smart after the event". This approach reduces the tendency to stick with existing solutions and allows for a more comprehensive evaluation of alternative solutions to transport problems [116].

However, to obtain more accurate data, it is necessary to enter as precise input data as possible, which is often burdensome, especially for small municipalities. Often, the necessary data are not collected at all. This highlights the deep uncertainty problem in transport planning. Deep uncertainty can be described as defined as “(i) the external context of the system, (ii) how the system works and its boundaries, and/or (iii) the outcomes of interest from the system and/or their relative importance” [117]. Adaptive planning is one of the possible solutions to this problem, which mitigates the effects of limited foresight on achieving future objectives. With

adaptive planning, it is possible to test various possible development scenarios and perform scenario analysis, which allows to adjust the initial development plan.

There are various modelling tools available to help local governments understand the complexity of the transport system and determine the potential outcomes of the chosen tactics, allowing for the development of sustainable policy options that work effectively under different (uncertain) scenarios [117], [118]. Given the problem of rising emissions from the transport sector, many researchers are looking into emission reduction strategies. Studies frequently focus on the influence of economic and technical factors on transport mode choice [119], [120], [121] but there is an increasing amount of research on the role of behavioural factors in transport mode choice [122], [123].

An alternative to modelling tools is to organize various workshops with industry stakeholders. This allows for the collection of information about existing issues, as well as the identification of patterns and gaps in support [124].

1.3.1. THE ROLE OF MUNICIPALITIES IN MOBILITY PLANNING

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 [56], [125], [126]. 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.

Communities such as cities, towns, and villages consume 75% of the world's energy and contribute to 80 % of GHG emissions [127]. This highlights the Thesis's focus on municipalities as crucial players in the Latvian decarbonisation process. A municipality is the lowest-level administrative division of local government and typically has the primary responsibility for devising and executing strategies that are appropriate for its specific geographic location [128]. 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 [129].

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 [130], [131]. This suggests that policymakers should consider economic, environmental, and social factors when developing policy frameworks. When it comes to municipal or city-level best practices, however, many local governments fall short. The dominance of automobile-centric planning in the mobility paradigm is often at the root of the problem.

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. This approach also allows for the assessment

of various scenarios and their combinations to understand how measures can complement one another and what role local governments play in this process.

To integrate sustainable transport policies and address people's mobility demands in a sustainable way, the European Commission established the Sustainable Urban Mobility Plan (SUMP). With a long-term perspective, this method encourages evidence-based decision-making and offers the opportunity to implement best practices in accordance with relevant laws [132]. Communities of all sizes benefit greatly from the implementation of the SUMP strategy, according to research [133].

The Sustainable Energy and Climate Action Plan (SECAP) is another tool promoted by the European Union's Covenant of Mayors to assist municipalities in implementing and monitoring emissions-reduction actions in several sectors, including transport [134]. In addition to reducing emissions, SECAP aims to promote energy efficiency and strengthen the ability of municipalities to adapt to the impacts of climate change. SECAP implementation is expected to encourage participatory governance and local awareness, as well as the development of cross-sectoral strategies for sustainable development [135]. Municipalities also have access to methodologies for prioritizing and monitoring actions, and their participation in the development of such a plan encourages public/private investment and access to EU funds [136].

1.3.2. MUNICIPALITY-SPECIFIC FACTORS IN SUSTAINABLE MOBILITY PLANNING

While there are many considerations to be made while developing sustainable transport policies, many municipalities do not have the resources necessary to conduct evidence-based planning. Further are explained common barriers which face municipalities.

LOCAL CONDITIONS AFFECTING SUSTAINABLE MOBILITY IMPLEMENTATION

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. Research shows that lower-income residents as well as older residents more often express a stronger need for sidewalks, pedestrianisation and green public spaces, while these needs are often set aside in favour of larger infrastructure projects [137], [138]. This means that 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.

According to a Chinese study, transport infrastructure, energy composition, and wealth all had an impact on emissions from the municipal transport sector [139]. Rural municipalities do poorly when it comes to developing sustainable transport networks, and this is frequently associated with lower per capita income, population density, and a more noticeable digital divide [140]. According to a Swiss study, bike-sharing rates are higher in small municipalities with a high private vehicle predominance and low population density [141]. Studies in the

Nordic countries also show similar trends. For example, research in Scandinavian countries has shown that population density is a key transport challenge, where low population density makes it difficult to implement effective public transport and encourages people to be more dependent on cars; while high population density is associated with congestion issues and additional pressure on infrastructure [142]. Milan Noordveld et al. provide a policy mapping of the requirements of Swedish cities, highlighting how various contexts, including location and size, affect the necessary policies [143]. Research in Denmark showed that low-stress cycling infrastructure and thus "bikeability" is much higher in dense urban areas, while rural areas have observed a large untapped potential for active mobility [144]. According to the Spanish study, the establishment of pathways for bicyclists and pedestrians, as well as the general acceptance of these modes of transport, can even reduce rates of depopulation and boost tourism in rural areas [145]. These findings are particularly relevant in Latvia, where rural-urban disparities have a similar influence on the adoption of sustainable mobility alternatives.

FINANCIAL RESOURCES

As they have a significant impact on the decisions made by the local government, the financial resources that are available should be considered. Usually, national financing is used to distribute funds, which usually offers insufficient assistance for regional sustainable transport projects [146]. Generally speaking, local governments have a big influence on local-level solutions but minimal ability to affect national policy [128]. It is advised that money be diverted from infrastructure-related projects to more extensive multilevel collaboration between state representatives and interested parties as a remedy [146].

POLITICAL AND CULTURAL BARRIERS

There are cultural and political barriers, which suggest that some social groupings resist new policies [132]. Coordination between stakeholders, inhabitants, and various decision-making levels, sectors, and public sector agencies is therefore crucial when creating and implementing sustainable urban transport strategies [147].

INSTITUTIONAL CAPACITY AND COMPETENCE

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 [132], [148]. 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 [149]. This is among the causes of the common gaps between the established framework and actual practices [148]. This issue is also present in Latvian municipalities, characterised by limited data availability and insufficient technical capacity. On the other hand, some argue that this gap should be seen as a window of opportunity, with positive implications for the implementation of novel policies [150]. Nevertheless, this strategy still necessitates investment in competence building.

PUBLIC ACCEPTANCE AND BEHAVIOURAL CHANGE

For the implementation of any innovation, it is important to achieve public support and acceptance of the proposed changes. According to the theory of diffusion, public acceptance occurs in five stages: knowledge, persuasion, decision, implementation, and confirmation [151]. This indicates that at first, a potential user must learn about the proposed technology, believe in the benefits of its technology, and only then is he ready to try it. If the trial met the user's expectations, he would continue to use it, while in another case he will reject it [152].

According to this theory, the first thing that must be provided is knowledge. Studies show that greater awareness promotes readiness to change habits, determining that people with a higher understanding of the benefits of sustainable transport and environmental problems are more likely to be willing to use alternatives to private road transport [153]. Access to information and the dissemination of knowledge are necessary not only to make it easier for residents to switch to public transport, but also to allow them to more easily adopt new technologies, such as the use of hydrogen in transport. For example, educational campaigns can influence the knowledge of residents about the safety of using hydrogen filling stations, reducing one of the existing barriers to starting to use such vehicles [154].

One way to influence the existing society is through information campaigns, as they increase public awareness of the benefits of sustainable transport, help reduce prejudices, and promote a positive attitude towards environmentally friendly transport options [155]. Furthermore, research shows that campaigns that use an emotional approach that emphasises pride or joy in sustainable behaviour, rather than emphasizing what is right or what others are doing, are more successful in increasing the use of public transport and active modes of transport.

However, it must be acknowledged that such campaigns are often not the most effective way to reach an audience. For example, there is a “boomerang” or “pushback” effect, and if a campaign emphasises that sustainable behaviour is not common, it can even reduce the desire to act sustainably [156], [157].

Generally, when formulating any policy decision, it is crucial to prevent such an effect, as the resulting resistance may postpone the achievement of objectives by a decade. In certain instances, the defined goals may remain unattainable if the execution of the policy becomes more challenging for an individual than expected [158], [159].

Research shows that environmental education for children and adolescents significantly improves knowledge, attitudes, behavioural intentions and even actual behaviour. This also highlights the influence of schools and other educational institutions in shaping the future transport sector demand [160]. It should be noted that factors such as family and especially parental behaviour [161]; teachers' personal interest and knowledge of environmental issues [162]; school and community support [163]; physical and social environment [163], [164]; as well as other socioeconomic and demographic factors [165] also play a significant role in the effectiveness of the study programme.

Besides knowledge there are several other factors that need to be considered to change current behaviour patterns. These factors are described further.

Costs – Although economic factors play an important role in all human decisions, they are sometimes not definitive when it comes to choice of transport mode. Frequently, the "cost of inconvenience" such as journey time, travel comfort, traffic, and others prevail and encourage consumers to utilize private transport [166], [167]

Travel time – Studies reveal that travel time plays a major part when choosing transport mode and is typically placed higher than "travel costs" as a reason why in places where public transport travel time is higher, individuals more frequently pick their private transport as a daily transport [168]. On the other hand, the probability of selecting public transport improves when the in-vehicle time of public transport is comparable to or shorter than that of private cars [169], [170]. Punctuality is a related factor, and improving it aids the mode shift to public transport [171].

Traffic jams – This factor is related to journey time but is treated separately. First, congestion is frequently local and time-specific, such as during peak hours, whereas travel time is a broader measure that incorporates all stages, such as waiting time, violation time, and journey duration. Second, because of its psychological impact, congestion may be viewed as a source of worry, causing some people to avoid cars or roads that are usually crowded [172].

Distance – It is considered that the shorter the distance to the stop, the greater the possibility that a person will start using public transport [165]. From the perspective of sociodemographic influence, several research demonstrates that the distance from the public transport stop is less significant for females than for males [166].

Comfort – According to studies, individuals with higher incomes place a higher value on travel comfort, as well as the necessity of public transport transfers and the need to wait at transit stations as barriers to public transport use [166], [173]. Some cases revealed that travel comfort is visibly more significant for individuals in the age bracket 25-44.

Availability – This aspect frequently indicates if commuters have the option of using other forms of transport besides private autos. It is frequently distinguished by available infrastructure, such as bike lanes, parking, and public transport access. At the same time, the impact of the accessibility factor differs according to sociodemographic characteristics. For example, with the same level of accessibility, the low-income group demonstrates greater use of public transport than the higher-income group [174]. Furthermore, one additional hurdle in choosing a sustainable mode of transport is that municipalities in rural areas have poor results in the construction of sustainable transport networks, which is frequently linked with lower population density and per capita income [140]. Investments in infrastructure that improve accessibility can lead to better transport mode decision [175].

Health and fitness – People's awareness of the benefits of shifting to active transport mode also helps to drive this change. Switching to active travel modes benefits not only physical health [176], [177], but also mental health, because cycling and walking are associated to reduced stress, improved mental health, and greater vitality [178], [179]. Furthermore, people receive social benefits, which appear in the belief that choosing such modes of transportation enhances social connections and reduces feelings of loneliness, contributing to overall well-being [176].

Weather and season – This is a factor that limits the use of active transport modes in adverse weather conditions, such as making walking unsuitable in the rain or cycling difficult in snowy conditions, particularly when necessary infrastructure maintenance activities are not provided, such as uncleared snow [180].

Safety – Although this factor, which includes the risk of accidents and personal safety, influences the ultimate decision, public and active transport options are frequently seen as less safe than private automobiles [181], [182]. Some studies also reveal the sociodemographic difference, with the results showing a stronger sensitivity of women to the level of personal safety in public transport, and for males, on the contrary, "riskier" thinking about safety in terms of accident frequency [181].

Impact on the environment – Individuals may be influenced to use more sustainable forms of transport based on social norms and perceptions of usual travel practices. According to data, those who are environmentally conscious are more likely to prefer public transport over private cars. For example, a positive association is established between mothers' non-transport pro-environmental actions and adolescents' public transport to school, however the strength of this relationship reduced over time [161].

Government policy and initiatives – The government has various crucial responsibilities in creating a sustainable transport system, including legislative and financial power, as well as significant influence over infrastructure construction and the dissemination of information campaigns. The government influences people's opinions when it promotes the implementation of decarbonisation targets. At the same time, just long-term planning is required to maintain a feeling of stability and boost public trust. This is significant since studies have found a link between faith in government and activism, readiness to support government programs, and willingness to pay for broad climate and environmental policies [183]. Similarly, the perception that policies impact their everyday life affects citizens' choices, because if the citizens do not feel understood, they will be less likely to support certain types of policies [183].

1.4. Stakeholder roles and multi-level interaction in transport decarbonisation

1.4.1. TRIPLE HELIX AS A STARTING POINT FOR STAKEHOLDER-BASED ANALYSIS

A variety of stakeholders participating in coordinated efforts makes public policy issues socially complex. They are often volatile due to changing circumstances or stakeholder activities. In fact, public policy problems are typically non-linear and extremely complex and solving them requires holistic thinking and cross-organisational collaboration. An option for creating and practicing strategic initiatives to address the issues in a methodical, organised, and responsible manner is provided by the systems modelling methodology [184].

To address the complexity of this issue, holistic thinking is required which is not a linear process, as it involves many stakeholders and their interactions. This indicates that policymakers must consider the dynamic nature of the decisions they make.

One way to look at this interaction is to use the “Triple Helix approach”, which is a spiral model of innovation that captures multiple reciprocal relationships at different points in the process of knowledge capitalisation. Etzkowitz describes the interaction of spirals in his work, indicating that it occurs at three levels - through the internal interactions within each spiral, through the mutual influence of the spirals on each other, and through the overlapping of the three-way influences of all spirals [185] – [187]. This interaction is illustrated by the Triple Helix model, in which the cooperation of the government, industry and academia creates a common innovation space (see Fig. 1.1.). This model shows that each of the three spheres has its own function in the creation and use of knowledge, but it is in their overlapping areas that trilateral networks and hybrid organisations are formed - institutional and organisational structures that combine experience and resources from different fields.

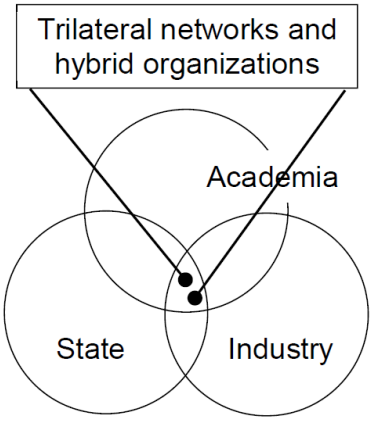


Fig 1.1. Illustration of the Triple Helix model (source: [187]).

Initially, this approach reviews the implementation and development of three stakeholder interaction innovations - university-industry-government by capturing the dynamics of both communication and organisation by introducing the notion of an overlay of exchange relations that feeds back on the institutional arrangements. It denotes the university-industry-government relationship as one of relatively equal, yet interdependent, institutional spheres which overlap and take the role of the other. Each stakeholder has its own role in the development and implementation of innovations in society - where the university as a source of new knowledge and technology (e.g. centre of excellence); industries are the locus of production and provider of customer demand; and the government as the source of contractual relations that guarantee stable interactions and exchange.

Three stages are considered essential for the successful deployment of new innovations [185]:

- The initial phase in the three-stage approach involves the establishment of "knowledge spaces" to facilitate the concentration of research and development efforts inside universities, business, or governmental entities.

- The establishment of a "consensus space" aims to unite individuals from diverse organisational backgrounds and viewpoints to formulate innovative tactics and concepts.
- The establishment of an "innovation space" aims to develop a novel organisational mechanism designed to fulfil the objectives outlined in the consensus space.

The main criticism addressed against this approach is that it typically ignores societal dynamics and civil society, making the concept originally better suited for innovation than social concerns [188]. Furthermore, because the model is insensitive to varying regional, cultural, or institutional settings, it is less effective in less developed countries with structural preconditions that differ significantly from those in advanced economies [188], [189]. As a result, this strategy occasionally oversimplifies the complex, dynamic nature of innovation systems, failing to consider new participants and variables that emerge throughout social change. This gap is especially evident in the fields of sustainability and climate governance, where policy success is dependent not just on technology and institutions, but also on behaviour and public acceptance.

Although the initially proposed method focuses on the interaction of universities, industry, and government, the issues of sustainable development in cities, such as the development of sustainable mobility, necessitate broader participation. Notably, the developers of the Triple Helix model underline that the number and composition of the required spirals may differ from the empirical setting [188].

Thus, some scholars and policymakers recommend expanding the existing Triple Helix model to include a fourth player: civil society, which includes both citizens (individuals) and non-governmental organisations. This approach adds a fourth spiral to the previously described strategy, resulting in the Quadruple Helix. In this way, more bottom-up efforts are included, resulting in a more inclusive and democratic system.

Society is separately distinguished in quadruple Helix models to recognize its unique and essential influence on innovations [190]. First, society is influenced by culture, social values and public engagement, which in turn shape the demand for acceptance of new ideas [191]. In this way, society brings in perspectives on social inclusion, ethical consideration and public needs, which are often overlooked in the Triple Helix models. Second, society's involvement ensures that the innovation implementation process is more democratic, transparent and reflecting broader public interests [188]. Legitimacy in innovation processes guarantees that decisions are accepted by the public, lowering resistance and improving the possibility of successful implementation, while transparency allows individuals to understand how decisions are made [192], [193]. This is significant because when individuals perceive that their voices are acknowledged and they have confidence in the process, it lowers doubt over disguised motives or elite manipulation, hence increasing the likelihood of their trust and support for new policies or technology [194], [195]. Third, local community development and wider involvement in innovation implementation can make this process more effective, especially in rural areas, where governments face difficulties in providing economically viable solutions [196], [197]. Rural areas are defined by unique characteristics, including a higher propensity for demographic decline and the associated reduction of public services, as well as a frequency

of insufficient infrastructural solutions, making top-down approaches less effective or relevant [198].

This chapter demonstrates that the Triple Helix remains a valuable framework for understanding the innovation process, but its application in the transport sector requires adaptation. Specifically, the inclusion of municipalities and citizens as active innovation agents.

1.4.2. ADAPTATION TO TRANSPORT DECARBONISATION: NATIONAL GOVERNMENT, MUNICIPALITIES AND SOCIETY

The original Triple Helix model approach (university-industry-government) views innovation as the result of the interaction between knowledge creation, product production and regulation. By applying this theory to sustainable mobility management, where there is also room for innovation, it extends beyond technological advancements – it outlines institutional, behavioural and policy innovations that collectively influence the transition to a climate-neutral transport system.

This Thesis employs a multi-level stakeholder perspective, guided by the principles of the Triple Helix and its subsequent extensions, to analyse the interaction between national policy, local implementation, and individual conduct in the decarbonisation of road passenger transport. Specifically, it examines how policies at various levels (national and municipal) influence and interact with individuals' mobility habits and behaviours. This study replaces the typical Triple Helix model with new subjects retaining the government while incorporating municipal and individual levels (society).

This adapted structure defines the following roles for the a forementioned stakeholders:

1. National level – the national level government is responsible for creating a conducive environment for innovation through regulatory frameworks, national strategy formulation and various support programs (such as transport tax reform, subsidy programs, and the implementation of the Renewable Energy Directive). The national government is also largely responsible for technological development and cross-sector research, which can be achieved by funding pilot projects and working with universities and private sector institutions.

2. The municipal level – the municipal level government acts as a link between policy development and implementation, turning national frameworks into local mobility policies. Municipalities play a key role, as they are not only policy implementers, but also innovators, experimenting with new governance tools including SUMPs, digital mobility management systems, and integrated emissions modelling tools (as discussed in this work).

3. The social level – This level is relevant for citizen involvement and actions. It is a section where behavioural innovation takes place: shifts in travel habits, a willingness to adopt sustainable transportation, and participation in co-creation processes. The spread of new ideas depends greatly on what people think, what they value, and how involved they are in their communities. Behavioural change is thus regarded as a socially innovative process that is accompanied by institutional and technological improvements.

In this approach, the industry and research sectors' inputs are indirectly represented in the technologies and measures being adopted, as well as other policies that encourage individuals to change their everyday habits. Industry contributes as an enabler, providing services (such as

transport systems, toll collection infrastructure, and data platforms) and generate essential data flows that support planning and innovation in municipalities. Meanwhile the science provides politicians with innovative research findings, technical advancements, and behavioural data to help with decision-making. In this way, their influence is captured through knowledge and technology flows within the policy-society interaction loop.

The industry sector contribution – On the one hand, it is considered that the national and municipalities' regulatory and incentive systems drive the industrial and commercial sector. For example, corporations' investment decisions are frequently influenced by current support (government subsidies), emission regulations, and other forms of support or restrictive measures. On the other hand, companies, also base their decisions on basic market principles of supply and demand, therefore industrial sector is analysed as an outcome rather than as an independent Helix. While it is understood that the private sector plays an important role as service providers and infrastructure developers, the analysis incorporates industry response without treating industry as a separate Helix.

The research sector contribution – The research sector is similarly considered, with academic contributors (such as battery improvements, hydrogen production technologies, or behavioural studies) being included into the analysis through the options and data used by policymakers and individuals. In this way, the research and development sector is incorporated through the technologies and data used by policymakers, not analysed as a separate strand.

As it was mentioned in previous chapter, in some cases the traditional Triple Helix is also adopted for other purposes. The original Triple-Helix approach, which examines the knowledge economy, is supplemented by the quadruple Helix method, which also includes knowledge society and knowledge democracy [199]. In this way, the role of civil society and citizens as active co-creators of innovation is recognised. However, there are studies that propose to go further and examine socio-ecological transition through quintuple Helix approach. This approach involves adding a fifth Helix – “natural environment” as an integral dimension of innovation processes [199]. This perspective combines knowledge and innovation to achieve ecological sustainability. In this way, sustainability is viewed not only because of innovation but also as its precondition. In this Thesis, the Quintuple Helix principles are included through the climate neutrality objective itself, which defines innovations as instruments for achieving sustainable climate neutrality.

To illustrate the mechanism of this adapted approach, Fig. 1.2 shows the connection between the national, local and societal levels, as well as their role in achieving climate goals that was discussed in Chapter 1.4.1. This structure reflects both a "top-down" process, in which strategic goals, legal frameworks and financing mechanisms are set at the national level, and a "bottom-up" approach, which is expressed in the actions of local governments and society, implementing practical solutions and behavioural change.

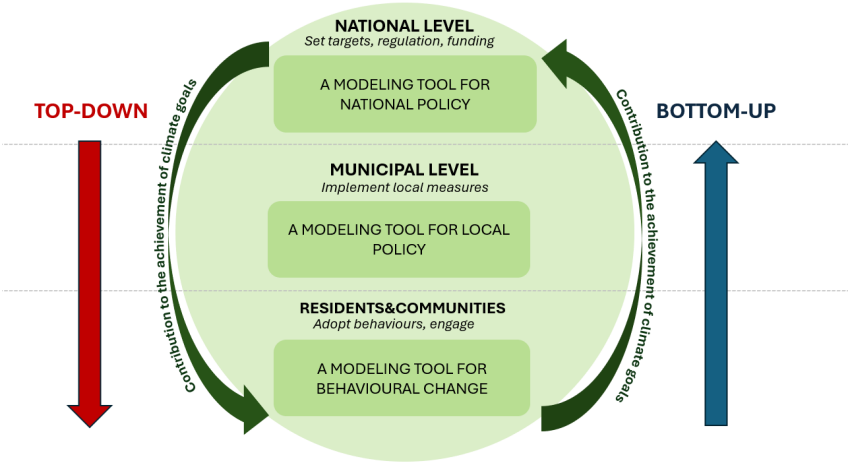


Fig. 1.2. Top-Down and Bottom-Up Interaction in Climate Policy Implementation.

In this perspective, the adaptation of the Triple Helix approach helps to capture both directions – the interaction between policy and society - by ensuring the link between national-level policy instruments and their implementation in the local context. Thus, this approach serves as a theoretical foundation for the following part of the work, which examines the use of similar strategies in the context of sustainable transport and local governance.

1.4.3. EVIDENCE ON MULTI-LEVEL STAKEHOLDER INTERACTION IN SUSTAINABLE MOBILITY

Although the original approach considers multiple levels of government (multinational, national and regional), most attention is paid to the national level, where overlapping institutional spheres exist, encompassing spaces of knowledge, consensus and innovation created at the intersection of spheres. However, studies are also being conducted that specifically look at the local government level [200], [201].

Research conducted in Germany indicates that municipalities are fundamental components of local innovation systems, with the Triple Helix model facilitating policy formulation and inter-institutional collaborations at the urban level [200]. Studies in Sweden used the Triple Helix method in the study of experimental governments in the municipalities of Stockholm and Gothenburg [202]. The results showed that the principles of such a method are already being used in practice, which indicates that this is not just a theory. However, shortcomings in the existing processes were also identified – insufficient transparency of the processes and elitism in the decisions made, as well as a general lack of citizen involvement, were observed. Such lack of information of citizens, even in cases where the decisions made directly affect their quality of life, can reduce the acceptance of the decisions made in society. The authors emphasize the need to create transparent structures so that it is possible to learn from previously made decisions rather than leaving them in a “black box”. This indicates a lack of data and appropriate tools in municipalities that would allow them to cooperate with citizens more effectively.

The study of the ethical dimension with the help of the Triple Helix model highlighted the role of individuals – so, not only institutional structures, but also the actions of individuals themselves "above duty" shape the success of innovations [203]. Thus, the study reveals that changing societal habits, such as switching to public transport or micromobility, can evolve from an initially altruistic action to a new societal standard. This supports the premise that individuals must be regarded as more than mere users of new technologies. They need to be regarded as active Helix agents whose ethical and behavioural decisions influence the efficacy of decarbonisation policies.

The reviewed studies emphasize the need to distinguish society (individuals) as a separate Helix in the context of sustainable mobility. Previous research rarely examines the triangle of society, local government and the national government in the context of transport decarbonisation. This Thesis addresses the gap by including stakeholders into a comprehensive analytical framework that connects technical transition, behavioural change, and coordinated policy formulation in the decarbonisation of road passenger transport. Thus, this chapter applies the premise of the Triple Helix and its extensions to justify the importance of stakeholder interactions in the decarbonisation of the transport sector. The approach further implements these stakeholder relationships through coordinated policy implementation, behavioural change, and technological transition.

Summary and conclusions of the literature review

The literature review summarised the main conceptual, policy, and methodological aspects of achieving climate neutrality in the transport sector. It was determined that the transport sector remains one of the largest sources of GHG emissions, and that decarbonisation requires both technological, behavioural, and institutional change. The analysis revealed that the current rate of decarbonisation is insufficient to meet the global and European goals, such as the emission reductions outlined in the European Green Deal.

The literature review evaluated the potential of individual technological solutions, the ASI policy framework, and the role of citizens and municipalities in achieving climate neutrality objectives. The literature emphasises that policy goals can only be achieved through a combination of "top-down" (national-level policies, regulatory instruments) and "bottom-up" (municipal and community initiatives) approaches. Municipalities are directly responsible for infrastructure, promoting mobility habits, and carrying out local initiatives; however, they frequently lack resources, data, and capacity.

This Thesis primarily examines the integration of technological transition, behavioural change, and coordinated policy implementation in evaluating decarbonisation pathways for road passenger transport. It employs the framework of stakeholder interactions, as outlined in the triple helix model and its variations, as a conceptual foundation for formulating a multi-level perspective on transport decarbonisation. It also provides a structured foundation for the study's scientific approach, which includes policy and technology evaluation, system dynamics modelling, scenario analysis, and empirical analysis of mobility behaviour and public acceptance. Thus, within the Thesis framework, this approach connects national policy with

local action and public participation together with assessment of how different combinations of technologies, policies and behavioural factors may influence the reduction of road passenger transport emissions.

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. They were chosen based on their potential for analysing policies, behaviour, and instruments and interactions between involved stakeholders (national, municipal, individual).

The research framework is designed as an integrated multi-level analytical approach, in which the decarbonisation of road passenger transport is considered by linking technological transition, policy implementation and population behavioural change. Such an approach enables the examination not only of the potential of individual technologies or policy initiatives, but also of their reciprocal interaction and implementation requirements. The research framework takes a multi-level approach to connecting the function of national-level policy and regulation, local government implementation capacity, and citizen decisions that influence transport system improvements.

The following methods were selected for establishing the research results:

- Bibliometric analysis was used to determine patterns in hydrogen technology development and policy direction in the transport sector industry.
- Causal loop diagrams method was used to structure the elements driving hydrogen introduction, as well as identifying feedback loops and systemic restrictions.
- Multi-criteria decision analysis (MCDA) was used for evaluating transport policies and technologies based on a variety of criteria, including social, economic, and environmental factors.
- System dynamics modelling was used:
    - to assess the development potential of biomethane,
    - to model national government policy impacts,
    - to model municipal level policy scenarios for estimating transport emissions and evaluating policy alternatives at the local level over time.
    - to assess the interaction between individual behaviour and national government policy.
- Empirical survey was conducted to better understand citizens' attitudes and willingness to change their travel habits, with a focus on the interaction between the public and municipal governments.
- Cost-benefit analysis (CBA) was used for determining the economic viability of employing electric vehicles in comparison to internal combustion engine vehicles.

The approaches were chosen for their capacity to provide qualitative insights into solving the challenges of decarbonisation in the road passenger transport sector. The combination of methodologies allows for the analysis of not only technological and political issues, but also social acceptability and behavioural factors.

2.1. Structural approach of study

The sequence of publications moves from identifying and evaluating technology and policy solutions to broader policy modelling, the perspective of local government implementation, public acceptance, and finally the integration of behavioural factors into a system dynamics model. The three analytical dimensions are not considered as separate blocks, but as interwoven elements that appear with different intensity in different publications.

To ensure the structure of the research process and methodological continuity, a logical research approach was developed in the doctoral thesis, consisting of six consecutive stages. In the first stage, technology and policy priorities were determined, identifying the most promising directions for decarbonizing road passenger transport. In the second stage, a more detailed assessment of individual technologies was carried out, analysing their potential, limitations and development prerequisites. In the third stage, national-level policy scenarios were modelled to assess the impact of various measures and their combinations on reducing GHG emissions. In the fourth stage, the analysis was supplemented with a perspective on the implementation of local governments, evaluating the role of the local level in implementing transport decarbonisation. In the fifth stage, public acceptance and support were studied, paying special attention to mobility habits and residents' attitudes towards various policy instruments. Finally, in the sixth stage, a behavioural modelling and integration framework was developed, which allows including behavioural factors in the overall analytical approach. Figure 2.1. describes the workflow of the study.

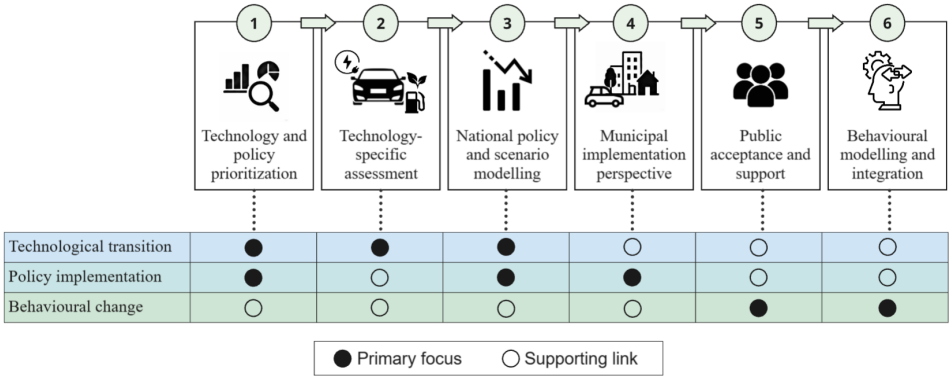


Fig. 2.1. Methodological structure of the integrated assessment framework.

The figure shows the logic of the six-stage research used in the doctoral thesis and its relationship to the three analytical dimensions: technological transition, policy implementation, behavioural change, and GHG emissions. Each of the six stages reflects a specific research focus, starting from the prioritisation of technologies and policies along with the integration of behavioural modelling. The black dots indicate the primary focus of the respective stages, the best white dots – the supporting connection with other dimensions. This figure shows that although the stages used are particularly important for a specific dimension, together they form an integrated analysis of the decarbonisation of road passenger transport.

Section 2.2.-2.8. further describes all the methods used in the development of the Thesis. The methodologies described in this chapter are organised based on their role in the study's structure and sequence of development, rather than chronologically. This sequence represents both the adaption of the Triple Helix approach (national government - municipality - society) and the logical progression from conceptual and economic models to their practical application and confirmation.

2.2. Multi-criteria decision analysis

MCDA is a general term for all the methods that exist to help people make decisions, even if the problem is complex or there are several conflicting criteria [204]. The application of the MCDA allows to make an informed decision, even if the criteria are contradictory [204].

The MCDA provides an opportunity to add weight to individual criteria that give different criteria different relative importance. This makes it possible to differentiate the contribution of different criteria in choosing the optimal alternative [204]. However, the weighting given to the criteria is to some extent subjective. One of the possible steps in the MCDA is to carry out a survey of specialists, which considers both the required criteria and their compliance with the final decision. Using a group of experts instead of one allows for a more objective assessment [204]. In this case, the risk of personal error is reduced. This makes it possible to differentiate the contribution of different criteria in choosing the optimal alternative [204].

One of the popular MCDA methods is Technique of Order Preference Similarity to the Ideal Solution (TOPSIS), which was first used by Yoon and Hwang in his work "Multiple Attribute Decision-Making Methods and Applications. A State-of-the-Art Survey" [205]. The TOPSIS method is based on determining the shortest distance to the ideal solution from the geometric point of view (in the Euclidean space).

The use of this method has also been widely used in the transport sector to assess sustainability, operational efficiency, and innovation in transport, helping prioritize policies that best align with long-term goals such as reducing emissions [206] – [208]. During this Thesis stage, TOPSIS algorithm was used to assess the potential of different alternative fuels and different transport sector's policy measures in Latvia. The necessity to systematically compare several factors that impact policy decisions, such as economic, technological, and sociological issues, supported the method's selection.

According to A. Shanian, O. Savadogo and Yoon and Hwang, the TOPSIS solution method consists of the following steps [209], [210].

1. Normalize the decision matrix. The normalisation of the decision matrix is done using the following transformation (Equation (1)):

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r^2{}_{ij}}}; j = 1,2,\dots,n; i = 1,2,\dots,m \quad (1)$$

2. Multiply the columns of the normalised decision matrix by the associated weights. The weighted and normalised decision matrix is obtained as (Equation (2)):

$$V_{ij} = n_{ij} w'_j; j = 1,2,\dots,n; i = 1,2,\dots,m \quad (2)$$

Where w'_j represents the weight of the *j*th attribute.

3. Determine the ideal and nadir ideal solutions. The ideal and the nadir value sets are determined, respectively, as follows (Equation (3) and (4)):

$$\{V_1^+, V_2^+, \dots, V_n^+\} = \left\{\left(\max_i V_{ij}\, Ij \in K\right), \left(\min_i V_{ij}\, Ij \in K'\right) Ii = 1,2, \dots, m\right\} \quad (3)$$

$$\{V_1^-, V_2^-, \dots, V_n^-\} = \left\{\left(\min_i V_{ij}\, Ij \in K\right), \left(\max_i V_{ij}\, Ij \in K'\right) Ii = 1,2, \dots, m\right\} \quad (4)$$

where K is the index set of benefit criteria and K′ is the index set of cost criteria.

4. Measure distances from the ideal and nadir solutions. The two Euclidean distances for each alternative are, respectively, calculated as (Equation (5) and (6)):

$$S_i^+ = \left\{\sum_{j=1}^n \left(V_{ij} - V_j^+\right)^2\right\}^{0,5}; j = 1,2, \dots, n; i = 1,2, \dots, m \quad (5)$$

$$S_i^- = \left\{\sum_{j=1}^n \left(V_{ij} - V_j^-\right)^2\right\}^{0,5}; j = 1,2, \dots, n; i = 1,2, \dots, m \quad (6)$$

Remark: In the so-called 'block TOPSIS' method, the two distances are obtained as (Equation (7)):

$$S_i^+ = \sum_{j=1}^n V_{ij} \quad (7)$$

5. Calculate the relative closeness to the ideal solution. The relative closeness to the ideal solution can be defined as (Equation (8)):

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}; i = 1,2, \dots, m; 0 \le C_i \le 1 \quad (8)$$

The higher the closeness means the better the rank. The methods for assessing the relative importance of criteria must be well defined. In the proposed methodology, the relative importance of criteria is clarified in an expert survey.

This methodology was employed to structure the prioritisation of policies and evaluate the potential of different technologies. Data, used in this study, was gathered through an expert survey that included 19 participants. The largest group of respondents were from the fields of research and was 7 respondents, while the public administration and municipalities had 4 experts in each sector. Industry was represented by 3 experts, while one respondent represented association or non-governmental organisation. In this way, the survey included representatives form science, policymaking, implementation and industry, all relevant to transport decarbonisation. Each expert had to evaluate both the 24 proposed transport policies, and five different kinds of alternative fuels.

Following a literature review, 24 policy instruments were selected. Countries with a high share of RES in transport, such as Sweden, Norway, Finland, the Netherlands and Austria, were analysed, along with the experiences of the Baltic countries (Estonia and Lithuania) and planned policy 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 full list of policy instruments is presented in detail in the results section, together with the expert ratings of each criterion. In the first part of the survey, all policy instruments were evaluated according to 4 criteria:

- required investments (P1), where 1 – the implementation of the measure does not require financial investment, and 10 – the implementation of the measure requires significant financial investments.;
- a monitoring mechanism (P2), where 1 – the implementation and monitoring of the measure is simple, and 10 – the implementation and monitoring of the measure is difficult;
- RES promotion potential (P3), where 1 – the measure has minimal or no effect on the increase of the share of RES, and 10 - the measure significantly affects the increase of the share of RES, and
- public support (P4), where 1 – the measure has no support or there is (is expected) minimal support in society, and 10 – the event has (is expected) high public support.

In the TOPSIS calculation, required investments and monitoring complexity were treated as cost criteria, while RES promotion potential and public support were treated as benefit criteria.

In the second part of the survey, respondents were asked to assess the potential of electric vehicles (EV), natural gas vehicles (CNG), biomethane vehicles (CBG), biofuel vehicles (BIO-F), and hydrogen (H2) vehicles in Latvia. The potential was evaluated on a scale of 1 to 5, considering the following aspects:

- Social aspect (F1), where 1 – support for the given technology does not promote the creation of social new jobs, and 5 – support for the identified RES promotes the creation of many jobs.
- Economical aspect (F2), where 1 – certain RES technologies are low-cost, and 5 – certain RES technologies are expensive.
- Environmental aspect (F3), in which 1 – the identified RES support will have a minor negative impact on the environment, and 5- the identified RES support will have a significant negative impact on the environment.
- Technological aspect (F4): 1 – Certain RES technologies are underdeveloped, 5 – Certain RES technologies are highly developed.

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.

In the third section of the survey, experts were asked to estimate the weights of all the factors and aspects mentioned above. The weights were estimated separately for policy instruments and fuel/technology assessment. The sum of the weights of both the policy assessment factors and the technology assessment aspect was 1, and these weights were used to weight the normalised matrix.

The TOPSIS approach, which enables identifying the best solutions based on the separation between the ideal and non-ideal solutions, was used once the data was collected. MS Excel was used for data analysis and the following steps were implemented:

1) a decision matrix was created from the average ratings of experts;
2) the matrix was normalised;
3) the weights of the criteria determined by the experts were applied;
4) the ideal and negative-ideal solutions were determined;
5) the distance to both solutions was calculated;
6) the relative closeness to the ideal solution was calculated;
7) the alternatives were ranked by relative closeness.

Recognizing the subjectivity of expert assessment, a sensitivity analysis was also carried out as a final step. During this, the weights of the criteria in both the policy and fuel/technology assessments were changed. The aim of the sensitivity analysis was to determine whether the ranking of alternatives changes significantly when the weightings are changed. Sensitivity analysis was performed by gradually changing the weight of one criterion and proportionally recalculating the weights of the other criteria so that the sum of all weights remained equal to 1. In the base scenario, all four criteria were assigned the same weight – 0.25. Then, the weight of the selected criterion was changed using the coefficients of variation $\beta k = 0.01; 0.5; 1; 1.5; 2$ and 3. Values below 1 characterize a reduced importance of the respective criterion, $\beta k = 1$ corresponds to the base scenario, while values above 1 characterize an increased importance of the criterion. This approach allowed us to assess the extent to which TOPSIS results depend on the choice of criterion weights.

Since expert assessments are subjective, the dispersion of opinions was also calculated with a 95% confidence interval, where a larger relative width of the interval indicates greater differences in expert opinions. Results of this study are presented in Section 3.1.

2.3. Cost-benefit analysis

As previously stated, the EU has determined that the decarbonisation of the transport sector should be based primarily on vehicle fleet electrification [27]. This has contributed to an increase in interest in these vehicles in terms of their long-term sustainability, considering the costs of fuel, maintenance, and taxes. At the time of the study, improvements in battery efficiency and cost reductions made this issue especially important, as Latvia lacked current analyses that included both economic and external (social and environmental) factors required for transport policy planning. To determine these life cycle analyses, a CBA was conducted, comparing the costs of EVs and internal combustion engine (ICE) vehicles.

A cost-benefit analysis is a systematic method for evaluating decisions that compares the overall estimated costs and benefits of a project, policy, or activity [211]. The primary premise is to choose an option if the benefits outweigh the costs, to maximize overall welfare or efficiency. A significant advantage of the cost-benefit analysis is that the analysis can consider not only economic aspects and indicators but also social and environmental aspects, including emissions and air pollution, climate change, noise and other aspects [212].

This study employed the CBA approach to determine the economic viability of electric vehicles and ICE vehicles (petrol and diesel) in Latvia. The analysis compared both new and five-year-old vehicles. The investigation aimed to establish which vehicle type is most favourable from an economic and socio-environmental standpoint, taking into consideration the entire life cycle (manufacturing, operation, and disposal). The analysis' structure included three main steps:

1. **Selection of car types and models.** The study examined three new and three five-year-old vehicles from Volkswagen vehicles. This choice of vehicles is justified by the need to ensure comparability. Therefore, vehicles of the same brand and similar class, comfort level and engine power are studied.
2. **Evaluation of total costs.** 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 system boundary included the vehicle's production, purchase, operation and end-of-life or disposal.
    a. **Evaluation of direct costs**. Direct costs included car purchase, maintenance, fuel or electricity expenses, taxes, and fees.
    b. **Evaluation of external costs.** External costs included air pollution, GHG emissions, noise. Environmental external 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. The social and environmental costs of each vehicle type were calculated using external cost guidelines and emission variables [213], [214]. The calculations also considered the expenses of electricity generation and battery disposal.
3. **Sensitivity analysis.** Sensitivity analysis was conducted to assess how changes in annual mileage, fuel and electricity prices, and CO_2 price affect the total cumulative costs of the analysed vehicles.

Results of this study are presented in Subsection 3.2.1.

2.4. 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 [215], [216]. For this study VOSviewer software was used, which is a scientometric

and knowledge graph analysis tool that has user-friendly interface design and reliable results [217], [218].

A bibliometric analysis of hydrogen technology development was included in the Thesis 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. Hydrogen is one of the main alternative energies, which is considered an essential element in achieving climate neutrality, therefore, the study of this topic provides a strategic context for the rest of the Thesis research. In the context of the Thesis, this study served as a systemic background analysis and scientific basis assessment that supports further modelling and policy evaluation. It complements other studies that analyse technology integration, cost-effectiveness and policy scenarios, creating a complete view of the possibilities of transport decarbonisation in Latvia.

This method helped to identify how hydrogen is positioned as a transport decarbonisation technology in the international scientific literature and what research directions, barriers and development trends are relevant for further technology evaluation. The aim of the article was 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 August 15, 2023. Articles, review articles, and conference papers in English only were analysed, and the initial overall search covered publications from 1975 to 2023.

The search string combined hydrogen-related keywords with sustainability- and SDG-related terms and sector-specific keywords.

The following request was used to obtain common insights: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR “sustainable development goal*” OR sustainability OR sustainable OR “sustainable development” OR “sustainability assessment” OR “sustainable energy” OR “sustainable energy systems” AND TITLE-ABS-KEY (sector AND industry) OR TITLE-ABS-KEY (sector AND power OR energy) OR TITLE-ABS-KEY (sector AND transport) OR TITLE-ABS-KEY (sector AND agriculture) OR TITLE-ABS-KEY (sector AND commercial) OR TITLE-ABSKEY (sector AND residential)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re) OR LIMIT-TO (DOCTYPE, cp)) AND (LIMIT-TO (LANGUAGE, English)).

Data were analysed using bibliometric performance indicators (publication dynamics, citations) and thematic mapping with VOSviewer software. A keyword co-discovery analysis was used to identify major research fields, with a particular emphasis on the transport, energy, industry, buildings, agriculture, and home sectors. Six sectors were analysed: energy/power, industry, transport, agriculture, commercial and residential.

Each publication was manually categorised by application sector. Furthermore, it was determined how frequently the study is linked to specific SDGs, as well as ideas like green hydrogen, circular economy, climate neutrality, and so on.

The doctoral thesis focused on the results of the transport sector, using comparisons with other sectors to contextualize the maturity and thematic focus of hydrogen-related research. To gain an insight into the stage of hydrogen development in the transport sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABSKEY (sdg OR

"sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND transport)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

Results of this study are presented in Subsection 3.2.3.

2.5. Causal loop diagram

Causal loop diagrams are visual tools for depicting and examining the feedback structure of complex systems. CLDs serve as a common language for collaboration, promoting the integration of various literary sources and enhancing comprehension of the examined subject [219]. 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.

The CLDs approach utilises 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 (balanced).

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 [220]. Other advantages include the ability to allow stakeholder involvement, which helps to identify crucial variables and feedback loops that policymakers must address [221]. Furthermore, its open structure allows for the supplementation of current CLDs, ensuring continual refinement and adaptability of the model [222]. The method also has drawbacks; for example, if too many parameters are introduced, they can become incomprehensible [223], while other authors express a lack of openness in documentation, noting that many publishers lack clear documentation about how the CLD was built [224]. Nevertheless, CLD has a great ability to depict the web of factors, stakeholders and feedback loops, which are very important to understand when introducing new technologies [225]. With its help, it is possible to determine how technical, financial, social, and policy variables interact, revealing reinforcing or balancing feedback that can accelerate or hinder technology uptake [225], [226]. Hydrogen is one of the innovative technologies that could be integrated into our daily lives in a variety of sectors, including transport, to achieve climate neutrality [27], [80]. To implement this technology more effectively, the CLD approach can be used, which helps to better understand dynamic, multi-factor interactions and feedback loops.

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 CLD methodology was employed to analyse the factors affecting the hydrogen economy. The methodology consisted of several parts.

The first part performed a literature analysis and desk research on hydrogen economy development factors. 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.

2.6. System dynamics modelling

System dynamics (SD) is a scientific approach where computer-based modelling and simulation are used to go beyond the systems structure and study how and why complex systems develop over time [227]. The structure of the model is intended to reflect a consistent description of the real system.

The concept of two-way causality, sometimes known as feedback, underpins system structure analysis. The concept requires linking decisions to data with regards to the state of the system or environment, which includes the decision maker himself. The purpose is to make judgments based on which actions will influence the state of the system. New system changes influence subsequent decision-making and, thus, future alterations. Each closed chain of causality defines a feedback loop; numerous such links interact to form patterns of SD [228].

Feedback loops in a system can be both positive and negative (Fig. 2.2.a). The nature of the loop determines how it affects the structure of the system under assessment. A positive (reinforcing) loop, for example, results in exponential development, whereas a negative (balancing) loop gets the system closer to an equilibrium point or objective. A negative loop with a delay can results in swinging behaviour, whilst a combination of positive and negative loops can result in an s-shaped behaviour pattern.

The system's structure and causal relationships are determined by the following basic elements (Fig. 2.2.b): variables, stocks and flows.

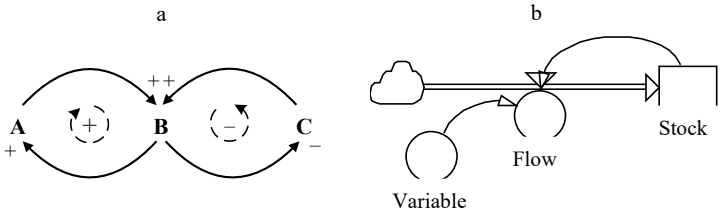


Fig. 2.2. Illustration of system dynamics modelling concepts: causal loop diagram (a); inventory flow diagram (b).

Stocks represent the accumulation of some material or information, such as emissions or population, over time. The amount of accumulation is determined by the intensity of flows (see Equation (9)).

$$Stock_t = Stock_{(t-dt)} + dt \cdot Flow_{(t,t-dt)} \tag{9}$$

Where:

$Stock_t$	– the size of the stock at time t;
$Stock_{(t-dt)}$	– stock size at time t-dt;
dt	– time interval;
$Flow_{(t,t-dt)}$	– flow rate affecting the stock during the time period from t-dt to t.

To calculate the exact volume in the time period from 0 to 1, an exact analytical solution with integration is used (see Equation (10)).

$$Stock(t) = \lim_{dt \to 0} \left[\sum_{t=0}^{t=1} Flow(t) \cdot dt \right] = \int_{t=0}^{t=1} Flow(t) \cdot dt \tag{10}$$

Flows are the only model component that can influence stock. A stock represents the simulation's current condition, but a flow depicts how the stock quantity changes over time. Unlike stocks, flows can be influenced by other model components, such as parameters and constants. Parameters are described using equations that match to the actuality of the real system.

System dynamics modelling is closely related to the CLD approach since it allows identification of initial system interactions, which can later be translated into SD models for simulation and analysis of diverse industries and processes [229].

The transport sector is a common focus of SD research [230] – [233]. It is used to investigate policies for various modes of transport, such as private vehicles, motorcycles, light and heavy trucks, and public transport buses [234], to identify the main barriers to the development of electric vehicles [235], and to evaluate the efficiency of urban rail freight transport systems, taking into account a variety of factors such as price, investment, social and environmental impacts, and subsidies [236].

System dynamics was used in four separate studies within the Thesis framework, each focusing on a specific aspect of the problem: national decarbonisation trajectories, assessment of the potential of a single technology, and the impact of behavioural factors on transport choice. The methodological Subsections 2.6.1.-2.6.4. provide detailed descriptions of each of these applications.

2.6.1. 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. For example, the first public natural gas filling station opened in 2019. 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 study on biogas potential and a comprehensive evaluation of policies aimed at increasing biomethane production. This study addressed this need.

The research methodology is based on SD modelling principles (see Section 2.6), which include 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;
- Modelling of CO_2 emission reduction depending on the chosen policy.

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.

Fig. 2.3. depicts the resource constraint and raw material cost balancing loop, which describes the core feedback mechanism for the created model.

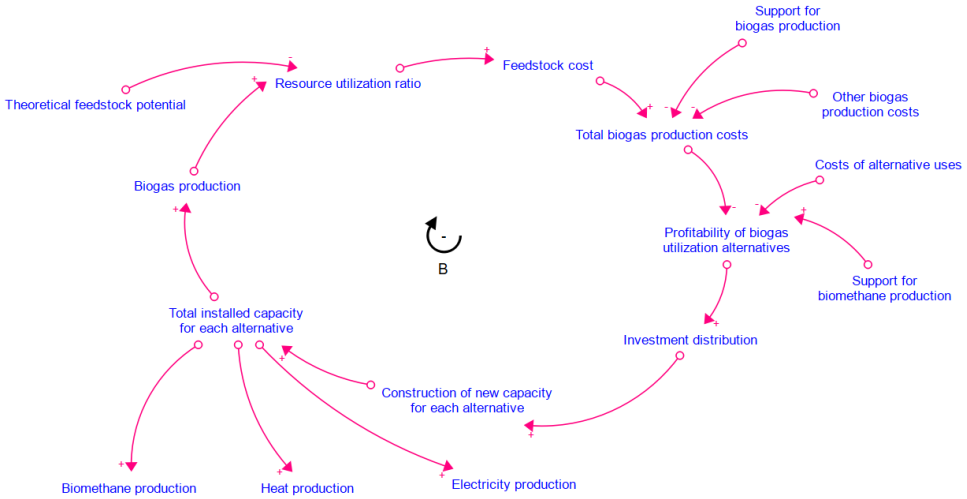


Fig. 2.3. Conceptual causal structure of biomethane production and potential use in transport.

The model is based on three main sectors: (1) Resource supply sector; (2) Biogas and biomethane production sector; (3) Transport demand (consumption) sector.

The resource supply model predicts changes in feedstock potential over time. The work considered feedstocks from the agriculture sector (maize, farming residues, manure of cattle, horse, pig, sheep/goat and poultry); from the waste management sector (biodegradable waste, landfill gas), and wastewater treatment sludge. The availability of feedstock is a limiting factor in biogas production. Thus, by determining the potential of each feedstock, the total biogas potential was also determined. Once the theoretical feedstock potential for biomethane production is determined, its ratio to the current feedstock demand is determined by the resource utilisation ratio, which in turn affects feedstock prices according to market mechanisms.

Feedstock costs are one of the parameters that influence the total costs of biogas production. There are also others, including capital costs for the construction of new plants and operational costs. The model also incorporates support mechanisms that can reduce the initial costs. The total costs of biogas are further used to determine the costs of alternative biogas uses. Thus, the biogas and biomethane production sector includes factors influencing biogas production capacity, as well as the following potential applications of the produced biogas: 1) Biogas use in CHP; 2) Biogas use for direct heat production; 3) Biogas upgrading (biomethane). To determine the proportion of use of each technology, the logit function described in Equation (11) was used.

$$S_i = \frac{exp^{\alpha C_i}}{\sum_j exp^{\alpha C_j}} \tag{11}$$

where:

S_i – market share of biogas utilisation alternative i;
α – coefficient representing cost sensitivity of market demand;
C_i – perceived operator's profit of using biogas utilisation alternative i;
C_j – perceived profit sum of all biogas utilisation alternatives.

According to Eq. (11) the larger is the perceived operator's benefit, the larger is the technology market share and vice versa. The perceived benefit (profit), *Pi* (EUR/MWh), is expressed as a percentage, where all costs (*Ci*, EUR/MWh) are subtracted from income (*Ii*, EUR/MWh), and the result is divided by income (Equation (12)):

$$P_i = \frac{I_i - C_i}{I_i} \tag{12}$$

The total cost *Ci* of each biogas utilisation alternative is calculated as a sum of three components (Eq. (13)):

$$C_i = C_{investment} + C_{feedstock} + C_{O\&M} \tag{13}$$

where:

$C_{investment}$ – investment costs per lifetime (EUR/MWh);
$C_{feedstock}$ – feedstock costs (EUR/MWh);
$C_{O\&M}$ – technology operation and maintenance costs (EUR/MWh)

These equations determine the investment distribution and, accordingly, the changes in the installed capacity of each alternative and the amount of heat, electricity and biomethane generated. After determining the demand for each alternative, the total demand for biomethane and, accordingly, its feedstocks are determined, which, together with the theoretical feedstock potential parameter, forms the resource utilisation ratio parameter, closing the loop described in Fig. 2.3.

To compare the current biomethane supply with the demand of the transport sector, empirical equations were created, based on historical data and future GDP projection, which was based on the calculations of the Ministry of Finance of the Republic of Latvia [237].

Figure 2.4. shows the core loops of the model structure in more detail, showing the individual cost, price, support and tax elements that affect the economic attractiveness of biogas and biomethane production.

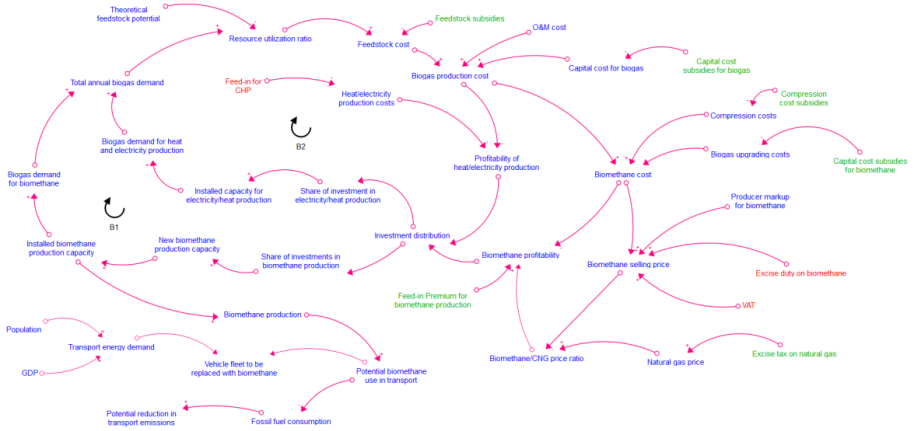


Fig. 2.4. Conceptual causal structure of the developed biomethane model.

The figure shows two basic loops that characterize the competition between different biogas use alternatives. Both loops are balancing, as higher profitability initially promotes investment

and capacity growth, but higher biogas demand increases resource utilisation and raw material costs, which in turn limits further profitability.

B1 – Biomethane profitability and feedstock cost balancing loop. This loop characterises the limiting mechanism for the development of biomethane production. As Biomethane profitability increases, Investment distribution and Share of investments in biomethane production increase, which promotes the growth of New biomethane production capacity and Installed biomethane production capacity. This increases Biogas demand for biomethane and thus also Total annual biogas demand. As total biogas demand increases, Resource utilisation ratio increases, which increases Feedstock cost and further also Biogas production cost. Higher biogas production costs increase Biomethane cost, which reduces Biomethane profitability. Thus, the initial increase in profitability has the opposite effect, which limits further development of biomethane capacity.

B2 – Heat/electricity production profitability and feedstock cost balancing loop. This loop describes a similar limiting mechanism in the case of heat and electricity production. As Profitability of heat or electricity production increases, Investment distribution and Share of investment in electricity/heat production increase, which contributes to the increase in Installed capacity for electricity/heat production. This increases Biogas demand for heat and electricity production and thus also Total annual biogas demand. Higher biogas demand increases Resource utilisation ratio, which increases Feedstock cost and Biogas production cost. This in turn increases Heat/electricity production costs and reduces Profitability of heat/electricity production. Thus, in this case too, the increase in capacity and production creates resource cost pressure, which balances the initial increase in profitability.

The full causal structure highlights in green the policy instruments that promote biogas or biomethane production, such as feedstock subsidies, capital cost support, compression cost support and support for biomethane production. In turn, red highlights the policy elements that increase the final cost of biomethane or hinder its competitiveness, such as excise duty on biomethane and VAT. These elements can be changed or excluded in the model to analyse the impact of different policy scenarios on the profitability of biomethane production and its potential use in the transport sector.

The model was validated by comparing market development projections with historical patterns and emission estimations with Latvia`s National Inventory Document data. After validating the created model with historical data, a set of policy instruments were applied to it, as well as their combined effect was tested. Applied policies are described in more detail in results section (Subsection 3.2.2.).

2.6.2. NATIONAL POLICY ASSESSMENT MODEL

During this phase of the research, a comprehensive system dynamic 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 [238].

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:

- Stage 1 – Policy measure identification and classification
    - Policy instruments for transport decarbonisation at the Latvian and EU levels were collated and classified by their type (regulatory, economic, informational) and purpose. The policy instruments were investigated by examining examples of good practice from the EU.
- Stage 2 – Development of cause-and-effect diagrams and model conceptualisation
    - Using literature and expert assessments, a conceptual scheme was created to depict the mutual influence of policy, technology development, and environmental effects.
    - This model considers the available biofuel volumes based on the feedstock available in the country. The agricultural and waste management sectors were considered as biofuel feedstocks. Passenger transport and freight transport were separately distinguished among fuel consumers. Passenger cars and public transport (buses, trolleybuses, trams and trains) were considered among the passenger vehicles. Trains and trucks were studied for freight transport. The potential for the use of six fuels was assessed (diesel, gasoline, LPG, natural gas, electricity, hydrogen).
- Stage 3 – Policy scenario simulation
    - 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 CO_2 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 section (Subsection 3.3.1.) describes the policy scenarios studied and the simulation results.

2.6.3. USER BEHAVIOUR MODELLING VIA SYSTEM DYNAMICS

One of the most important aspects of modelling the transport sector is behaviour modelling, because it is people's behaviour that determines the demand for various modes of transport. In the model described above (Subsection 2.6.2.), the behaviour of residents was described in a simplified way, without providing insight into what directly affects the changes. In turn, the literature analysis showed how important factors such as travel time, availability, cost, comfort, etc. are (see Subsection 1.3.2).

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 modelling technique is based on the previously published SD concepts but is strengthened with a parameterised decision logic. The dynamic hypothesis of the developed model is that mode shift from private cars to public transport does not depend on one factor only; isolated effects may overestimate the actual shift potential. Research consisted of three phases (Fig. 2.5.).

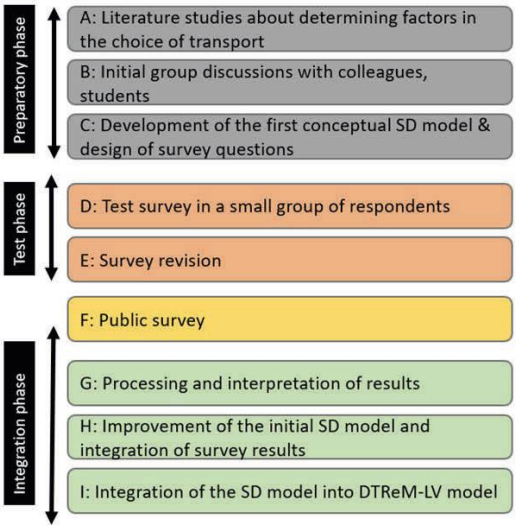


Fig. 2.5. Research methodology for behaviour influence integration into DTReM-LV model.

In the first (preparation) phase, a literature analysis was performed, as well as the initial concept of the SD model was developed. The literature analysis focused on determining factors that affect the transport choice. In this way, 11 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. Before distributing the final survey, the initial version of the questionnaire was tested on a small group of respondents, and several questions were shortened or reformulated to improve their clarity and reduce the risk of misunderstanding.

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

The survey used several types of questions: closed-ended questions, questions with the possibility of choosing multiple answers, rating questions on a scale, as well as some open-ended questions. Closed-ended questions were used to determine the respondents' travel habits, place of residence, income group and vehicle usage characteristics. Rating scales were used to assess the importance of factors influencing the choice of transport mode, the comfort of public transport and the availability of infrastructure. In turn, scenario-based questions were used to

determine respondents' willingness to replace some of their private car trips with public transport if the time spent on the road was reduced, comfort was improved or travel costs were changed. Some questions also allowed respondents to indicate numerical values, for example, the acceptable increase in car use costs or the number of trips out of ten that they would be willing to replace with public transport. The obtained data allowed for the analysis of responses by income group and place of residence, which was later used in the parameterisation of the model.

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 (Dynamic Transport emission Model for Latvia) [238]. The developed model further examined two of the five main factors influencing mode choice identified by the research, namely, travel time and cost. This study builds upon the previous work and aims to supplement the existing model to represent the inconvenience costs that are associated with public transport use. 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. Thus, the survey results were not used only as descriptive information, but also as an empirical basis for developing model assumptions, including the creation of graphical functions characterizing 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, and not as a representative assessment of the entire Latvian society. The results of the modelling are described in Subsection 3.4.2. Further is described the developed model.

MODEL DEVELOPMENT

Travel time factor

To assess the importance of the travel time factor, survey results were used, in which respondents described the current travel time needed to perform daily trips. This time was compared with the time that would be needed to travel by public transport, which was indicated by the respondents. Respondents also provide their assessment of the desired time ratio so that they would be willing to consider the possibility of changing to public transport. Based on these responses, travel time satisfaction curves were created, which are depicted in Fig. 2.6.

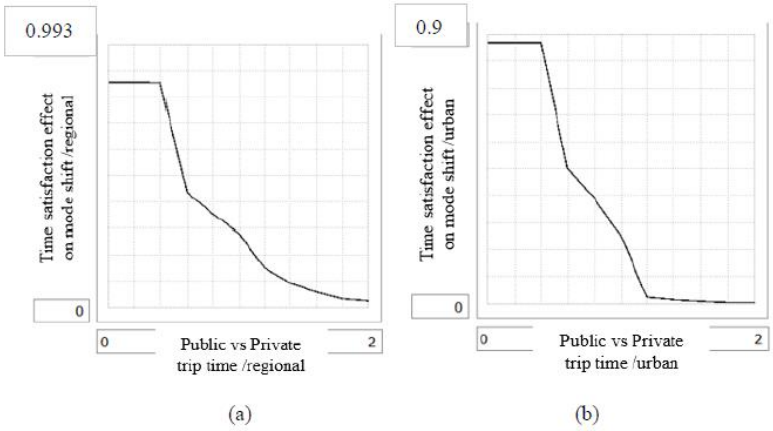


Fig. 2.6. Travel time satisfaction effect on mode shift (a – regional, b – urban) .

Based on the respondents 'answers, a time satisfaction effect on the mode curve is created according to the respondents' place of residence (urban and regional), which indicates the share of users who would switch to public transport. Respondents were also asked how many out of 10 trips they would replace if the public transport's travel time was significantly less than private cars. To understand how many people would switch the total time effect on mode shift is calculated according to the Equation (14).

$$E_{time} = T_{r\_time} \times S_{r\_time} \times R_{r\_time} + T_{u\_time} \times S_{u\_time} \times R_{u\_time} \quad (14)$$

where

E_{time} Time effect on mode shift
T_{time_r} Share of trips for income group out of all trips in regions of total trips
S_{time_r} Share of users who would switch to public transport in regions
R_{time_r} Share of car trips replaced in regions
T_{time_u} Share of trips in the urban area of total trips
S_{time_u} Share of users who would switch to public transport in the urban area
R_{time_u} Share of car trips replaced in the urban area

The overall structure of the travel time effect is represented in Fig. 2.7.

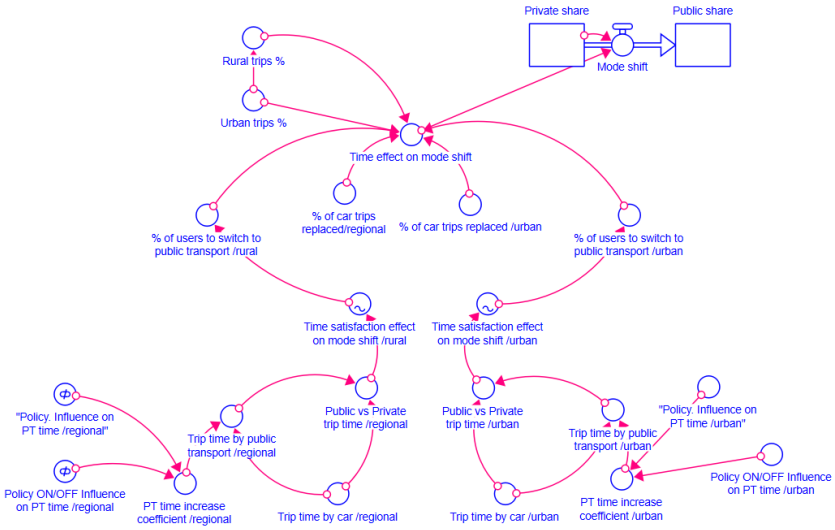


Fig. 2.7. Travel time effect on mode shift.

As the result, the difference in the share of public transport users is modelled.

Travel cost factor

To determine the cost effect on travel mode choice, respondents were divided into three income groups and asked about their average monthly car expenses as well as the maximal average monthly costs of a private vehicle exceeding which they would switch to public transport. These costs were compared and the cost satisfaction effect on mode shift was developed (see Fig 2.8.)

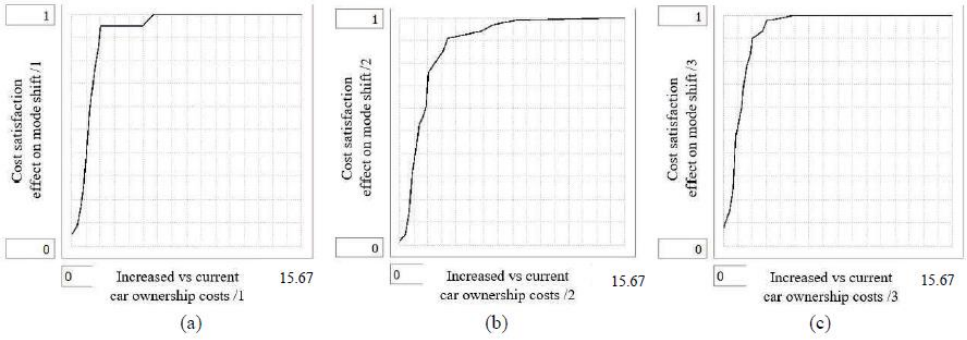


Fig. 2.8. Travel cost satisfaction effect on mode shift according to household income group (a – up to EUR 750 per household member, b – EUR 750-1500 per household member, c – over EUR 1500 per household member).

To understand how many of them would switch towards public transport question “Let’s imagine that using a private car remains very expensive (rising fuel prices, parking fees, taxes, etc.) and that makes you consider alternatives. What will be your choice?” was asked with following possible responses:

1. I will travel by public transport
2. I will walk
3. I will ride a bicycle
4. I will combine the above
5. I will still drive a car, but I will look for fellow passengers
6. I will still drive the car, but I will combine it with other modes of transport (I will reduce the number of trips made by car)

The maximal population accepting public transport alternative (people who would switch towards public transport use) was calculated by summing up the share of respondents who chose the first and fourth answers. The share of people who would switch to public transport was calculated accordingly to Equation (15):

$$S_{cost\_i} = SE_{cost\_i} \times M_{cost\_i} \quad (15)$$

where

S_{cost_i} The share of people who would switch to public transport
SE_{cost_i} Cost satisfaction effect on mode shift
M_{cost_i} Maximal population accepting public transport alternative
i Income group

To understand how many people would switch due to travel cost, the total cost effect on mode shift is calculated according to the Equation (16).

$$E_{cost} = T_{cost\_i} \times S_{cost\_i} \times R_{cost\_i} \quad (16)$$

where

E_{cost} Cost effect on mode shift
T_{cost_i} Share of trips for income group out of all trips of each income groups
S_{cost_i} Share of users who would switch to public transport of each income group
R_{cost_i} Share of car trips replaced of each income group
i Income group

It was assumed that the share of the urban trips was 68% while the share for the regional trips is 32% according to the statistics [105]. The share of the car trips that should be potentially replaced was taken from the survey results.

The overall model structure for travel cost effect on mode shift is represented in Fig. 2.9.

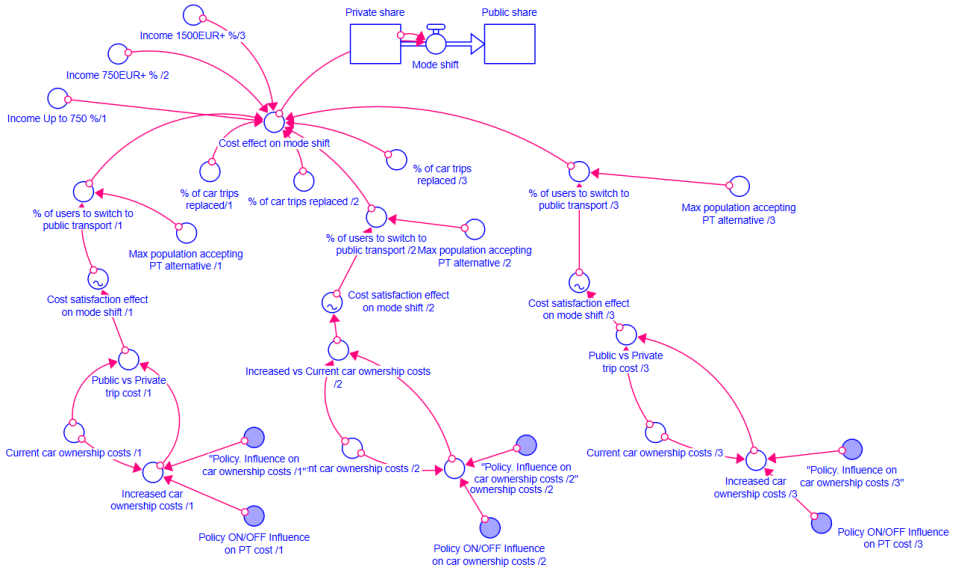


Fig. 2.9. Travel cost effect on mode shift.

As a result, the difference in the share of public transport users is modelled.

Combined effect of travel time and travel cost factors

To get the total impact of travel cost and travel time effect on mode shift both previously shown models (Fig. 2.8. and Fig. 2.9.) were put together (see Fig. 2.10).

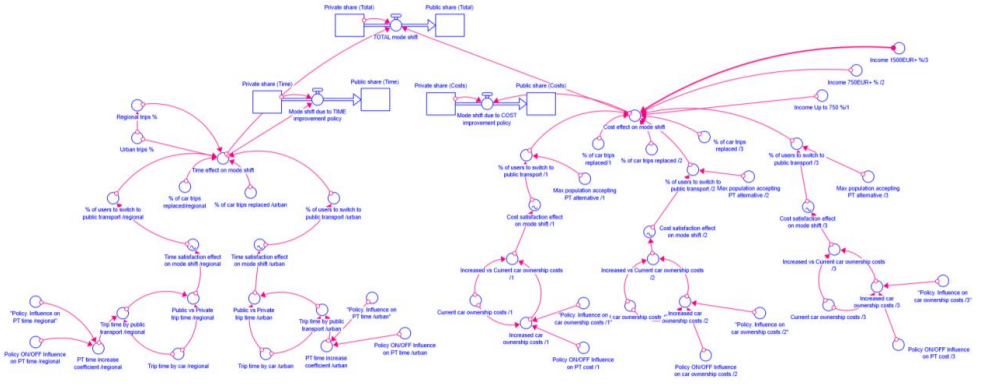


Fig. 2.10. Total effect on mode shift.

The total mode shift is calculated using Equation (17).

$$Total\ mode\ shift\ (\%) = Private_{share} \times E_{time} \times E_{cost} \qquad (17)$$

where

Total mode shift	Rate of share change of people who uses public transport
$Private_{share}$	Share of people who uses private cars

E_{time}	Time effect on mode shift
E_{cost}	Cost effect on mode shift

Lastly, public transport share is calculated by using Equation (18). The share of each transport mode (Public transport and private cars) is assumed to be accordingly to the statistics.

$$Public\ transport_y = Public\ transport_{(y-1)} + Total\ mode\ shift \quad (18)$$

where

Public $transport_y$	Public transport users at a year y
Public $transport_{(y-1)}$	Public transport users in the previous year (in 2020 = 0.18)
Total mode shift	Rate of share change of people who uses public transport
y	Year

2.6.4. 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 modelling principles was developed.

A scenario-based model tailored to the municipal level to assess the influence of transport policies on GHG emissions through 2050 was developed. The purpose of the model is to assess the role of the transport sector in the overall municipal GHG emissions balance and to assess possible ways to reduce these emissions. 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). The model was developed in *Stella Architect* software using system dynamics principles and a stock-flow structure. This approach was used to depict changes in transport activities, vehicle structures, energy consumption and emissions over time under the influence of different policy scenarios. The main goal of such a model was to provide a transparent, relatively simple in terms of data and practical tool for municipalities to compare scenarios and support decision-making. Another novel aspect is the user-friendly interface of the simulation tool. The aim of the developed interface is to help municipalities better understand their transport sector and its impact, as well as to promote evidence-based decision-making to achieve climate targets. Another aim was to support communication between decision-makers and stakeholders for better policy implementation.

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 figure (Fig. 2.11.) illustrates the model development process. 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.

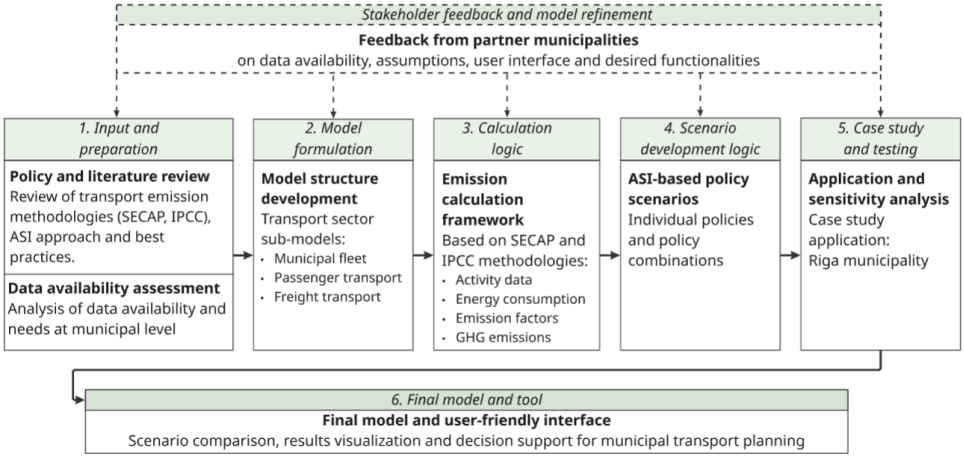


Fig. 2.11. Model development process for the municipal transport emission scenario modelling tool.

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. Representatives of the municipalities 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:

- Municipal fleet – where the municipality may provide more precise statistics on mileage, fuel consumption, and fleet structure.
- Passenger transport – which is dependent on population travel patterns, mobility demand, and vehicle option distribution.
- 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. Thus, the developed model allows users to determine transport

activities, their associated energy consumption and the amount of GHG emissions generated from the base year to 2050.

Further, several policy instruments were incorporated into the model, which correspond to the ASI approach, providing the opportunity to test both individual policies and combinations of policy instruments. All developed policy instruments are listed in the results section (see table 3.5.). After the policy instruments were incorporated into the calculation structure, they were also included in the user interface, which allows the target audience to analyse various municipal development scenarios without in-depth knowledge of the model structure. The final version of the model was refined based on comments from municipal representatives on its practical usability, input data requirements and display of results.

Emissions from the transport sector are calculated by multiplying fuel consumption in each transport group by appropriate emission factors. Emission factors, energy content and fuel density are considered calculation parameters in this model, not mandatory input data to be provided to the municipality. The model allows for modification of these parameters, but if specific values are not available to the municipality, default values based on IPCC, SECAP or national GHG inventory methodologies can 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: promoting remote work and e-services, optimising the municipal car fleet;
- "Shift" (S) strategies: optimistic and moderately ambitious rate of replacement of private cars with public or active mobility;
- "Improve" (I) strategies: encourage switching to more efficient vehicles, increase the use of renewable energy sources, and ban 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 boundaries of the developed model are the territory of the municipality and those transport processes that can be described with municipal or publicly available data. Transport activity and corresponding fuel consumption are determined from the municipality's input data. The necessary data for the model are summarised in Table 2.1.

2.1. table

Input Data and Calculation Logic of the Municipal Transport Emission Scenario Model

Model component	Required input data	Calculation logic
Municipal vehicle fleet	Number of vehicles by type and fuel, annual mileage, fuel/energy consumption, fleet structure	Emissions are calculated using required input data by determining the total energy consumption and then multiplying it by the emission factor of the relevant energy source.
Passenger transport	Population, migration, number of trips or travel intensity, distribution of transport modes, distance travelled, vehicle load, fuel/technology distribution	Passenger transport activity is calculated using required input data and then linked to the efficiency of the vehicles, the fuel or energy used and the corresponding emission factors.

Freight transport	Freight transport demand, vehicle type, fuel structure, mileage or activity assumptions	Freight transport activity is calculated using required input data and then linked to the efficiency of the vehicles, the fuel or energy used and the corresponding emission factors.
Policy scenarios	Start/end years of ASI policies, target values	For each scenario, the selected model parameters are changed according to the assumed impact of the policy instrument. Avoid policies affect travel demand, Shift policies affect the modal split or vehicle load, while Improve policies affect vehicle efficiency, technology mix or energy mix. The model recalculates emissions for each year up to 2050.

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.

2.7. 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. Empirical surveys are frequently used in research for gathering data from large groups to analyse trends, correlations, and draw general conclusions. This approach is particularly popular in the social sciences, business, healthcare, and software engineering, where researchers want to test ideas and construct models using real data [239], [240]. To ensure dependability and accuracy, a thorough questionnaire must be carefully designed, tested, and validated. This procedure involves defining variables, formulating clear questions, and applying statistical methods to evaluate reliability and validity [241].

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 Pałecznica 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. Therefore, the results were interpreted as a comparative insight into the mobility habits and policy preferences of the population of the selected Baltic Sea region territories, and not as fully representative results at the national level.

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 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. Open-ended questions allowed respondents to supplement their answers with individual comments and indicate locally specific mobility restrictions that were not always included in the predefined response categories.

Descriptive statistics were used to analyse the survey data. The analysis included calculating the percentage distribution of responses for each question and comparing the results 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 survey question blocks and their further use in the analysis are shown in Table 2.2.

2.2. table

Survey Question Blocks and Their Use in Analysis

Survey block	Main variables	Question type	Use in the analysis
Sociodemo-graphic characteristics	Country, municipality or territory, age group, household characteristics, type of residence	Multiple choice and numerical questions	Used to characterise the respondent population and compare results by country, age group and type of residence.
Mobility patterns	Travel frequency, main purpose of travel, most frequently used mode of transport, factors influencing the choice of transport mode	Single-choice, multiple-choice and open-ended questions	Used to determine dominant mobility habits, travel purposes and factors influencing the choice of transport mode
Assessment of municipal action in the transport sector	Respondents' assessment of the extent to which municipal services, infrastructure and initiatives promote environmentally friendly mobility	Rating scale question and open-ended comments	Used to assess public perception of municipal transport policy and identify local mobility challenges
Support for transport policy measures	Respondents selected supported transport policy measures from a predefined list, as well as the option to indicate another measure	Multiple-choice question with the possibility to indicate "other answer"	Used to identify the most supported policies and classify them according to the ASI approach

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 [242]. The results of the survey analysis are described in Subsection 3.4.1.

2.8. Justification and integration of method selection

The study of the road passenger transport sector's decarbonisation encompasses multifaceted issues such as technical progress, policy efficacy, societal behaviour, and local government capacity. The analysis of such complex systems necessitates a multidimensional research strategy that may connect qualitative and quantitative features, as well as stakeholders at many levels (national agencies, municipalities, and residents).

Multi-criteria analysis was used to analyse various policy and technology solutions in an organised manner, evaluating them based on environmental, economic, and social criteria. It acted as a link between technological analysis and public acceptance. In turn, cost-benefit analysis enabled the evaluation of the cost-effectiveness of electric vehicles in comparison to internal combustion engine vehicles, providing an initial economic rationale for future investigation. Causal loop diagrams provided a conceptual framework for structuring the factors impacting hydrogen technology development, as well as identifying systemic hurdles and reinforcing mechanisms.

System dynamics modelling allowed for the long-term analysis of transport development scenarios, considering both the impact of national-level legislation and changes in societal behaviour. In addition, a system dynamics model for estimating transport emissions in municipalities was created as a practical application of the theoretical findings.

The empirical survey collected information on public behaviour, perception, and preparedness to modify transport habits, as well as the perspectives of citizens and municipalities on the challenges to sustainable mobility. These data were utilised to validate the models and uncover synergies at both the individual and municipal levels.

Overall, the mix of methodologies enabled researchers to investigate the decarbonisation of the transport sector from both a systemic and user perspective, connecting policy instrument effectiveness to public readiness for change and local government capacity. This approach enables policymakers at all levels of government to make sound recommendations based on both theoretical models and empirical facts.

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 emphasize 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) and the methodology of which is described in Section 2.2.

Achieving climate neutrality requires the introduction of additional policy measures, as the current path will not achieve significant emission reductions. Policymakers can choose from a variety of initiatives addressing both the mobility habits of residents and the development of public transport, as well as promoting the development of various alternative fuels. The MCDA study serves as a first step in prioritizing 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.

Table 3.1 continued

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.
Biofuel / biomethane support	9. Increasing the mandatory biofuel blend.
	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.
	10D. Proofs of origin for biomethane.
Urban mobility measures	11A. Free parking for zero-emission and low-emission vehicles.
	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.
Public transport and rail measures	13. Electrification of the railway network.
	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 results reflect 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 obtained by performing MCDA analysis for all policy instruments according to the assessments provided by experts and the weights of all criteria.

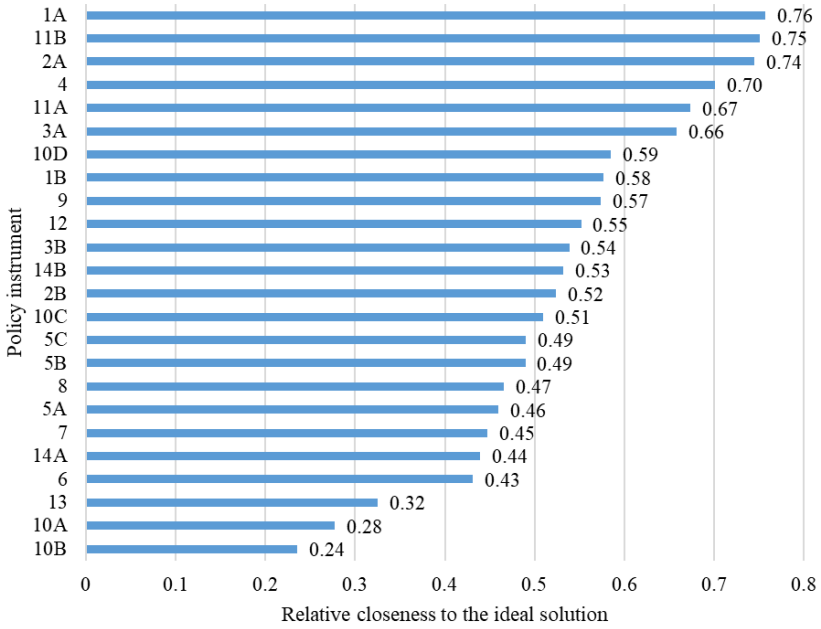


Fig. 3.1. Relative closeness to the ideal solution of policy instruments.

The highest-rated policy instruments mainly fall into the tax incentives and urban mobility measures groups. 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). 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.

To avoid over-interpretation of the results of individual instruments, the policy instruments were also analysed at the level of thematic groups (Fig. 3.2.). This allows for comparison not only of individual measures but also of broader policy directions.

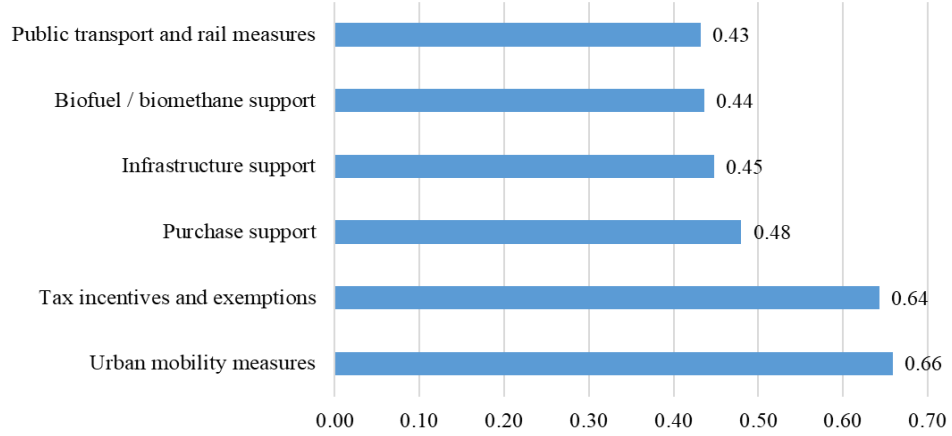


Fig. 3.2. Average TOPSIS relative closeness by policy group.

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 analysis of the contribution of criteria, based on the distance from the positive ideal solution, shows which criteria most constrained the evaluation of each policy group (Fig. 3.3.). Therefore, a larger part of the bar means that the respective criterion is more restrictive in assessing the specific policy group. The analysis was performed by dividing the average

distance of each policy group from the positively ideal solution by four TOPSIS criteria: required investments, monitoring mechanism, RES promotion potential and public support.

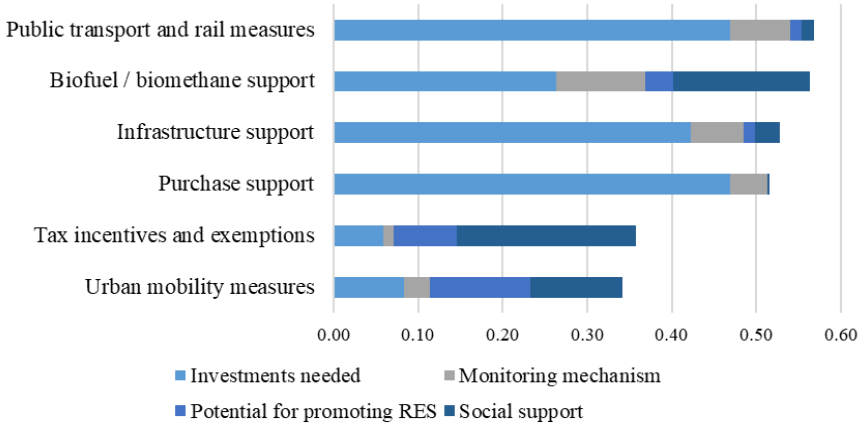


Fig. 3.3. Limiting criterion contributions for policy instruments: distance from the positive ideal solution.

For capital-intensive groups, such as infrastructure support, acquisition support, as well as public transport and railway measures, the greatest distance from the ideal solution was formed by the necessary investments. In contrast, the tax incentives and urban mobility measures groups were less constrained by this criterion, which helps to explain their higher average TOPSIS evaluation.

It should be noted that the results obtained come from subjective opinions. Therefore, to investigate the robustness of the TOPSIS results, a sensitivity analysis was performed by changing the weights of the individual criteria. 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. Measures that perform well when investment needs are prioritised may not perform well when RES promotion potential is prioritised. Similarly, capital-intensive measures may receive lower overall TOPSIS scores, despite their importance for long-term emissions reduction. 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 (Table 3.2.). Wider confidence intervals indicate greater differences in expert opinions on the importance of the respective criterion.

Table 3.2

Dispersion of The Weights of Criteria for Evaluating Policy Instruments

Criteria for evaluating policy instruments	Weight of criteria	The dispersion of the weights
P1 - required investments	0.33 ±0.09	26.72%
P2 - a monitoring mechanism	0.19 ±0.08	42.94%
P3 - RES promotion potential	0.25 ±0.09	35.77%
P4 - public support	0.23 ±0.08	33.59%

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 5 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. 3.4.

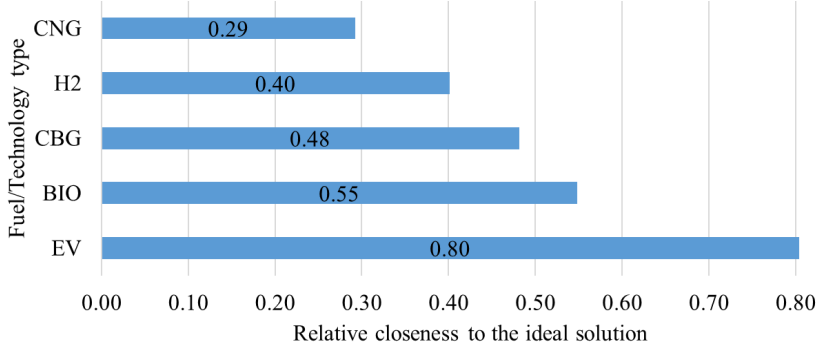


Fig. 3.4. Relative closeness to the ideal solution of each selected fuel type.

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. To investigate how the technology evaluation changes depending on the changes in the weight of the criteria, a sensitivity analysis was performed. The results are presented in Fig. 3.5.

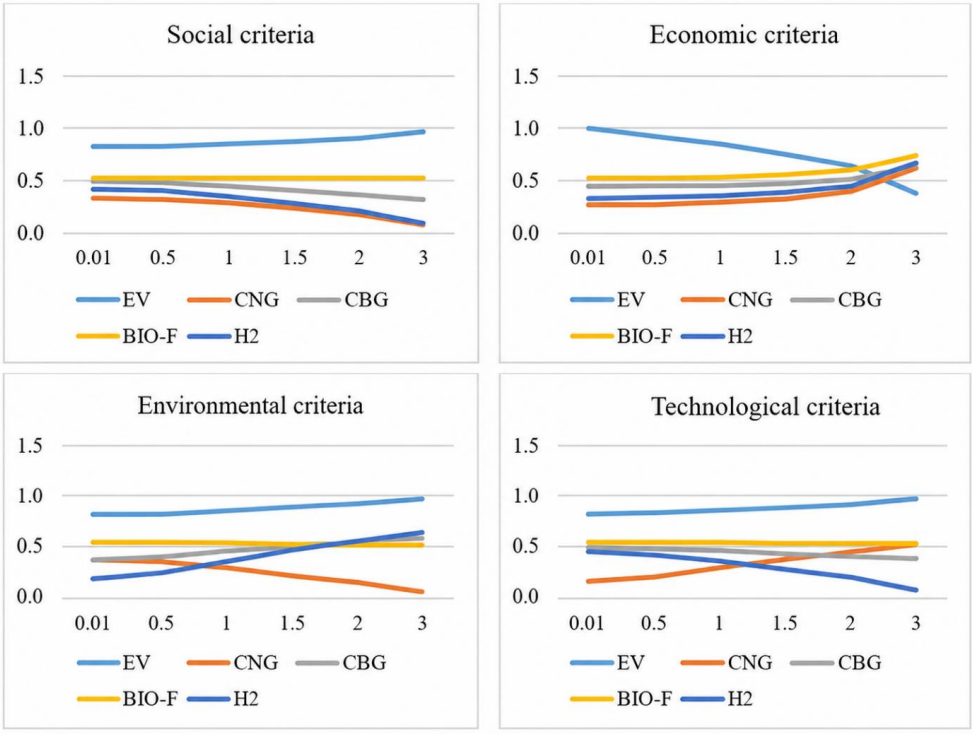


Fig. 3.5. Sensitivity analysis for fuel evaluation.

Sensitivity analysis showed that the evaluation of technologies depends on which criterion is given greater importance. As the importance of environmental and technological criteria increased, electric vehicles maintained a high rating, while hydrogen became more favourable. By changing the weight of the economic criterion, the relative positions of individual alternatives also changed, indicating that cost assumptions played a significant role in the evaluation of technologies. However, the overall trend remained unchanged – electric vehicles received the highest rating, while natural gas retained the lowest position.

Additionally, the dispersion of the weights assigned to the criteria by the experts was also analysed using 95% confidence intervals (Table 3.3.). Wider confidence intervals indicate greater differences in expert opinions on the importance of the respective criterion.

Table 3.3

Dispersion of The Weights of Criteria for Evaluating Alternative Fuels and Vehicle Technologies

Criteria for evaluating policy instruments	Weight of criteria	The dispersion of the weights
F1 – social aspect	0.22 ±0.09	41.08%
F2 – economic aspect	0.31 ±0.07	22.38%
F3 – environmental aspect	0.25 ±0.09	35.49%
F4 – technological aspect	0.21 ±0.09	41.08%

Thus, the technology assessment shows that there is no one-size-fits-all solution for decarbonizing 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”, the methodology of which is described in Section 2.3.

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. 3.6.

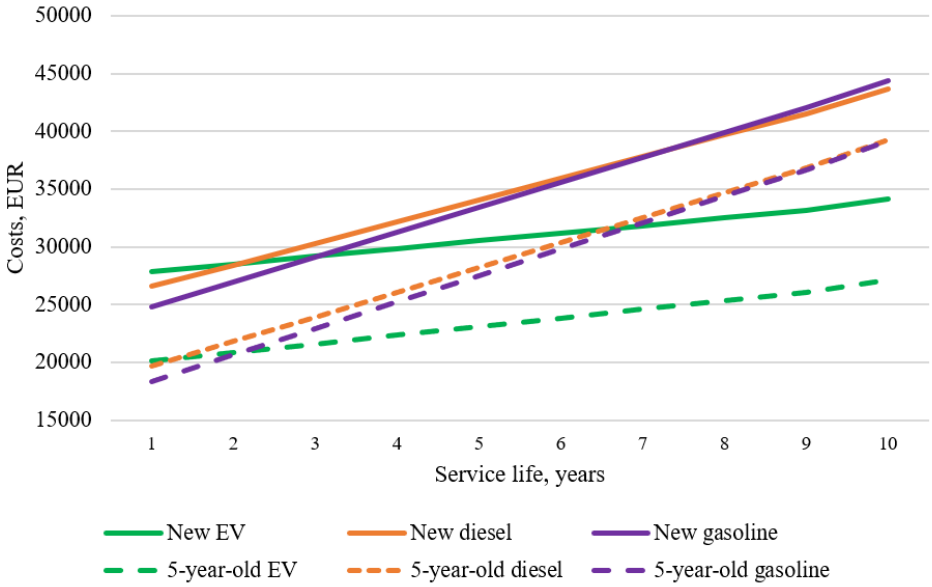


Fig. 3.6. Comparison of total calculated cumulative costs of different technologies.

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 a 10-year period, 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 CO_2 price on the results (Fig. 3.7. – 3.9.). 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.

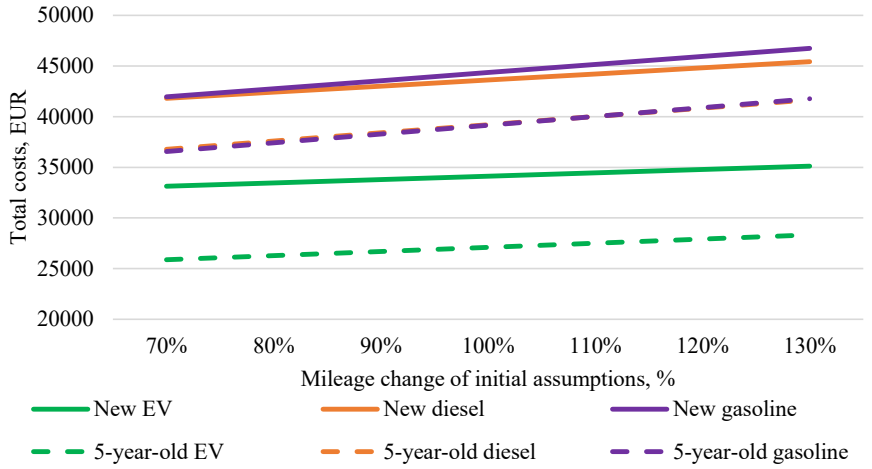


Fig. 3.7. Sensitivity analysis results for mileage parameter.

It was determined that changing the initial assumptions on mileage from 70 % to 130 %, the price of ICE increases by 8.7 % for diesel and 11.4 % for gasoline-powered vehicles, while EVs caused a price increase of only 6 % for new vehicles (see Fig. 3.7.). In turn, for 5-year-old vehicles, the price changes were not more significant – 13.3 % and 14.2 % for diesel and gasoline-powered vehicles, respectively, while EVs increased by 9.5 %. Therefore, it was found that the advantage of EVs over internal combustion engines increased with mileage.

Meanwhile, rising fuel and CO_2 costs affect ICE vehicles more than EVs, so the relative advantage of EVs increases in such scenarios. Thus, as fossil fuel and CO_2 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.

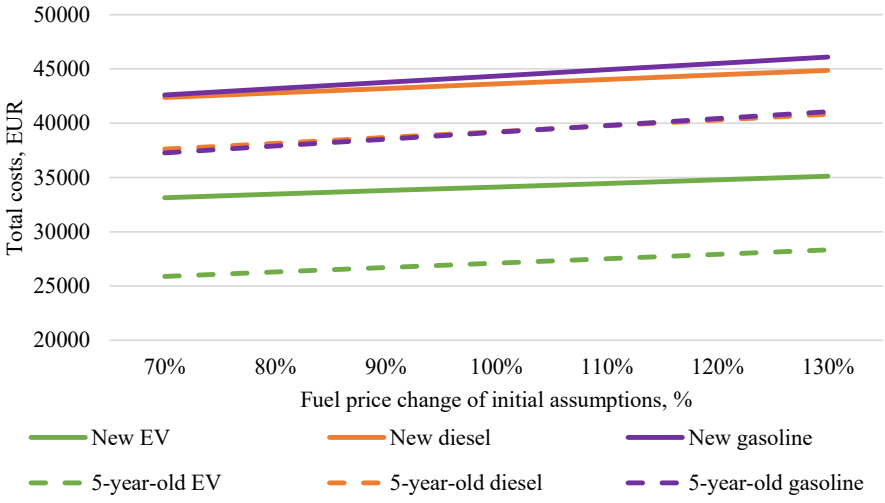


Fig. 3.8. Sensitivity analysis results for fuel price parameter.

The sensitivity analysis of fuel and electricity prices shows how the total cost of vehicles changes as direct energy costs increase or decrease (see Fig. 3.8.). Since ICE vehicles are more dependent on fossil fuel consumption, increases in fuel prices increase their total cost more significantly (8.2-8.5% for new vehicles, and 9.5-10.2% for five-years-old vehicles), while the increase in EV costs is more moderate (<6% for both age categories).

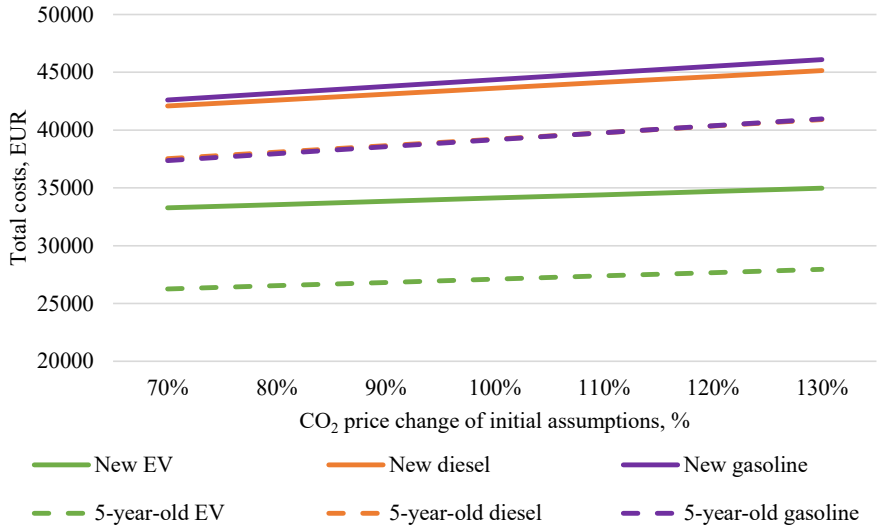


Fig. 3.9. Sensitivity analysis results for CO_2 price parameter.

A similar sensitivity analysis was also performed for CO_2 costs (see Fig. 3.9.). This parameter was analysed separately because it does not reflect the end-user costs, but rather the monetisation of external costs caused by climate change. Therefore, an increase in the CO_2 price specifically affects the total costs of ICE vehicles, while in the case of EVs the impact is mainly related to the emissions of electricity generation.

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 the stereotypes of 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 section 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 Section 2.6.1.

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. 3.10. 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.

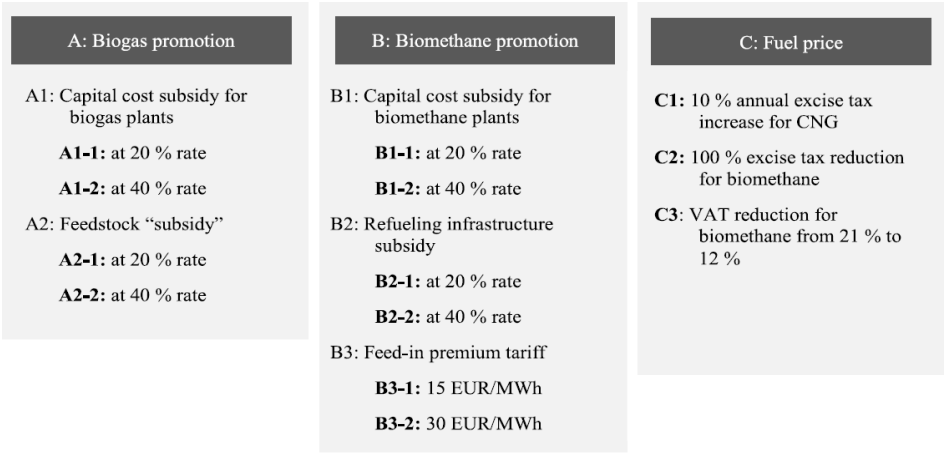


Fig. 3.10. Summary of policy instruments tested in the model.

In addition to the policies described in Fig. 3.10., 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 3.11.).

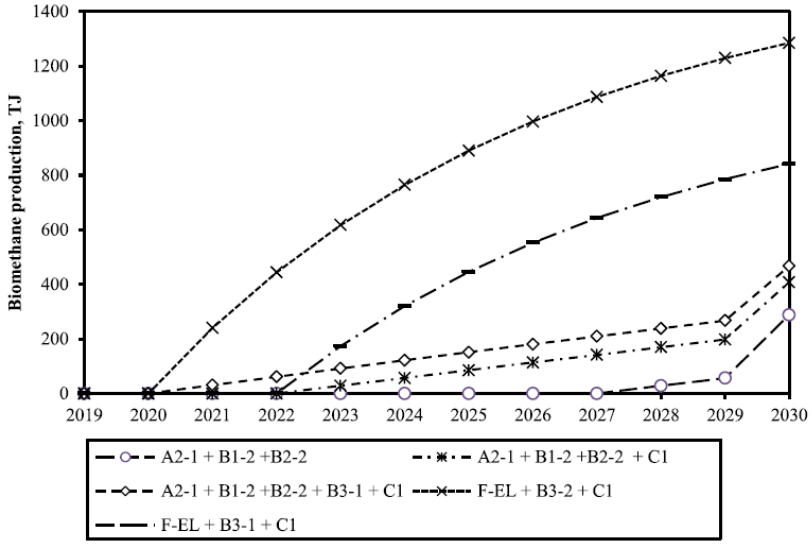


Fig. 3.11. The effect of a selection of combined policies on biomethane production (A breakdown of the policy instruments is available in Fig. 3.10.).

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
- It is possible produce around 250 mil. m^3 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 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 decarbonize, such as aviation and heavy road transport. More on the potential of hydrogen and the related legislative documents are described in Chapter 1.3.2.

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 2.4. 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. This result helps explain why hydrogen utilisation in transport sector should be viewed with caution – as a potential complementary solution for specific applications, not as a universal solution for decarbonizing road passenger transport.

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.

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.

Keyword co-occurrence analysis revealed four main clusters (see Fig. 3.12.). The first relates to fuels, emissions and climate aspects, the second to energy, storage and hydrogen economy, the third to transport and mobility, and the fourth to economic analysis and decision-making.

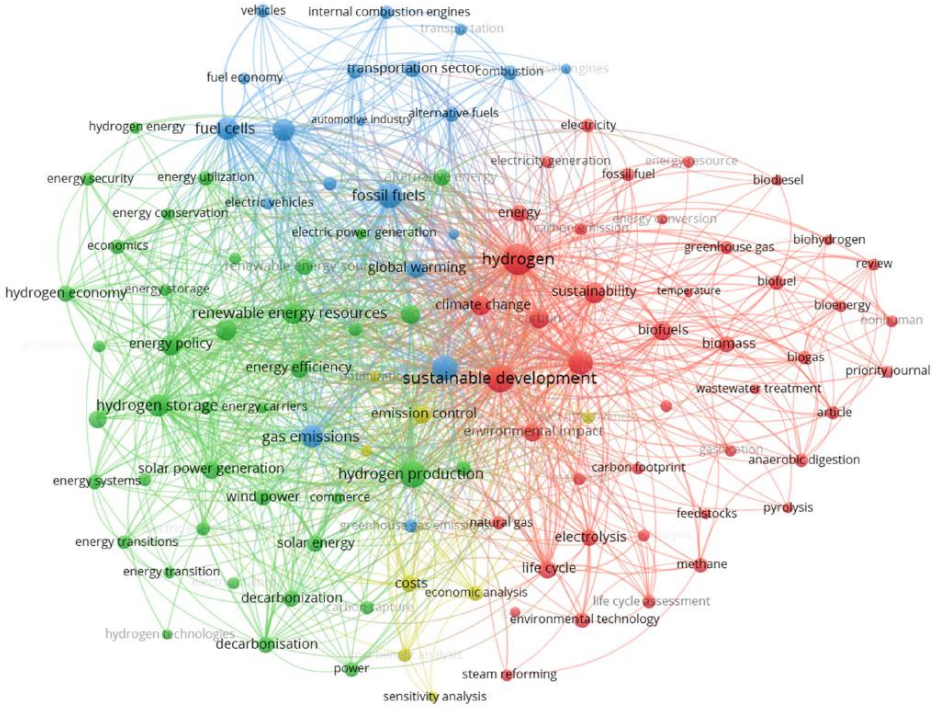


Fig. 3.12. Co-occurrence network generated by VOSviewer.

The main finding is that hydrogen in transport is not studied in isolation. It is closely linked to the wider energy system, infrastructure, costs and policy issues. Therefore, it was important to look not only at transport, but also at the readiness of the entire system in the further analysis. keyword analysis showed that hydrogen transport research focuses on several interrelated topics.

Additionally, sustainability is often discussed in hydrogen research, but the direct link to the SDG 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. The analysis also showed that the concept of sustainability is used much more often than direct reference to the SDGs. In the transport sector analysis, the terms SDGs appeared rarely – "sustainable development goal" and "sustainable development goals" were found in only two publications. 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.

To gain insight into the stage of hydrogen development in the transport sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABSKEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND transport)) AND (LIMIT-TO (DOCTYPE, ar)

OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TP (LANGUAGE, English)). 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. 3.13.).

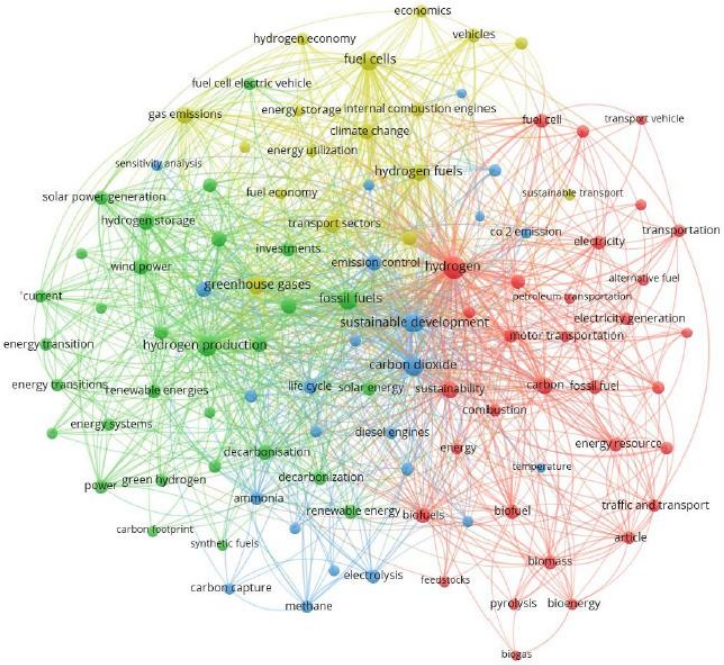


Fig. 3.13. Co-occurrence network generated by VOSviewer.

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. Analysis of research trends over time further showed that recent research directions are increasingly related to decarbonisation, energy transition, green hydrogen and hydrogen storage.

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 “Realizing a Green Hydrogen Economy: An Examination of Influencing Factors” (7), the methodology of which is described in Section 2.5., 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 electrolysers, storage and transportation costs, infrastructure availability, and competition with fossil hydrogen and other low-emission technologies [243], [244]. Therefore, the use of green hydrogen in many sectors is not yet economically competitive without policy support or targeted financial instruments [79].

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 [80], [245]. 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 [246], [247].

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 [248], [249]. 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 [250].

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 [154], [248], [251]. 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 [158], [159], [252].

Overall, 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. Fig. 3.14. depicts a graphic representation of the interrelationships between these factors and stakeholders, displaying the relationships between stakeholders through a barrier and possible solution perspective.

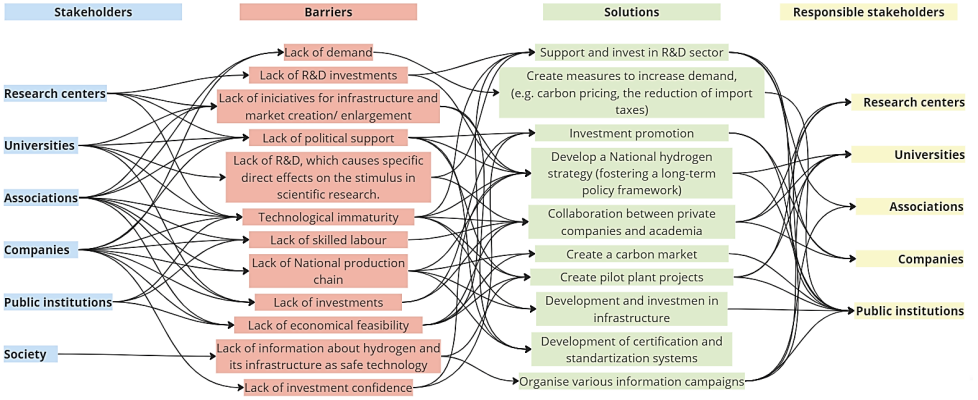


Fig. 3.14. Diagram of hydrogen economy barriers and stakeholder relationships.

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 (Figure 3.15). The picture 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. An important conclusion is about feedback mechanisms, which illustrate the possible consequences of public resistance to overly ambitious or unclearly communicated policies.

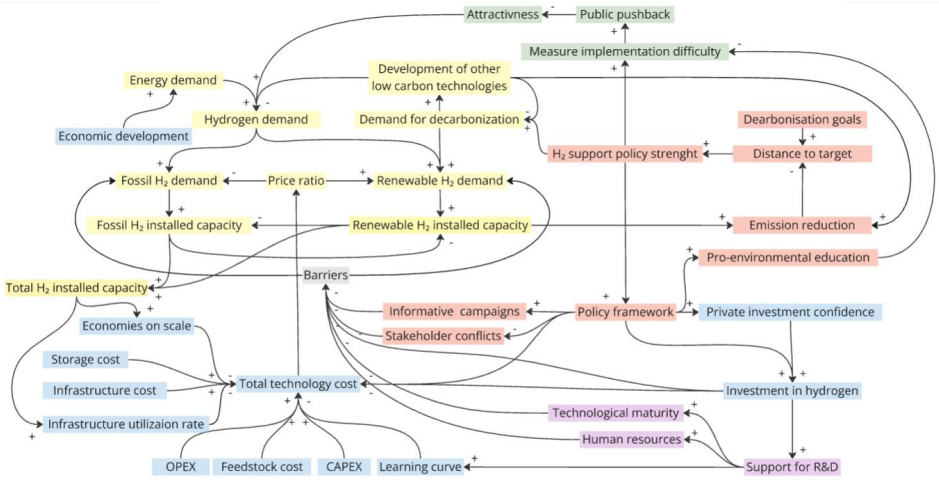


Fig. 3.15. Causal loop diagram of simplified system dynamic model structure.
(The parameters in the yellow, red, purple, blue, and green boxes are linked to hydrogen demand, policy, R&D, the economy, and the social component, respectively).

During the literature review, several feedback loops were identified, for example:

- *R1 – Capacity, Economies of Scale and Cost Reduction Loop*
  This is a reinforcing loop, which describes the following relationship:

Renewable H2 demand (+) → Renewable H2 installed capacity (+) → Economies of scale (-) → Total technology cost (+) → Price ratio (-) → Renewable H2 demand. The loop shows that as demand for renewable hydrogen increasess, so does the installed renewable hydrogen capacity. Meanwhile, increased capacity needs fosters economy of scale, lowering total technological costs. Lower technology costs improve the price ratio between renewable and fossil hydrogen, thereby further increasing demand for renewable hydrogen. This loop therefore acts as a reinforcing mechanism for cost reduction and market development.

- *B1 – Policy Support, Investment and Cost Reduction Loop*
  This is a balancing loop, which describes the following relationship:
  H2 support policy strength (+) → policy framework (+) → investment in hydrogen (+) → Support for R&D (+) → Learning curve (-) → Total technology cost (+) → Price ratio (-) → renewable H2 demand (+) → renewable H2 installed capacity (+) → emission reduction (-) → Distance to target (+) → H2 policy strength
  This balancing loop shows that the strength of hydrogen policy support is related to the distance to the decarbonisation target. The greater the gap between the current situation and the set decarbonisation targets, the stronger the hydrogen support policy strength becomes. This strengthens the policy framework, encourages investment in hydrogen, and supports research and development. Research and development accelerates the learning curve effect, reducing the overall technology costs, improving the price-performance ratio and increasing the demand for renewable hydrogen. As the installed capacity of renewable hydrogen increases, the emission reduction increases. In turn, the emission reduction reduces the distance to the target, thereby reducing the need for additional policy pressure. Therefore, this loop acts as a balancing target adjustment mechanism.
- *R2– Public acceptance and policy feedback loop*
  This is a reinforcing loop, which describes the following relationship:
  H2 support policy strength (+) → Measure implementation difficulty (+) → Public pushback (-) → Attractiveness (+) → Hydrogen demand (+) → Renewable H2 demand (+) → Renewable H2 installed capacity (+) → Emission reduction (-) → Distance to target (+) → H2 support policy strength.
  This reinforcing 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. As the policy strength of support for hydrogen increases, the measure implementation difficulty may increase, especially in cases where infrastructure, costs or public readiness are not yet sufficient. This may increase public pushback, which reduces the attractiveness of hydrogen technology and limits hydrogen demand. Reduced demand prevents growth in renewable hydrogen consumption and installed capacity, which in turn leads to smaller emissions reductions and a further distance to target. This in turn may create even more policy pressure. This loop therefore shows that policy pressure and public resistance can reinforce each other if policies are not accompanied by clarifying and facilitating measures.

- *B2 – Public acceptance and education loop*
  H2 support policy strength (+) → Policy framework (+) → Pro-environmental education (-) → Public pushback (-) → Attractiveness (+) → Hydrogen demand (+) → Renewable H2 demand (+) → Renewable H2 installed capacity (+) → Emission reduction (-) → Distance to target (+) → H2 support policy strength.
  This balancing loop shows the role of environmental education and information in reducing public resistance. Stronger hydrogen policy support can strengthen the policy framework, which also includes pro-environmental education and communication measures. Greater public awareness reduces public pushback and increases the attractiveness of hydrogen technologies. This contributes to hydrogen demand, as well as the growth of demand for renewable hydrogen and its installed capacity. As the use of renewable hydrogen increases, emission reductions increase, which reduces the distance to the decarbonisation goal and therefore the need for additional hydrogen support policy strength. Thus, this loop shows that education and information can reduce the social risks of policy implementation and make hydrogen development more acceptable to society.

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.

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 2.6.2.

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 3.4.

Table 3.4.

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 CO_2 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 CO_2 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 CO_2 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 2.6.4.

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. 3.16.

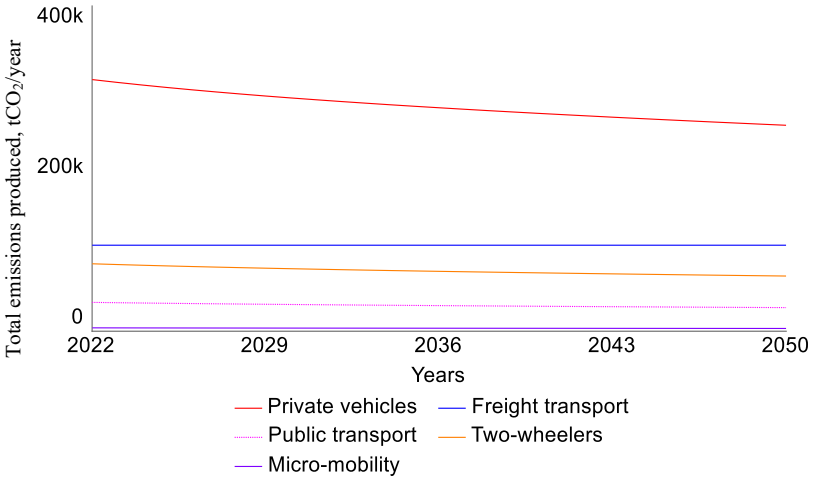
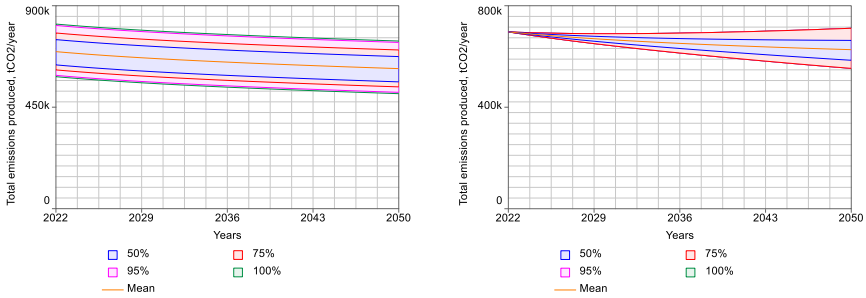


Fig. 3.16. Distribution of generated emissions by mode of transport in the baseline scenario, (tCO_2/year).

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.

Previously, in section 1.4., it was described about the low capacity of municipalities 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.

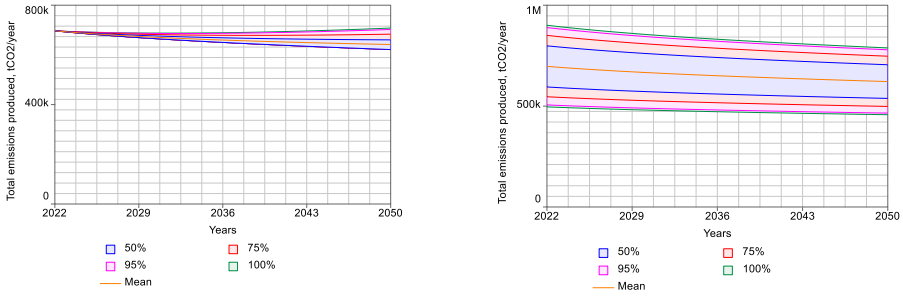
Since freight is not the focus of the analysis, the Riga case study assumes that cargo transport emissions will stay constant in the baseline scenario due to historical stability, limited forecast data, and the need to simplify the model for easier comparison with policy scenarios. To evaluate changes in cargo transport demand ranging from -50 % to +50 %, a sensitivity analysis was carried out. The change in freight transport demand, which varied from -1 % to +1 % instead of staying at 0 % as in the baseline scenario, was treated similarly. The results are presented in Fig. 3.17.



(a) (b)

Fig. 3.17 The probability of the amount of emissions produced by changing the demand for freight transport (a) and by changing the rate of change in the demand for freight transport (b).

Passenger transport parameters were tested using a similar procedure. For example, Fig. 3.18. depicts the effects of increasing the number of movements from 0.5 to 1.5 times, as well as the variation in results as the population grows under the influence of migration at intervals ranging from -1.5%/year to +1.5%/year.



(a) (b)

Fig. 3.18. The probability of the amount of emissions produced by changing the rate of change of migration changes (a) and the number of movements (b).

The effect of car occupancy on the results was also investigated by changing car occupancy from 1 to 2.5 (see Fig. 3.19.).

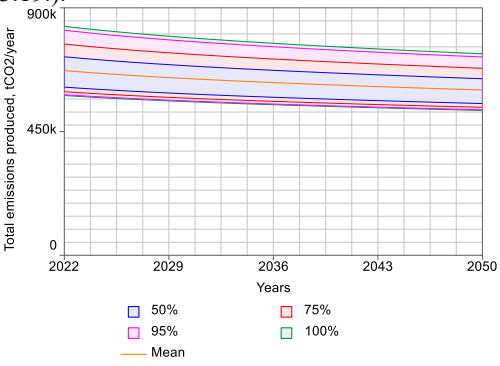


Fig. 3.19. The probability of the amount of emissions produced by changing the rate of car occupancy.

The sensitivity analysis showed that the created model works in compliance with logical principles, and how much the results are affected by the considered parameters. It revealed that the parameters under consideration can have a significant impact on the final results, emphasizing the importance of collecting more precise data and making corrections when newer data becomes available.

To examine the impact of various policies, the following scenarios were developed, as described in Table 3.5.

Table 3.5

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.

To determine the impact on road passenger transport emissions, a total of 12 individual policy analysis simulations and 5 policy combination simulations were conducted. 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 3.20. displays the outcomes for each policy.

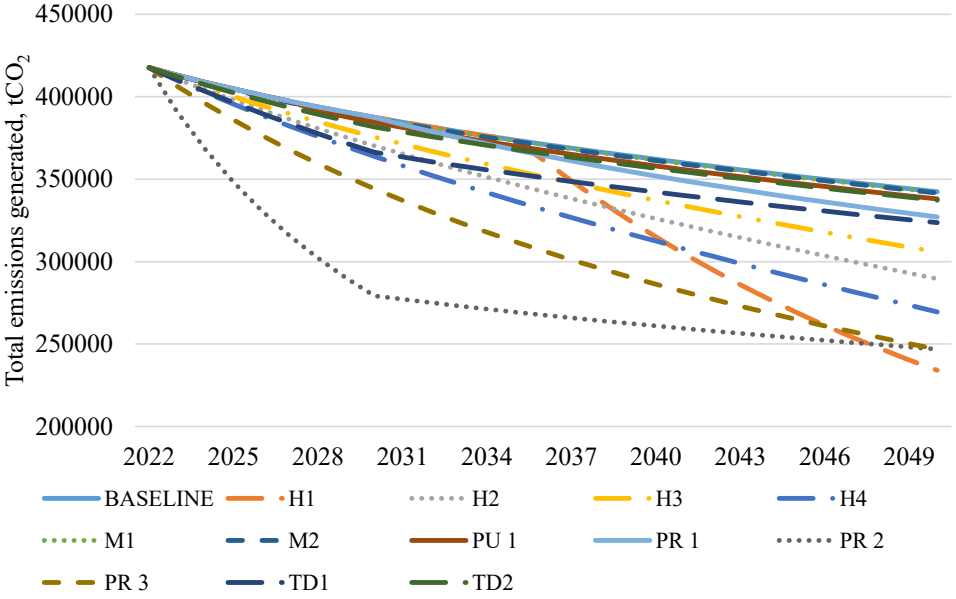


Fig. 3.20. Comparison of the impact of the developed policies on the amount of generated emissions (a transcript of the policy instruments is available in Table 3.5.).

According to the analysis, the development of e-services (TD2), 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, each containing a combination of various policies.

- 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").

Further down, combinations of multiple policies are covered (Fig. 3.21.).

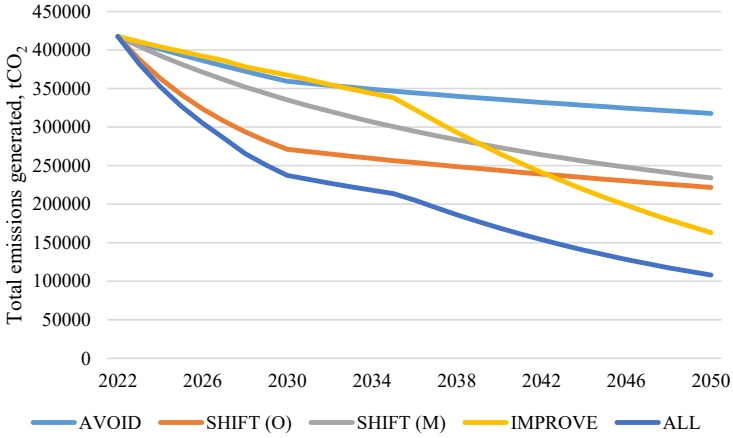


Fig. 3.21. Comparison of the impact of the developed policy combinations on the amount of generated emissions.

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. It’s notable to recognize that the biofuel blending policy, when combined with other "improve" policies, offers a great measurable and evident decrease in emissions; however, to optimise its effects, higher concentrations of modern fuels must be used.

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, decisionmakers 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 2.7.

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 study was carried out as part of the Interreg BSR project *CommitClimate* and allows for an analysis of the interaction between the public and municipal levels in the context of transport decarbonisation. 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 (Table 3.6.). Meanwhile the impact on the environment and government policies were rated as insignificant influencing factors (2 % on average).

Table 3.6

Factors Influencing the Choice of Mode of Transport

Factors	Latvia, %	Estonia, %	Poland, %	Sweden, %
Distance	19.9	19.8	22.1	21.3
Time	18.9	20.9	26.0	19.7
Comfort	11.5	18.0	19.0	12.5
Availability	11.9	13.9	13.6	16.4
Weather and season	13.1	10.7	4.7	10.5
Costs	9.1	7.7	7.0	5.3
Health and fitness	4.4	5.4	0.4	5.7
Safety	3.0	*no data	5.4	1.1
Impact on the environment	2.3	0.6	0.4	4.9
Traffic jams	4.4	1.5	0.8	0.1
Other	0.9	1.0	0.8	2.2
Government policy, incentives	0.6	0.5	0.0	0.4

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). Comparing the results by type of residence, it was determined that urban residents rate the work of their local governments significantly higher than rural residents (on average 4.17 versus 3.31). This is most likely due to better infrastructure in cities and more active communication between institutions and the public. Middle-aged groups in rural areas have particularly low ratings because they frequently deal with issues related to accessibility, mobility, and public transport. Younger generations are

generally more optimistic about future development opportunities, while older generations (particularly in urban areas) acknowledge observable improvements in safety and mobility. This suggests that while local government initiatives are more frequently evaluated and implemented in urban areas, there is still a disconnect between policy and its actual effects in rural areas. The distribution of the results by age and country of residence is displayed in Table 3.7.

Table 3.7.

Distribution of the Results by Age and Place of Residence Across All Countries.

Age group	18-24	25-34	35-44	45-54	55-64	65-75	75	Total
Rural area	4.0	3.4	3.3	3.0	3.2	3.4	3.7	3.3
Urban area	4.1	4.3	4.2	3.9	4.0	4.3	4.7	4.2
Total	4.1	3.9	3.8	3.4	3.4	3.9	4.3	3.8

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 three most preferred transport policies. The results are available in Table 3.8.

Table 3.8.

Most Supported Policies by Respondents in The Transport Sector.

Policy type*	Policy	Sweden	Poland	Estonia	Latvia	All respondents
S	P.1. Improving public transport	**36%**	**42%**	**38%**	**24%**	**34%**
S	P.2. Improvement of cycling infrastructure	**24%**	**29%**	**23%**	**31%**	**26%**
A	P.3. Pedestrian-friendly urban planning	**21%**	**19%**	**18%**	**23%**	**20%**
A	P.4. Promoting remote work options	**19%**	**9%**	**21%**	**22%**	**20%**
I	P.5. Support for low-emission car purchases	10%	4%	**18%**	10%	**13%**
S	P.6. Park-and-ride facilities	7%	**9%**	15%	15%	12%
I	P.7. Electrifying public transport	13%	3%	16%	9%	12%
S	P.8. Launching public awareness campaigns	**15%**	**11%**	10%	12%	12%
I	P.9. Smart traffic management	2%	5%	15%	**17%**	11%
I	P.10. EV charging infrastructure	11%	5%	12%	8%	10%
I	P.11. Using data to optimise transport services	4%	3%	16%	10%	10%
I	P.12. Navigation & route-finding apps	5%	5%	12%	11%	9%
S	P.13. Car-sharing & ride-sharing promotion	11%	5%	7%	9%	9%
S	P.14. Car-Free Days & Events	7%	6%	6%	14%	9%
I	P.15. Speed reduction measures	6%	5%	10%	9%	8%
I	P.16. Eco-driving training	6%	5%	5%	6%	5%
S	P.17. Higher tax on polluting vehicles	2%	5%	5%	6%	4%
I	P.18. Public education on transport & CO_2	5%	3%	3%	5%	4%
S	P.19. Creation of low-emission zones	2%	3%	3%	4%	3%
-	P.20. Other	5%	5%	0%	5%	3%
S	P.21. Congestion tax	1%	2%	3%	4%	3%

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. Thus, 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 %). Avoid-type initiatives (remote work, pedestrian-friendly urban development) received widespread support while improved policies (smart traffic management, emission zones, and levies) received significantly less support.

Based on the policy assessment by respondent age and type of residence (Table 3.9, and Table 3.10.), it was determined that younger residents aged 18-34 are more supportive of digitally focused solutions. This demonstrates that this age group is open to innovations that improve efficiency and freedom in their daily lives. Meanwhile, middle-aged respondents were more likely to support measures that would have a direct practical impact, such as improvements to public transport or congestion relief. This age group also showed slightly higher support for public awareness campaigns. Older generations (64 and up), like other age groups, actively supported measures to improve public transport and were more likely to support policies that improved convenience and accessibility.

Table 3.9.

Distribution of Policy Support Across Age Groups in Urban Areas

Policy Nr.*	Age group of respondents from urban areas						
	18-24	25-34	34–44	45-54	55-63	64-75	75+
P.1	10%	16%	17%	18%	18%	17%	22%
P.2	7%	9%	9%	8%	9%	5%	4%
P.3	4%	4%	3%	3%	3%	3%	3%
P.4	9%	12%	14%	13%	13%	9%	3%
P.5	6%	5%	4%	6%	6%	4%	2%
P.6	11%	7%	7%	8%	9%	13%	23%
P.7	4%	3%	2%	2%	2%	4%	1%
P.8	4%	5%	6%	8%	6%	8%	3%
P.9	3%	5%	5%	4%	3%	3%	1%
P.10	6%	4%	5%	5%	5%	4%	7%
P.11	0%	0%	0%	0%	0%	0%	0%
P.12	3%	0%	1%	1%	0%	1%	2%
P.13	3%	3%	2%	2%	2%	3%	3%
P.14	7%	5%	5%	6%	4%	6%	4%
P.15	8%	3%	4%	3%	3%	3%	5%
P.16	6%	6%	4%	4%	5%	4%	2%
P.17	2%	3%	2%	2%	3%	5%	3%
P.18	3%	1%	1%	0%	0%	0%	1%
P.19	5%	3%	2%	2%	3%	3%	2%
P.20	2%	6%	5%	5%	5%	7%	7%

*Policy numbers correspond to those in Table 3.8.

Further are described results of rural areas (Table 3.10)

Table 3.10.

Distribution of Policy Support Across Age Groups in Rural Areas

Policy Nr.*	Age group of respondents from rural areas						
	18-24	25-34	34–44	45-54	55-63	64-75	75+
P.1	12%	10%	12%	10%	13%	14%	18%
P.2	10%	9%	9%	9%	9%	11%	4%
P.3	5%	8%	8%	8%	8%	4%	6%
P.4	10%	10%	12%	11%	10%	8%	6%
P.5	4%	5%	6%	4%	3%	2%	0%
P.6	7%	10%	14%	17%	17%	18%	30%
P.7	3%	3%	1%	2%	0%	0%	0%
P.8	3%	4%	4%	5%	4%	5%	3%
P.9	7%	4%	4%	4%	2%	2%	2%
P.10	4%	4%	2%	2%	2%	3%	2%
P.11	2%	1%	0%	0%	0%	0%	0%
P.12	4%	1%	0%	1%	0%	2%	0%
P.13	1%	4%	2%	2%	3%	5%	6%
P.14	5%	4%	5%	6%	4%	5%	8%
P.15	5%	6%	5%	6%	7%	4%	3%
P.16	5%	5%	6%	6%	7%	6%	3%
P.17	3%	2%	2%	2%	1%	2%	1%
P.18	2%	1%	1%	1%	1%	2%	1%
P.19	3%	2%	1%	1%	3%	2%	2%
P.20	5%	5%	6%	5%	6%	4%	7%

*Policy numbers correspond to those in Table 3.8.

Overall, age dynamics show that support for sustainable mobility goals increases with age, but motivation changes: younger groups respond more to innovation and flexibility, while older ones respond more to safety, convenience, and social justice. Across all demographic and geographic groups, restrictive fiscal measures such as congestion taxes or higher fees for polluting vehicles received the least support. This demonstrates that people prefer "carrot-type" measures, which make things easier to get to and provide better service, to "stick-type" measures, which limit behaviour or money.

Generally, the policies that can be regarded as restrictive and fiscal, such as increased taxes on polluting vehicles; public education on transport sector's impact and CO_2; establishment of low-emission zones; congestion tax, received the lowest approval ratings. If the proposed policies are viewed through the lens of carrot and stick or push and pull policies, in which policies that benefit citizens are distinguished from those that restrict and cause inconvenience, it can be concluded that citizens prefer supportive and non-restrictive policies.

Together with literature analysis, results highlight, that it is vital to consider people's perceptions, explain the benefits, and avoid unduly harsh limitations without public support to prevent causing "social resistance" and delaying objective achievement.

3.4.2. BEHAVIOURAL FACTORS IN TRANSPORT MODE CHOICE MODELLING

This section 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 2.6.3.

To reduce carbon emissions in the transport sector, it is necessary to stimulate a change in human behaviour. Shifting human flows from private to public transport is influenced not only by the costs of the transport but also by the cost of inconveniences, such as travel time, travel comfort, congestion etc.

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 (Fig. 3.22.).

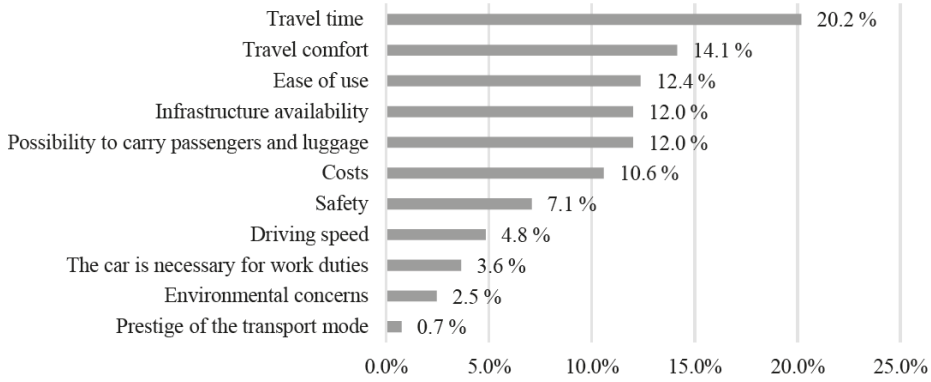


Fig. 3.22. Answers to the question "Which of these factors do you find most important? (3–5 answers)".

These results go along with a previously performed study in Poland about the main reasons for choosing a private car for daily commuting [86] For the integration into the SD model, factors influencing travel mode choice from the survey were grouped creating five major groups: (1) trave 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 a SD model based on responses collected from the survey.

MODELLING RESULTS

The results of the model, which examined situations where users base their choice on just one parameter, showed that both time and cost factors would lead to an increase in public transport usage. The difference is that if the only factor influencing transport mode choice was travel cost, then the public transport share would be much higher (by 57.3 %) in comparison with the situation when only travel time is important when public transport usage increased by

6.1%. In turn, when modelling the effects of both factors on the shift to public transport simultaneously, it was concluded that their combined effect was significantly lower than the individual potential of each factor (only +0.6% increase from the baseline scenario).

To investigate the impact of different policies, the following policies and all their possible combinations were considered:

- Travel time changes for public transport trips – no change, a 20 % increase, a 20% decrease and 40% decrease compared to the baseline scenario.
- Travel cost – price increase by 0, 50, 100, 150, 200 and 250 EUR

Three scenarios were considered separately:

- Travel time matters scenario (travel time is the only important aspect);
- Travel costs matter scenario (travel cost is the only important aspect);
- Both matter scenario (the combination of travel time and travel cost impact).

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. Combination of both factors showed that 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. It was confirmed in adding the second influencing factor. Thus, more modest results were obtained when the “both factor 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 public transport share, whereas a 40.1% increase could be attained by cutting the travel time of public transport in half when compared to private vehicles.

Similarly, an assessment of the travel costs is presented. In this case, raising the cost of private vehicle travel results in a significant mode shift. Therefore, a EUR 50 increase in the average monthly cost of a car would bring the public transport share to 81.5%, whereas a EUR 150 increase would push the share to 90.0%. The maximum percentage of public transport that could be attained in the "Both matter scenario" is reduced by 74.6% and only reaches 19.2% if monthly car expenses rise by EUR 500. An increase of EUR 50 to the average monthly car price results in an 18.7% share of public transport, whereas a EUR 150 increase results in a 19.0% share. The 'Both matter' scenario was broken down into smaller components to better understand how travel time and the cost affected the overall mode shift. Figure 3.23. displays the combinations that were taken into consideration.

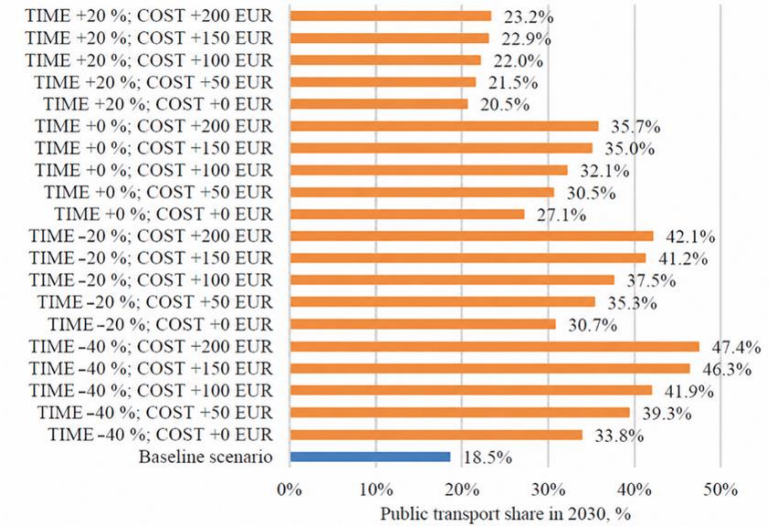


Fig. 3.23. The total effect on public transport share in 2030 (Both matters scenario).

(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 20 % reduction in public transport time and a EUR 50 increase in costs achieves a similar effect as a EUR 200 increase in costs 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 only technologies or only policy measures in isolation. An integrated approach is needed that simultaneously considers technological transition, behavioural factors and policy implementation options. This Thesis summarises the author's research conducted over a 7-year period from 2019 to 2025 on the topic of decarbonisation of the transport sector. Although the main object of research is the Latvian case study, the results obtained are also applicable to other contexts with similar requirements.

The Thesis was based on the approach, which seeks interaction and synergy among three main dimensions – technological transition, behavioural change and policy implementation – which aims to reduce emissions from road passenger transport. The following section presents the conclusions according to the six research stages that was applied in this thesis and described in the Section 2.

Integrated assessment of policy and technology prioritisation

A multi-criteria analysis (TOPSIS) was performed to evaluate various technologies and policy measures. The aim of the analysis was to understand how technology choices and policy priorities are evaluated using common criteria that are relevant at both the national and local government levels. The experts assigned the highest weight to economic factors, while the results of the sensitivity analysis reveal significant uncertainty in the decision-making process related to the relative importance of different criteria. Sensitivity analysis showed that the rating of the top-rated policies decreases when required investment weight becomes lower and RES promotion potential becomes higher. This indicated a strong dominance of economic factors in decision-making, that can lead to the selection of policy measures that are financially beneficial in the short term, but not always optimal for achieving long-term decarbonisation goals. This also pointed to the need for a balanced approach in which economic, environmental and social aspects are integrated into a single policy evaluation system.

The experts also rated different technologies. Electric vehicles were rated the highest in economic and environmental terms, followed by biomethane, but ranked CNG last due to its negative climate impact. Importantly, the sensitivity analysis indicated that EVs remain in the leading position in all aspects, except for economic ones, where their rating decreases significantly. Biomethane demonstrates relative stability across scenarios, indicating its potential as a transitional technology, whereas the assessment of hydrogen technologies is particularly sensitive to the selected criteria, indicating the uncertainty and reliance on technological progress. The results confirm that technology priorities change significantly depending on the selected evaluation criteria, emphasizing the need for a multidimensional approach to policy planning.

Technology-specific assessment for technological transition pathways

In the second stage, several alternative technologies were evaluated. The cost-benefit analysis of electric vehicles and their comparison with conventional fuel-powered vehicles was performed. Cost-benefit analysis determined that despite the high initial costs, the use of electric vehicles is economically justified, especially with increasing mileage.

The use of hydrogen was also investigated as a potential future alternative. The bibliometric analysis revealed (2011-2022) that, despite accounting for only 13% of the total number of publications reviewed, the transport sector has the highest citation rate and a rapid increase in the number of publications, indicating a high level of interest and potential in the use of hydrogen in transport. However, introducing hydrogen into the transport sector necessitates the state developing all aspects of the hydrogen economy.

The hydrogen economy stakeholder and barrier research conducted revealed that developing hydrogen policy requires a collaborative effort from the government, research, and society. Literature and system dynamics analysis revealed that policy support and public acceptance are critical factors in technology implementation, and mechanisms are needed to reduce public resistance.

Modelling the potential of incorporating biomethane into the transport sector revealed that market development without support mechanisms is limited, whereas policy instruments such as subsidies and changes in tax policies can significantly advance this sector. The results also showed the need to coordinate policy measures across sectors, as significant development of the biomethane sector is only observed in cases where the use of biogas in other sectors is not supported.

The study of all the mentioned fuels shows that introducing alternative fuels to the market necessitates both stakeholder involvement and legislative and financial support from the state. The state must demonstrate a clear commitment to the industry's development, instilling confidence in industry representatives to invest in and develop new technologies.

National policy and scenario modelling

A system dynamics modelling approach was used to create a model of the Latvian transport sector and investigate the impact of various policies. The study tested individual policies and their combinations according to avoid-shift-improve groups. An impact assessment of several strategies combinations was conducted, revealing the potential to achieve a 30 % reduction in emissions compared to the baseline scenario for 2030. The proposed model recognised potential emission reductions from various policy implementations and simultaneously enriches the existing knowledge base with innovations.

Coordinated policy implementation at municipal level

To assess policy implementation at municipal level, system dynamics model for transport sector policy modelling was developed. The Riga case study used both local government data and goals and methodologies set at the national level (publication No.9). The modelling results showed that in an optimistic combined scenario, it is possible to achieve a 68% reduction in emissions in passenger transport. Although these are significant results, they were insufficient to achieve climate neutrality and indicated the need for the implementation of additional national-level measures. Results demonstrated that local government policies focused on local government and public transport fleets have limited results. Whereas regulations and goals adopted at the national level largely influenced results. This indicates that when setting goals at the national level, it is important to understand what local government implementers need to do to achieve the goals. Equally important is the policy support and behaviour of citizens, which determine the success of policy implementation. Sensitivity analysis confirmed that indicators

such as the number of trips, migration intensity and car occupancy (factors that are largely determined by travel habits) significantly affect the result, which highlights the need for more accurate data collection and coordination between the national and local government levels, as well as the need to enhance behavioural change.

Public acceptance and local-level mobility preferences

A survey was conducted at the municipal level to gain insight into how municipalities might promote changes in travel habits. The results of an international survey (N=1151) showed that rural residents assessed municipal transport initiatives more critically than urban residents. This highlights the large number of barriers related to public transport availability, accessibility and sustainable mobility infrastructure and the necessity to develop it. The results of this survey also confirmed previous studies and showed that residents value factors such as distance to the bus stop, travel time, comfort, availability and weather and season more highly than cost factors. The results also showed that the greatest public support is received by "Shift" measures (development of public transport and bicycle infrastructure), as well as some "Avoid" measures (urban planning, remote working). "Improve" measures, especially those of a restrictive nature (low emission zones, fees), receive significantly less support.

Behavioural factors in mode shift modelling

To determine how various factors influence car drivers' willingness to switch to public transport, a survey of Latvian car drivers was conducted. The results of the survey (N=350) indicated that implementing pricing policies alone will not achieve climate neutrality goals – citizens value factors such as time, comfort, ease of use, infrastructure availability and possibility to carry passengers and luggage above price. A survey integrated into a system dynamics model showed that using only one factor influencing choice in policy evaluation creates misleading results. Conversely, it was determined that the combined effect of several factors more accurately indicates changes in the system after the implementation of the policy. These results indicate the need to evaluate several (most important) decision-making factors when planning modal shift transitions. It is necessary not only to introduce fiscal policies that make road transport more expensive and public transport cheaper, but also to improve public transport accessibility, travel time and comfort

Synthesis of the integrated assessment framework

The developed policy framework provided a systematic approach to the evaluation of various policy measures and technologies, based on several criteria, and explains the importance of such an approach in decision-making. It allowed comparing the costs of new technologies with currently used alternatives, as well as structuring knowledge about new technologies, and analysing their implementation system and main barriers.

The framework provided the opportunity to model technology-specific system dynamics, while considering the linkages of the transport sector with other sectors, including macroeconomics, availability of raw materials and energy.

An essential component of the framework is also the integration of social factors, including the use of population surveys to determine opinions and preferences, the use of results to identify and improve weak areas, as well as the assessment of public support. It also provided insight into the integration of behavioural aspects into policy modelling.

From the perspective of policy implementation, the work has developed and analysed both system dynamics models on the scale of Latvia, and a municipal model, which has been tested with a case study of the city of Riga.

Summarizing the results obtained, it can be concluded that:

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 to support technological transition

- EVs are economically viable over a longer operating period but they require additional support. Thus, to support medium-term priorities broad development of electric transport should be ensured, providing support for both the purchase of vehicles and the creation of charging infrastructure;
- Biomethane integration in the transport sector requires introduction of long-term policies and support mechanisms (e.g. subsidies and tax policies) that would ensure a stable framework; therefore, a long-term support program should be developed, including production support, tax relief and investment subsidies for biomethane producers.
- Biomethane integration in the transport sector requires to support the synergy of biomethane and electricity in the transport sector, with special emphasis on the use of biomethane in vehicles that are more difficult to electrify, therefore, introduction of targeted support for public transport and logistics is required, where the combination of biomethane and electric transport provides the greatest effect.
- Development of the hydrogen economy requires long-term policies, which would be expressed in a national hydrogen strategy. This would define clear goals and support mechanisms that would create a sense of security for the stakeholders involved and drive the industry. Therefore, a national hydrogen roadmap that clearly defines the goals of the transport sector (e.g. pilot projects with hydrogen buses) should be created.
- Hydrogen economy development also requires special attention to R&D funding and public-private partnerships. Therefore, public-private partnership programs and an R&D fund that incentivises technology testing and local innovation should be provided. Recognition of the strategic role of hydrogen in sustainable transport is required for long term development by launching support mechanisms now, especially for research, pilot projects and infrastructure preparation.
- It is also important to develop public awareness programmes to reduce public resistance and accelerate the introduction of new technologies by creating focused public awareness campaigns, to increase social understanding and acceptance of hydrogen technologies.

Recommendations to promote behavioural change

- To encourage residents to switch to public transport, great emphasis should be placed not only on pricing policy but also on improving comfort (cleanliness, perceived safety,

acceptable occupancy levels and overall service quality), as well as ensuring the availability of vehicles.

- Special attention should be paid to rural areas, where it is more difficult to implement economically sound solutions, for example, by introducing public transport on demand.
- Improvements in public transport speed should be prioritised (create separate lanes for buses, high-speed routes and digitalise the ticketing system) and targeted pricing policy should be implemented (e.g., introducing targeted financial instruments that make public transport financially attractive, while gradually increasing costs for private road transport).
- To improve the implementation of new policies, information campaigns should be introduced, and the public should be educated. It is necessary to develop public involvement in policy discussions, educating and explaining the need for action.
- It is recommended to prioritize "Shift" type measures that would promote the development of public transport and cycling infrastructure, as well as "avoid" type measures that would promote remote working and the possibility of receiving e-services, as such measures are more likely to gain public support. Therefore, it is recommended to direct municipal budget funds primarily towards the development of public transport and bicycle infrastructure, as these measures have the greatest public support, as well as to develop remote work programs in cooperation with companies (e.g., provide tax breaks to employers who support remote work).
- Evaluate the implementation of restrictive and fiscal "improve" type policies – insufficient public support can cause a pushback effect that can delay the achievement of climate neutrality goals. Therefore, before implementing restrictive measures (low emission zones, fees), organize public consultations and public campaigns with a pilot phase.

Recommendations for coordinated policy implementation

- The study revealed that cooperation between all parties – national, municipal and individual – is required to ensure that the implemented policies are coherent and consistent between different levels. In this way, the national policies can be implemented more effectively and, by involving the public in the formulation of policies, better adapted to real needs. This would ensure, not only the implementation of sustainable mobility but also the system's long-term viability and fairness.
- To promote dialogue between local governments and national government representatives for ensuring coordination in the implementation of policies, local government climate plans should be integrated with national goals and each national goal (e.g., the share of electric cars) should be reflected in local government investment priorities.
- To avoid technological lock-in and ensure flexibility in long-term, it is important to ensure dynamic policy design. Therefore, Policy planning should regularly conduct multi-criteria decision analysis (MCDA) or use similar assessment methods to adapt support instruments to changing market and technological conditions. Such analyses

should be renewed every 3–5 years, involving a wider range of experts (including national and local governments, entrepreneurs, academia).

- Decision-making on technology support should consider not only economic indicators but also the level of public support. It is recommended to conduct population surveys and consultations to prevent social resistance and create greater public involvement in policy implementation.

Recommendations to improve data, monitoring and further analysis

- The studies determined that the reliability of the modelled results largely depends on the reliability of the available data. This emphasises the need to introduce a unified data collection system for transport data, which would include not only mileage data but also the number of trips, migration intensity, and car occupancy. Therefore, solutions like establishing an obligation for local governments to conduct annual mobility surveys to improve the quality of modelling, and implementing a single national transport data platform, where local governments regularly upload standardised data on mobility could be introduced.

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APPENDICES

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Research article

Future transport policy designs for biomethane promotion: A system Dynamics model

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ABSTRACT

In this paper, we present a dynamic simulation tool for biomethane policy design in Latvia. A new System Dynamics based computer simulation model covering the whole biogas-to-biomethane value chain including bioresource availability, biogas production and biogas utilization pathways is proposed. The goal of the model is to evaluate the efficiency of a set of policy instruments on increasing the transition from biogas for electricity production to biogas upgrading to be used as a transportation fuel thus contributing to national renewable energy targets in the transport sector by 2030. According to the modeling results, policy design should be focused on two directions, reducing the existing support mechanisms for electricity producers and subsidizing biomethane production, namely. Additional benefits are brought by tax policies aiming to increase the price of competing fossil fuels.

1. Introduction

Transport consumes around a quarter of European Union's (EU's) final energy demand and is the second largest greenhouse gas (GHG) emission producer in Europe after the energy sector (Eurostat. Statistic Expla, 2020). Historic emission trends show that while emissions from other sectors are generally falling, those from transport have continued to increase over recent decades by more active usage of different types of transports. People's needs for transport, as well as the desire to travel, are growing significantly. According to latest estimates carbon dioxide (CO_2) emissions from the transport sector amounted 1212.7 million tons of CO_2 in 2016, which was a 27.5% increase compared to the 1990 level (European Commission. Stat, 2018). Significant reductions in transport emissions are needed if the EU is to achieve its ambitions climate commitments stipulated within the Europe's 2030 climate and energy framework.

The high CO_2 emissions are due to the high dependence on fossil fuels in the transport sector as EU's transportation fuel demand relies 92.4% on fossil fuels (Eurostat, 2019). The EU's Renewable Energy Directive sets a binding target for each Member State to have at least 10% of its transport energy to come from renewable sources by 2020 (Directive, 2009/28/of t, 2009). A rather slow progress to the mandatory 10% target in the transport is observed. European Commission's evaluation (European Commission. Repo, 2013) showed that 22 of 27 Member States failed to achieve their indicative 5.75% renewable energy in the transport target in 2010. In 2017, Sweden and Finland were the only two Member States to fulfil the target with 38.6% and 18.8%, respectively, while Austria (9.7%) and France (9.1%) where relatively close to reaching the goal. These numbers point to the inefficiency of policies (or a lack of policies) in Member States to meet energy and climate policy goals in the transport sector. Further on, the renewed Renewable Energy Directive (RED II) sets a goal for Member States of a minimum share of at least 14% of fuel for transport purposes coming from renewable sources. It also sets a limit for the maximum share of first-generation biofuels at 7% level of final consumption of road and railway transport and at least 1% share of advanced biofuels and biogas in 2025 (increasing to 3.5% in 2030). Decrease of CO_2 emissions from transport sector is one of the priority challenges at energy sector also for many another regions and countries in the world (Kittipongvises et al., 2016).

Among others, such as liquid biofuels, electric mobility and hydrogen, biogas upgrading to biomethane and application in vehicles is one of the alternatives available for the decarbonization of the transport sector ensuring additional benefits such as closed waste management cycles (Barisa, 2016) and reduced air pollution (Ferreira et al., 2019). The use of biomethane as a transport fuel is not a novelty. Biomethane is used as transportation fuel in such countries as Sweden, Germany, France, Netherlands, etc. Overall, the biomethane production in Europe

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has increased significantly during the past decade: from 750 GWh in 2011 to 17.300 GWh in 2016 (Biogas Association (EBA), 2017). Majority of the produced biomethane is injected into natural gas grids with transport applications being around 15% of total biomethane production. The availability of natural gas grids at region and integration possibilities of existing grids have strong influence of biogas production and upgrading sector development (Hoo et al., 2019). Outcomes of a review on supporting mechanisms for the development of biomethane in transport in Europe (Van Grinsven et al., 2017) showed that there are different approaches among countries leading to large differences in terms of vehicle uptake, number of natural gas/biomethane filling stations and biomethane share. However, a unifying trend can be seen that the uptake of biomethane in transport is mostly result of complex policy strategies targeting more than one element. In order to speed up this transition, there is need for scientific proof assisting policy makers to create policies leading to achievement of national targets. This is especially important for countries where there is no or little previous experience in the production and use of biomethane. Such countries also include Latvia.

The transport sector in Latvia accounts for 30.1% of energy consumption and is the main source of GHG emissions. With a 3.6% share of energy from renewables in transport Latvia is among European countries furthest from the 10% target in 2020. In 2018, the total energy consumption of alternative forms of energy in the transport sector was 0.7% electricity, 0.7% bioethanol and 2.3% biodiesel (Central Statistical Bureau of Latvia (CSB), 2019).

Up to date, several research papers have been published discussing biomethane utilization pathways (Dzene et al., 2014), economic configurations (Paturska et al., 2015), (Klavs et al., 2016), policy implications (Repele et al., 2016) and application (Barisa et al., 2015) under Latvian conditions. These studies contribute to a better understanding of the local biomethane aspects. However, there is still missing a comprehensive evaluation of policies accelerating biomethane production. The simulation model presented in this study is the first that gives a unified view of dynamic interaction between resource availability, energy demand in the transport sector and the impact of policy implementation on achieving transport energy goals. The model is also the first attempt to analyze the shift from current biogas use for electricity generation to biogas upgrading. The biogas industry in Latvia is in front of significant changes. The construction of existing biogas plants (61 MW in 2017) has been driven by generous support in terms available subsidies for biogas capital costs and feed-in tariff for electricity production in cogeneration (CHP). However, there is now a wide-ranging debate on the suspension of feed-in tariffs to reduce the cost burden for electricity consumers. Existing biogas operators are therefore ahead of the choice of whether and how to develop their business models in the future. The proposed simulation model helps betters understanding of future market development trends for biogas operators and the necessary supportive measures accelerating biomethane market development for policy makers.

The aim of this research is to provide a scientific basis for biomethane support policy design in the transport sector in Latvia. This paper describes the development of a methodology for policy analysis that includes a cycle of resource availability for biogas and biomethane production, an alternative assessment of biogas use and increased competitiveness in the transport sector.

2. Methodology

To estimate biogas potential for transport in Latvia, a dynamic mathematical energy-economy model was developed and applied to the Latvian case study. The model is based on System Dynamics modeling approach. System Dynamics is a scientific approach where computer-based modeling and simulation is used to go beyond the systems structure and study how and why complex systems develop over time (Blumberga et al., 2011). The structure of the model is intended to reflect a consistent description of the real system. Modeling is done with a purpose of understanding behavioral patterns (dynamic tendencies) of complex systems (Meadows, 1980). The major strength of the System Dynamics modelling approach is the 'open structure' of the models making them flexible in the input parameters and structural modifications.

The analysis of systems structure is based on the concept of two-way causation or feedback. According to this concept, it is considered that decisions derive from information about the state of the system or environment surrounding the decision maker (Meadows, 1980). These decisions are transformed into actions with an aim to introduce changes in the state of the system. New information about the changed state of the system induced further decisions and changes. E.g. increasing traffic congestions and more time spent on travelling by car may motivate car users to choose public transport. Whereas increased number of public transport passengers might give a stimulus for public transport service operators to improve the level of their service thus even more increasing the positive attitude towards public transport. Each such closed chain of causal relationships forms a feedback loop; many such loops linked together makes up system dynamics models (Meadows, 1980). The nature of the feedback loops underlying the structure of the system under study leads to its behavior. A positive (reinforcing) loop causes exponential growth while a negative (balancing) loop moves the system toward an equilibrium point or goal. A negative loop with a delay can lead to an oscillating pattern of behavior while a combination of a positive and a negative loop can result in an s-shaped pattern.

The introduced System Dynamics model brings new knowledge to the existing field of research by:

1. Bringing in new policy tools and assessing the impact of these measures on the competitiveness of biomethane compared to fossil fuels;
2. Looking at biomethane policy making from a new prism, analysing the possibilities of accelerating transition from biogas use for electricity generation to a new product – biomethane;
3. Assessing the impact of biomethane production and use on achieving renewable energy targets in the transport sector, viewed within the context of local bioresource availability.

2.1. Model contextualization and formulation

The main aim of the model designed in this study is to analyze the effectiveness of a set of policy instruments proposed for biomethane promotion in Latvia. Since strong synergies exist between elements involved in biomethane supply chain, the boarders of the model includes three major sectors:

4. Resource supply sector;
5. Biogas and biomethane production sector;
6. Transport demand (consumption) sector (Fig. 1).

Following the model building process, the structure presented in Fig. 1 is transformed into causal loop diagrams and mathematical equations described in more detail in the following sections. The model was built using the *Powersim Studio* 10 modeling software. The modeling time step was 1 year.

2.1.1. Resource supply sector

In the resource supply module, the availability of feedstock for biogas production is calculated. The goal of this sub-module is to explore to dynamics of annual feedstock availability by 2030. Three subsectors are considered as existing and potential sources of organic feedstock for biogas generation, including:

7. Agriculture sector (cattle breeding and farming);

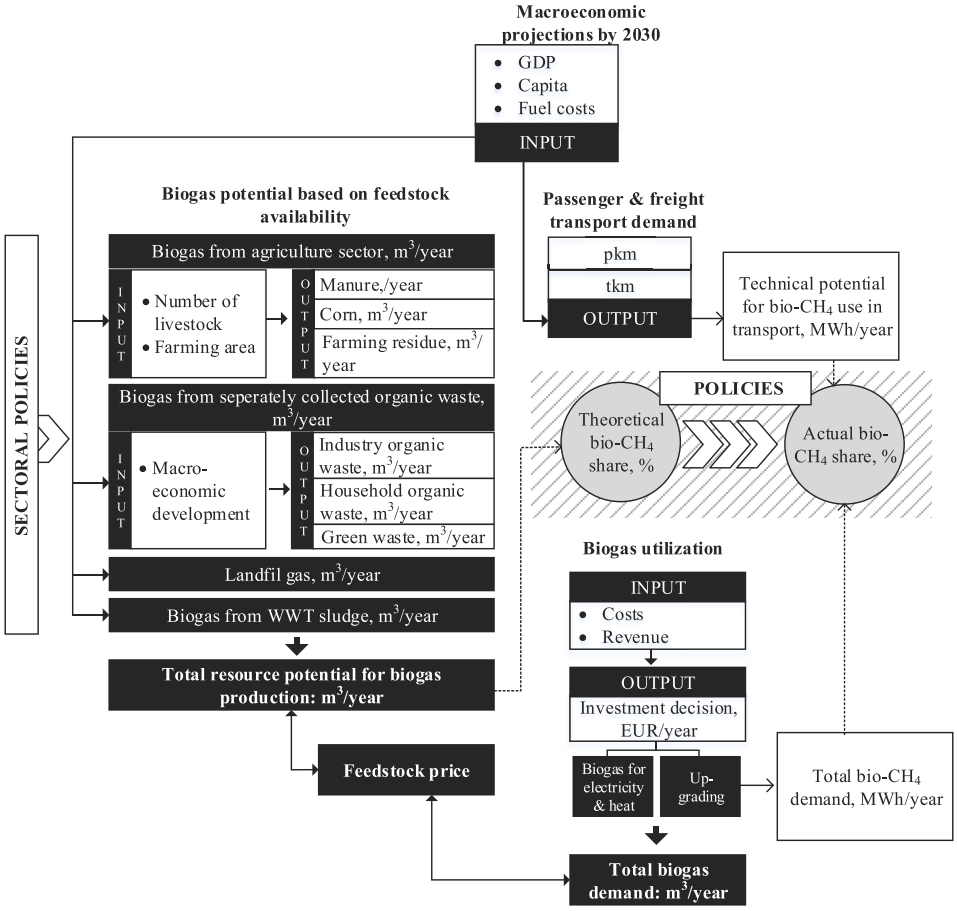


Fig. 1. The overall structure of the proposed System Dynamics model.

8. Waste management sector (source separated biodegradable organic waste collection and landfill gas collection);
9. Wastewater treatment sludge as shown in Fig. 2.

Each feedstock option is examined in a separate sub-model. The outcome of the modeling is a yearly projection of feedstock available for biogas production in biogas cubic meters. Marine algae can be used also as sources for biogas production (Elegbede and Guerrero, 2016). However, biomethane production from algae at Latvia is not economically reasonable and sustainable at this moment (Pastere et al., 2014). Therefore, at these study algae was not included at feedstock list for biogas generation. Assumption values for determining the average biogas yield and the respective references are given in Table 1.

The availability of feedstock for biogas production is considered to be a limiting factor for biogas production. Feedstock import from other countries is not considered as an option within the context of this study. It should be also noted that the theoretical potential of each feedstock type is considered, meaning that economic and technical constraints related to feedstock collection are considered to a limited extent, including cost due to biogas purification. Further explanations regarding

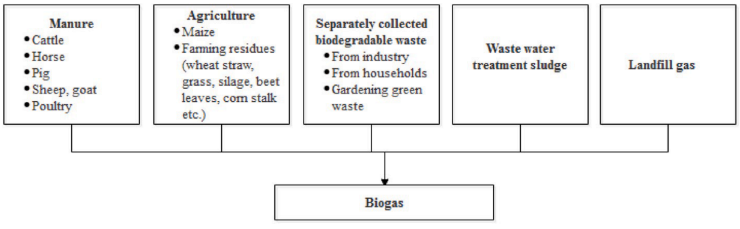


Fig. 2. Feedstock types considered in the resource supply module.

Table 1
Assumptions used to calculate biogas potential from various feedstock.

Feedstock	Dry matter (DM) content, % of fresh mass	Volatile solids (VS) content, % of DM	Biogas yield, Nm^3/t VS	References
Cattle manure	25–30	75–85	200–300/ 550–680	(Steffen et al., 1998), (Bharathiraja et al., 2018)
Horse manure	28	30–90	500	(Merlin and Boileau, 2013), (Hadin, 2016)
Pig manure	20–25	70–80	250–500	(Merlin and Boileau, 2013), (Hadin, 2016)
Sheep manure	25	21–80	450	(Achinas et al., 2018), (Ramos-Suárez et al., 2019)
Goat manure	25	73–91	450	(Zhang et al., 2013), (Li et al., 2011)
Poultry manure	89	70–80	350–600	Zhang et al. (2013)
Corn	86	88	200–220	(Merlin and Boileau, 2013), (Li et al., 2011)
Other agriculture residue	15	60–86	200–500	Parralejo et al. (2019)
Organic fraction of municipal solid waste	75	62–85	220–400	(Zhang et al., 2012), (Bala et al., 2019), (Abad et al., 2019)
Waste water treatment sludge	3	86–90.7	470	(Bala et al., 2019), (Reinola, 2048), (Arlabosse et al., 2005)

assumptions are given in the following subsections.

2.1.2. Agriculture

The feedstock availability in the agriculture sector is considered to be made up from three resource flows, namely livestock manure, specially grown energy cultures (represented by corn) and other biodegradable waste from farming such as straw, leaves and prunings.

The availability of manure feedstock is dependent on the population of animals, the type of animals and the manure management system. The following formula is used to calculate the biogas potential from livestock manure, Eq. (1) (Plume et al., 2012):

$$B = \sum_i M_s \cdot q_i, \quad (1)$$

where B *is b*iogas potential from livestock manure (Nm^3/year); M_s is available theoretical amount of manure dry matter available for biogas production (t/year); q is biogas output from the dry matter of manure (m^3/t); i is type of animal (cattle, horse, pig, etc.).

By knowing the number of selected livestock and average amount of manure produced by one animal of selected livestock, total produced manure is calculated (Eq. (2)):

$$\sum_i M_s = Q_i \cdot m_i \cdot S_i \cdot OM_i\ , \quad (2)$$

where Q *is l*ivestock population per type i, animal heads; i *is t*ype of animal (cattle, horse, pig, etc.); m is average manure production per animal per type i (fresh mass) (t/year); S_i is dry matter content in manure by animal type i (% of fresh mass); OM is organic matter content in dry matter of manure per animal type i (% of dry matter).

The projections of the number of livestock by 2030 were taken from Ministry of Agriculture (Ministry of Agriculture o, 2015) and are presented in Table 2. The average change (%/year) of each type of animal at period from 2020 to 2030 year is presented at table and used to obtain the projected numbers of livestock.

The respective values for average manure production per animal and assumptions regarding manure management systems are presented in Table 3.

Besides manure, the availability of corn and agricultural residues is considered in the model. In the model, the development of corn cultivation area is demand-driven. There is no data reference on actual distribution between corn use for animal feed and biogas production, therefore it is assumed that half of the produced corn is used for energy and the rest for other purposes. Corn demand for energy depends on the demand by biogas plants. The limiting factor for corn area growth is availability suitable soils. According to expert evaluation the maximum arable land suitable for corn cultivation in Latvia is around 42 000 ha (Vides aizsardzības un reģ, 2017).

It is assumed that 2% of agricultural production of crops is organic residue that can be used for biogas production. The projection of sown area was developed based on historically observed correlation between the land usage for crop production and the gross domestic product (GDP). There is linear correlation, that shows that the growth of GDP promote the increase the land usage for crop production. The limiting factor for agricultural production of crops is the available arable land.

2.1.3. Municipal waste and landfill gas

Municipal solid waste can be sustainable energy source (Klavins et al., 2018). Although currently barely utilized in Latvia, source separated organic municipal waste is a valuable resource for biogas production. Under the category of household waste for the purpose of this research we consider all non-hazardous waste generated by the household, trade, service or other process, provided that it is comparable with respect to household waste. The historic data on municipal waste generation were collected from the national waste management database indicating an increasing per capita generation of municipal waste over the past decades (Latvijas Vides and ģeoloģija, 2009–2017). The following equation was used to project municipal waste generation by 2030 (Eq. (3)):

$$\textit{Municipal waste (kg/capita)} = 0.0498 \cdot \text{GDP/capita} - 151.86, \quad (3)$$

Further to calculate the biogas potential from municipal waste, it was assumed that a minor share (8%) of generated municipal waste is source separated organic waste (based on national statistics). The rest unsorted municipal waste is collected and brought to landfills where part of the biodegradable waste is separated from municipal waste by mechanical treatment and used for biogas generation. The rest is landfilled and ensures landfill gas production. The amount of produced landfill gas is determined using first-degree waste decomposition equation as described by Eq. (4) (Kuplais, 2010):

Table 2
Assumptions on Livestock Numbers used in Modeling (Ministry of Agriculture o, 2015).

Type of animal	Statistical data, thousand animals		Projections, thousand animals			
	2009	2017	2020	2025	2030	Average change 2020–2030, %/year
Cattle	378	406	485	521	556	1.46%
Horse	13	9	10.1	13.6	10	−0.10%
Pig	377	321	374	391	412	1.02%
Sheep	71	112	119	142	165	3.87%
Goat	13	13	16	16	17	0.63%
Poultry	4829	4944	6089	6746	7452	2.24%

Table 3
Assumptions on manure production (Bharathiraja et al., 2018), (Merlin and Boileau, 2013).

Type of animal	Manure production		Waste management system		
	Litter manure, t/year	Liquid manure, t/year	Pasture, %	Litter manure, %	Liquid manure, %
Cattle	15	19	15	42.5	42.5
Horse	10	–	50	50	–
Pig	1	2	–	50	50
Sheep	2.4	–	60	40	–
Goat	2.4	–	40	60	–
Poultry	–	0.1	–	–	100

$$m_{pg} = S_a \cdot Q_a, \quad (4)$$

where *mpg* is amount of produced landfill gas (m^3/t); *Sa* is amount of municipal waste (t); *Qa* is landfill gas yield (m^3/t).

2.1.4. Biogas utilization

Three alternatives have been identified for the use of biogas:

1) Biogas use in CHP;
2) Biogas use for direct heat production;
3) Biogas upgrading.

The distribution between the three alternatives is based on the expected operator benefits. Logit function (Moxnes, 1990) is used to describe biogas utilization choice based on estimation of the perceived benefit, see Eq. (5):

$$S_i = \frac{\exp^{\alpha C_i}}{\sum_j \exp^{\alpha C_j}}, \quad (5)$$

where S_i is market share of biogas utilization alternative *i*; α is coefficient representing cost sensitivity of market demand; C_i is perceived operator's profit of using biogas utilization alternative *i*; *Cj* is perceived profit sum of all biogas utilization alternatives.

According to Eq. (5) the larger is the perceived operator's benefit, the larger is the technology market share and vice versa. The perceived benefit (profit), *Pi* (EUR/MWh), is expressed as a percentage, where all costs (*Ci*, EUR/MWh) are subtracted from income (*Ii*, EUR/MWh), and the result is divided by income (Eq. (6)):

$$P_i = \frac{I_i - C_i}{I_i}, \quad (6)$$

The total cost *Ci* of each biogas utilization alternative is calculated as a sum of three components (Eq. (7)):

$$C_i = C_{investment} + C_{feedstock} + C_{O\&M}, \quad (7)$$

where $C_{investment}$ is investment costs per lifetime (EUR/MWh); $C_{feedstock}$ is feedstock costs (EUR/MWh); $C_{O\&M}$ is technology operation and maintenance costs (EUR/MWh).

Modeling assumptions for biogas utilization alternatives are explained in Table 4.

It is assumed that methane content at produced biogas is constant 60% and biogas heating value is 6.0 kWh/m^3. Feedstock costs for biogas generation are dependent on the availability of different feedstock types calculated in the resource module. The higher the demand for particular feedstock, the higher the price of the feedstock. Besides, an annual feedstock price increase of 1%/year irrespective of demand is introduced in the model reflecting overall inflation. The feedstock availability limit is the available local resource potential calculated in the resource module. Technology operation and maintenance costs.

Table 4
Modeling assumptions for modeled biogas utilization pathways (Blumberga et al., 2010).

Costs	Electricity generation (CHP)	Heat generation	Biomethane production
Capital costs (CC), mil. EUR/MW	1.04	0.06	0.6
O&M costs, % of CC	10	10	10
Biogas conversion efficiency	0.6	0.9	0.5
Full load working hours, h/year	6700	4400	8000
Lifetime, years	20	20	10
Installed capacity in 2019, MW	61	0	0

2.1.5. Transport energy demand

The transport energy demand module projects the annual energy demand in the transport sector. The output of this module is the theoretical biomethane potential. I.e. share of total energy consumed in the transport sector which potentially can be achieved with biomethane.

As suggested in the research literature (Liddle and Lung, 2013) transport energy consumption is causally related to GDP. A good correlation between GDP and energy consumption in the transport sector can be observed in Latvia. To model the future demand of transport, a historic relation between the GDP and energy consumption in Latvia were collected and applied during the period 1995–2017 (European Commission. EU reference scenario, 2016). Data sets were chosen corresponding to the data availability in national statistics. The following empirical equation was used to describe energy demand in the transport sector based on GDP projections ($R^2 = 0.91$), Eq. (8):

$$E_t = 0.0019 \cdot GDP + 11306 \quad (8)$$

where E_t energy demand of transport sector (TJ); *GDP* is gross domestic product per capita (EUR).

Projections of GDP development in Latvia were based on national long-term forecasts as shown in Table 5. For population projections, it was assumed that no major changes in historically observed trends will occur by 2030, i.e. the population will continue to decline with an average rate of 1.1% per year reaching 1.71 million in 2030.

2.2. Scenario development

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 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.

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. The biomethane production price was then compared with the costs of the other two alternatives for biogas utilization proposed within the framework of this study, biogas use in CHPs and biogas use for direct heat production, namely, to determine corresponding market shares for each alternative (Eq. (4)). The final price of biomethane (including taxes) was compared to the natural gas price to evaluate its competitiveness.

The developed methodology and System Dynamics model is used for analysis different scenarios of biogas sector development for Latvia.

Table 5
Macro-economic projections.

	Year		Projection			Average 2019–2021	2022–2030 (assumption)
	2017	2018	2019	2020	2021		
Changes in GDP, at constant prices (in %), (Ministry of Finance of Republic of Latvia, 2019)	4.6	4.8	3.2	3.0	2.9	3.0	3.0
Population, mil.	1.95	1.93					−1.1%/year

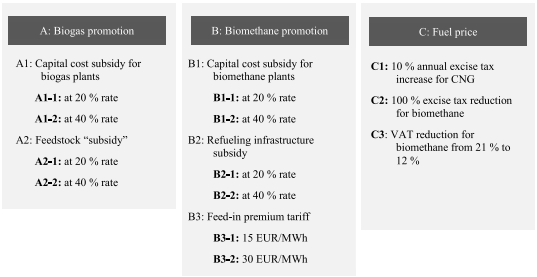


Fig. 3. Summary of policy instruments tested in the model.

However, the described Latvia's case can be moreover similar with many other EU countries which have feed-in tariff for electricity production from renewable energy sources, including biogas. The developed System Dynamics model based on the universal structure, which can be easer modified and used for analysis of policy designs effect on biomethane production for other countries.

3. Results and discussion

With GDP growing at a rate of 3%/year, the expected energy consumption in the transport sector in 2030 is 69 500 TJ, which is an increase of 33.8% compared to 2017 level. This projection is based on historically observed trend of development and assumes that no changes in transport use behavior are observed. If the growth of GDP slowed down to half (1.5%/year on average), the expected energy consumption in the transport sector is 61 500 TJ, which is an increase of 18.3% compared to 2017.

Currently, around 200 million m^3 of biogas are produced annually and used for electricity generation in CHP plants with the total installed electrical capacity of 61 MW. Modeling results show that the existing feedstock demand is about 55% of the theoretical potential.

At the existing biogas production capacity is expected that the availability of feedstock for biogas production will not decrease due to projected increase in the number of livestock and the increasing feedstock generation in other sectors. The currently unexploited bioresource potential is associated with increased use of agricultural residue and source separated organic waste collection. If biogas production remains at current level or decreases, the availability of feedstock is sufficient and should not have a significant impact on bioresource prices.

3.1. Baseline scenario results

In the baseline scenario with assumptions about resource costs and technology costs, biomethane production costs per MWh are about 20% higher than electricity production costs from biogas in 2030. The cost of biomethane production (0.85 EUR/m^3), including the cost of biogas production and upgrading, the remaining loan repayment for the CHP unit, biomethane compression, and the producer's profit (5%), is higher than the current price of natural gas for transport (0.98 EUR/kg). The price of natural gas has been subject to a moderate price increase of 1%/year. Given that such a business model is not profitable for operators, no transition from biogas use in CHPs to biogas upgrading is observed. The major driver of biogas use in CHPs is the existing electricity feed-in tariff (188 EUR/MWh) ensuring high profitability for existing operators. The baseline scenario assumes that the feed-in tariff is valid for 20 years with a 20% reduction after the first 10 years of operation according to the national legislation. Likewise, there is no transition from biogas to direct heat generation in district heating. Assuming an average heat sales price of 50 EUR/MWh, direct heat generation from biogas is not able to compete with the other two technologies, as investments in the production of heat from biogas are too high. The use of heat in this case should only be considered together with CHP electricity generation.

3.2. Scenarios with policy measures

The first action considered is a full interruption of feed-in tariff for electricity generation in existing CHP plants. Active discussion on the termination of feed-in tariff in Latvia began in 2018 as a response to the high additional costs for electricity consumers. At the political level, decision-making is now postponed to a more precise assessment of the possible consequences. However, this measure is necessary if the future policy is to promote the transition towards biogas upgrading. Modeling results show that if the feed-in tariff for electricity generation is excluded (assuming from 2021 onwards), the use of biogas in cogeneration plants becomes economically unfeasible, as the profits from the sale of electricity on the market and the sale of heat do not cover production costs with the existing utilization rates. The feasibility is improved, if utilization of heat capacity in CHP plants is increased from 4400 full load hours (reference assumption) to 6700 full load hours (equaling electricity generation full load hours). The income from heat selling should be at least 30 EUR/MWh to ensure 5% profit.

Further policy measures are considered in both scenarios, keeping the feed-in tariff for electricity generation till 2029, and interrupting the feed-in tariff starting from 2021 onwards.

3.2.1. Costs of biomethane production

Fig. 4 shows the impact of different policy instruments on

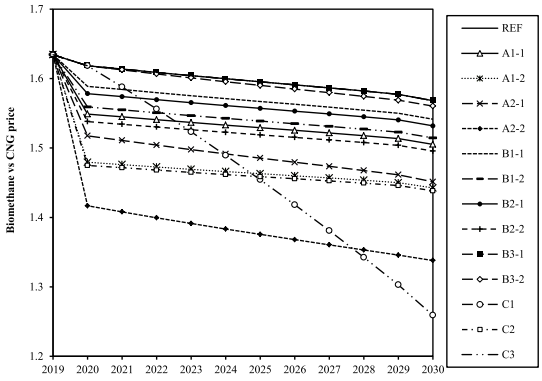


Fig. 4. Impact of policy instruments on biomethane price compared to natural gas price for transport.

biomethane production costs. The price of biomethane is compared to the price of natural gas for transport. An explanation for abbreviations of the policy instruments is given in the previous Fig. 3.

In the REFERENCE scenario, the price of biomethane is on average 1.6 times higher than the price of natural gas in the studied time period. The effect of the selected policy measures is in range 0–19.7% with majority of policies falling in range 0–8.3% reduction compared to the reference scenario. None of the analyzed policy instruments can reduce biomethane price at the level of natural gas price or below.

Of the proposed, policy instruments giving the most effect on biomethane price reduction are C1 (annual excise tax increase on natural gas by 10%) and A2-2 (reduction of biogas feedstock costs by 40%). Policies giving almost no or a minor effect are: B3-1 and B3-2 (feed-in premium tariffs for biomethane production), C3 (VAT reduction for biomethane) and B1-1 (subsidy for biomethane capital costs at a 20% rate). The rest of the proposed policies give 3.4–8.3% biomethane price reduction compared to the baseline scenario.

In any case, certain policy instruments are unable to achieve the price of biomethane competitive with the price of natural gas. The results are however influenced by the price of natural gas. In the baseline scenario, a moderate price increase of 1%/year is assumed for the price of natural gas. In Fig. 5 we test the reference scenario in case natural gas price is ±10–20% compared to the baseline scenario.

The price of natural gas at filling stations is a determining factor for the competitiveness of biomethane. The rise in the price of natural gas pushes the price of biomethane closer to the price of natural gas, but it is still higher than the price of natural gas. On the other hand, the price of natural gas is subject to high uncertainty and the price of natural gas may also decrease. Such a scenario is possible, for example, if natural gas is subject to excise duty relief. This can happen if the state decides to promote the use of natural gas in transport as one of the alternative fuels under the Alternative Fuel Directive.

3.2.2. Policy effects on biomethane production capacity

Fig. 6 shows the impact of different policy instruments on biomethane production capacity. The effect of selected combinations of policy measures on the speed of transition from biogas use in CHPs to biomethane production is shown.

Modeling results show that different trajectories are potentially achievable using different policy instrument combinations. The initial goal of the policy must be to make the price of biomethane more competitive with natural gas or other competing fuels. It cannot be achieved through individual measures, but through combinations of policy instruments. For example, one of the combinations that allow achieving minimum trajectory of biomethane development in 2030 is a 20% feedstock subsidy (A2-1) combined with a 40% subsidy to cover the cost of capital for biomethane production (B1-2) and 40% subsidy for biomethane compression infrastructure (B2-2). As a result, in 2030,

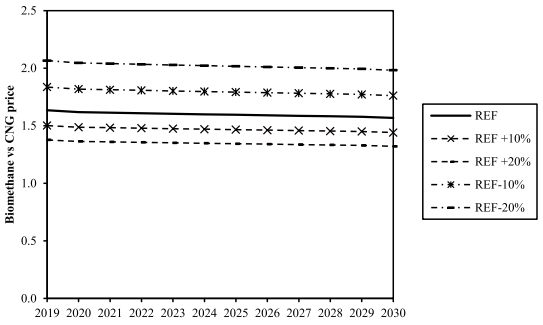


Fig. 5. Impact of natural gas price variation (±10–20% of original price) on biomethane price compared to natural gas price for transport.

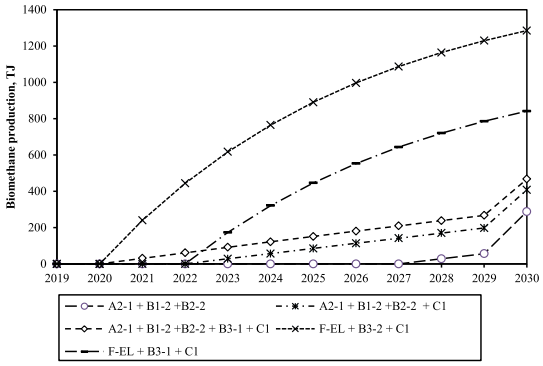


Fig. 6. The effect of a selection of combined policies on biomethane production.

about 16 million m^3 of biomethane are produced.

A slight above the minimum trajectory can be achieved in addition to the previous scenario, introducing an increasing excise duty (+10%/year) on natural gas (C1). In that case, the production of biomethane in 2030 amounts to 24 million m^3/year. A similar result is possible with additional introduction of a feed-in premium tariff for biomethane (15 EUR/MWh) in combination with the excise tax policy for natural gas. In all three scenarios, a sharper increase in biomethane generation is observed starting from 2029. This can be explained by the interruption of the feed-in tariff for the production of electricity in cogeneration in 2029 (an existing support mechanism that is interrupted for 20 years after the plant is put into operation). After the feed-in tariff is cut off, the transition to biomethane production takes place at a higher speed than before.

A more rapid increase in biomethane production capacity can be achieved by combining feed-in tariff policies with higher taxes on natural gas. One of the policy instrument combinations that gives the fastest increase in biomethane installed capacity is the interruption of feed-in tariff for electricity (F-EL) before the set time (assuming from 2021 onwards) in combination with a 15 EUR/MWh feed-in premium for biomethane and increased excise tax natural gas (F-EL + B3-1 + C1). In such a scenario, biomethane production is developing rapidly already before 2025 and biomethane production capacity reaches 50 million m^3/year. In case, the feed-in premium tariff for biomethane is increased to 30 EUR/MWh, the biomethane production capacity reaches 75 million m^3/year. This amount of biomethane can be produced using biogas from the existing biogas plants. According to modeling results, the availability of bioresources exceeds current demand, thus it is possible to increase the production capacity of biomethane, if new biogas plants are installed. Results from developed model shows that it is possible produce around 250 mil. m^3 biogas with existing availability of bioresources.

The Renewable Energy Directive requires Member States that the share of advanced biofuels and biogas in final energy consumption in transport should be at least 0.2% in 2022, at least 1% in 2025 and at least 3.5% in 2030. Considering that the contribution of energy derived from the feedstock listed in Annex IX of the Directive to this objective is double counted, such a development scenario F-EL + B3-1 + C1 allows Latvia to fulfill its obligations under the Directive.

4. Conclusions

This paper investigated the future development potentials of biomethane in Latvia. The study uses a newly developed System Dynamics model to analyze the development of the biomethane sector involving interactions between the bioresource supply sector, biogas production

and utilization, biomethane competitiveness with natural gas, and the share of final energy in transport to achieve transport goals.

The baseline scenario modeling results show that biomethane production is not able to compete at the existing conditions, as the cost of biomethane production is higher than the market price for natural gas for transport. The existing feed-in tariff for electricity production in combination with a high biomethane price does not stimulate biogas producers to switch from electricity production from biogas to biogas upgrading. We conclude that the imposition of additional taxes on fossil fuels is a powerful tool, thus increasing the competitiveness of biomethane. At the same time, it should be noted that there is a disagreement between renewable energy and alternative energy targets in the transport sector. For example, reducing excise duty on natural gas to increase the share of alternative fuels in the energy mix required by the Alternative Fuel Directive will make biomethane even more unattractive for end-users and thus will not contribute to the renewable energy target.

With the existing installed biogas production capacity it is possible to achieve target set in the Renewable Energy Directive for at least 3.5% share of advanced biofuels and biogas in final transport energy consumption in 2030. Conclusions was supplemented: The deeper analysis of different European's countries situation related to biomethane production, used policy instrument and achieved results is preferable in a future researches. The best examples in terms of biomethane supporting action will be determined and analyzed possibilities and shortcomings of similar approaches to be applied for Latvian specific conditions. The economical evaluation with cost-benefit assessment, including economic allocation of CO_2 production must be done. Determination of impact of exportation in the cost, increase of the efficiency of the conversion of biomass, analysis and selection of a specific biomass to increase the efficiency and improve the feasibility can be done in the future works and integrated into the developed System Dynamics model.

Author statment

Aiga Barisa – Conceptualization, Methodology, modelling, Formal analysis, conclusions. Vladimirs Kirsanovs – introduction; Writing-Reviewing and Editing. Alina Safronova – modelling, Methodology, result analysis.

Declaration of competing interest

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

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Abbreviatations

B: Biogas potential from livestock manure, Nm^3/year
M_s: Available theoretical amount of manure dry matter available for biogas production, t/year
i: Type of animal (cattle, horse, pig, etc.)
q: Biogas output from the dry matter of manure, m^3/ton
Q: Livestock population per type *i*, animal heads
m: Average manure production per animal per type *i* (fresh mass), t/year
S: Dry matter content in manure by animal type *i*, % of fresh mass
OM: Organic matter content in dry matter of manure per animal type *i*, % of dry matter
S_i: Market share of biogas utilization alternative *i*
α: Coefficient representing cost sensitivity of market demand;
Ci: Perceived operator's profit of using biogas utilization alternative *i*
Cj: Perceived profit sum of all biogas utilization alternatives
$C_{investment}$: Investment costs per lifetime, EUR/MWh
$C_{feedstock}$: Feedstock costs, EUR/MWh
$C_{O\&M}$: Technology operation and maintenance costs, EUR/MWh
A1-1: Capital cost subsidy for biogas plants at 20% rate
A1-2: Capital cost subsidy for biogas plants at 40% rate
A2-1: Feedstock "subsidy" at 20% rate
A2-2: Feedstock "subsidy" at 40% rate
B1-1: Capital cost subsidy for biomethane plants at 20% rate
B1-2: Capital cost subsidy for biomethane plants at 40% rate
B2-1: Refueling infrastructure subsidy at 20% rate
B2-2: Refueling infrastructure subsidy at 40% rate
B3-1: Feed-in premium tariff 15 EUR/MWh
B3-2: Feed-in premium tariff 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%
F-EL: interruption of feed-in tariff for electricity before the set time (assuming from 2021 onwards)

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Cost-benefit assessment of electric vehicle vs internal combustion engine in Latvia

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***Abstract*— Transport sector in Latvia have several challenges: energy consumption decrease, produced CO_2 emission decrease, air pollution decrease, reduction of the average age of the car in the country, integration of renewable energy source to replace fossil fuel. Electric vehicles have high potential in the future to help achieve directive 2018/2001/EC targets. This study presents a cost-benefit analysis of electric vehicles, as well as an internal combustion engine with diesel and gasoline. The cost-benefit analysis methodology was developed considering car production, purchase, operating and utilization costs. Environmental aspects such as air pollution, climate change and noise were also taken into account.**

Keywords*— *electric vehicles, internal combustion engine, cost-benefit analysis, operating costs, CO_2.

I. INTRODUCTION

The transition from fossil fuels to renewable fuels is taking place at the European and global level. The main objective is to reduce CO_2 emissions, which are one of the main greenhouse gas emissions contributing to climate change and global warming. Energetics is the most important creator of greenhouse gas emissions. In Latvia over the last five years, energy consumption in the transport sector has increased by 16.4 %, in 2018 consumption was 53.9 PJ [1]. This consumption accounts for a third of Latvia's total energy consumption. The main source of energy in the transport sector are oil products, but the share of renewable energy sources is low and was 4.73 % in the 2018 year [1].

In 2018, the target set by EU countries under directive 2018/2001/EC amounts to at least 14 % of the share of RES in the transport sector in gross consumption for 2030 [2]. In this way, electromobility is one of the ways to increase the share of renewable energy sources in final energy consumption to meet the EU's targets. The introduction of electromobility not only contributes to increasing the share of renewable energy sources but also reduces CO_2 emissions [3]. One of the problems in big cities is noise, the introduction of electromobility can also solve this problem because electric vehicles (EV) makes much less noise than cars with internal combustion engines [4].

Based on the statistical data the number of EV in Latvia increased from 1 unit in 2012 to 442 units in 2018. [1] The sharp increase of registered EV was in 2014 thanks to the financial support received from the Climate Change Financial Instrument (CCFI) fund. The share of EV concerning the total number of passenger cars is slightly small – just 0.06 % in 2018. EV buyers mostly are municipalities, state institutions, companies, as well as universities. The main reason for such a tendency is a relatively high purchase price. At European Union level the share of new EV increased from 0 % in 2010 to 1.5 % in 2017 and 2 % in 2018. The share of battery electric vehicles increased by 50 % in 2018 compared with 2017 while sales of plug-in hybrid electric vehicles increased by 15 % at the same period of time [5].

The second factor, which hinders the more rapid increase of EV is the undeveloped infrastructure for EV charging. Nowadays there are around 80 fast public charging stations at Latvia which are distributed by country [6]. The relative indicator national road length per charging stations for Latvia is 315 km/unit. It means that the distance between charging stations in Latvia is big. In comparison in Denmark, Germany and France this number is around 20 – 40 km/unit, which is significantly better [7-8]. Therefore, the development of infrastructure is an important action for Latvia. Up to 150 EV fast-charging stations are planned to be built in Latvia by the end of 2021 during the implementation of the project "Establishment of charging infrastructure for electric vehicles" financed by the European Regional Development Fund.

Each country sets its own goals and tools for the development of electromobility. Dependence on the set goals, the current economic and environmental situation in the country, certain instruments and support mechanisms can be used. Based on the European country experience the more effective support instruments are subsidies for the purchase of a new EV, exemption from the registration fee and operating tax, development of charging station infrastructure, free parking [9-12].

The existing legislation and planning documents are too general and do not sufficiently stimulate the development of EV in Latvia. Legislation and planning documents do not mention support for the purchase of new EV, although based on the other country's experiences this is the most effective support instrument [13].

The main goal of this study is cost-benefit assessment performance for EV in comparison with the internal combustion engine to understand the economical reasonability and benefits for EV development in Latvia. The research presents complex cost-benefit analysis including not only the exploitation stage but also vehicle production and utilization stages.

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II. METHODOLOGY

The cost-benefit analysis method was chosen for this study. A significant advantage of the cost-benefit analysis is that the analysis can consider not only economic aspects and indicators but also social and environmental aspects, including emissions and air pollution, climate change, noise and other aspects [14].

The specific methodology was developed for the cost-benefit assessment of EV with an internal combustion engine. The methodology is based on the EU Handbook "Guidelines for Cost-Benefit Analysis of Investment Projects, an Economic Assessment Tool for Cohesion Policy 2014-2020" and handbook on external costs of transport [15-16]. The scheme is presented in figure 1. The first stage is the definition of car types. For this study were selected three types of vehicles – electric, gasoline and diesel. After, each car type was selected a specific vehicle model. It is important, that the same class vehicles having similar characteristics are presented in this research to provide a correct evaluation. Car specification data was collected after.

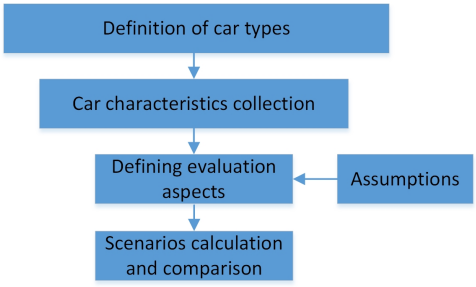


Fig. 1. Cost-benefit analysis method scheme.

The next step is the main and includes a definition of the aspects of evaluation. Developed methodology include such aspects related to a vehicle:

- Car production costs;
- Car purchase costs;
- Operating costs;
- Car utilization costs.

After all aspects are selected data collection was performed. Undoubtedly, the accuracy of the analysis and calculation depends on the availability of raw data. Often, some level of assumptions is needed. When making assumptions (fuel and car price), it is important to base them on existing examples from the literature and other sources. The final step is data calculation and the comparison of all scenarios.

As environmental aspects were considered - air pollution, climate change, noise. The cost of air pollution is one of the most analyzed categories of external costs. Emissions costs are calculated using average emission factors for each vehicle type. Total emissions are derived from emission factors and transport performance data, resulting in a consistent set of emissions that is consistent with emission databases and official transport statistics. The overall results for the main pollutants (NOx, PM) are well comparable, although there are some differences due to different transport data and different sources [16].

In the field of transport, CO_2 is emitted, these are greenhouse gases that contribute to climate change. Greenhouse gas emissions into the atmosphere cause global warming and climate change. The costs of climate change are defined as the costs associated with all the consequences of global warming, such as rising sea levels, declining biodiversity, water management issues, increasing weather extremes and crop failures. Are used three input data values: GHG emission factors for each vehicle type, vehicle performance data and climate change costs per ton of CO_2 equivalent.

Traffic noise is a growing environmental problem as it combines the trend towards greater urbanization with an increase in traffic. In general, noise can be defined as unwanted sounds of various durations, intensities, or other qualities that cause physical or psychological harm to humans. [16]

III. RESULTS

Based on the methodology developed in the work, the costs of 3 new vehicles and 3 five-year-old vehicles were compared, electric, gasoline and diesel cars were selected. The cars are selected according to the most popular cars in Latvia, to make the comparison more objective, cars of the same brand (Volkswagen) with similar engine power, similar class/comfort car were chosen.

A. Car operation

There are costs in various aspects during the operation of the car, economic, social and environmental aspects will be considered in the work. The economic aspects were costs related to mileage, maintenance and servicing costs. Maintenance and servicing costs included costs that include self-service, it is an oil change, spare parts change and others. The annual mileage costs were compared, the average mileage in Latvia is 13 000 km, so it was considered that exactly this distance will be driven per year. The difference in energy price between EV and diesel car is 0.11 EUR, between EV and gasoline car 0.09 EUR. On the other hand, the energy consumption per 100 km of the new EV is 22.4 kWh lower than that of a new diesel car and 29.4 kWh lower than that of a new gasoline car. The consumption of a 5-year-old EV is 3 kWh higher than that of a new EV. For a 5-year-old diesel and gasoline car, the energy consumption of a 5-year-old EV is greater than 29.4 kWh and 30.1 kWh, respectively. The calculations based on the total mileage costs per year show that usage of a new or of a 5-year-old EVs will cost for its user 5 times cheaper than diesel vehicles and 6 times cheaper than gasoline vehicles.

The operating tax depends on CO_2 emissions in Latvia, so for the EV this tax is 0 EUR, but for diesel and gasoline cars 12 and 48 EUR, respectively. EV is also exempt from the natural resources tax, but it will cost 55 EUR for the internal combustion engine car. Parking costs were counted as other social costs. EV is also exempted from paying for parking,

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while parking for internal combustion engines will cost around 600 EUR per year as an assumption.

Vehicles emit emissions and noise, as well as emissions during fuel production. CO_2 emissions are counted as both air pollution and climate change emissions. Emission factors that convert emissions into costs in EUR. In Latvia, according to CSB data, 47% of electricity is produced from fossil energy resources [17]. New and 5-year-old EV does not emit any emissions, so from an environmental point of view, EV costs are only related to noise and electricity generation. The emission costs are much higher for the old fossil fuel car, the difference between the gasoline car at that time is not so great.

Figure 2. summarizes the economic, social and environmental aspects of the operation of the vehicle. The car price was not added to the economic aspects of the schedule. New and 5-year-old EVs have the lowest costs. Gasoline and diesel cars have a smaller difference in cost than 5-year-old cars. Most of the costs of the EV, for the new and the 5-year-old, are made up of economic aspects, a smaller part is made up of environmental aspects.

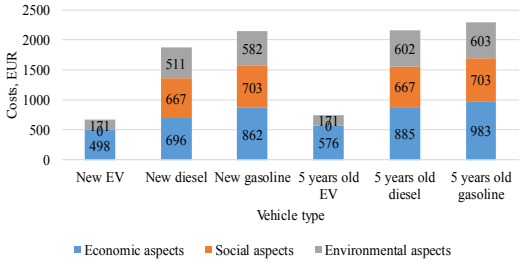


Fig. 2. Car operating costs.

B. Additional costs

An important aspect is the purchase cost of a car. Based on the official car seller data the cost of new EV, diesel and gasoline car prices are 26 000, 24 000 and 22 000 respectively. The purchase price of a 5-year-old car was 70% of the price of the new vehicle. EVs are exempt from the car registration fee, while car registration for an internal combustion engine will cost 43.93 EUR.

Also, there is a cost from the emissions generated during the production phase of the vehicle. These emissions were transferred to EUR. The constant CO_2 price 116.3 EUR/t was used for calculation. The production of one EV generates twice as many emissions (10 tCO_2 eq.) as the production of internal combustion engine vehicles (5 tCO_2 eq.). This is explained by the fact that the production of EV produces batteries with high emissions during production.

Finally, the car utilization costs were calculated from CO_2 emissions during utilization. EVs utilization generates more CO_2 emission (2,35 tCO_2 eq.) in comparison with diesel and gasoline cars (1,70 tCO_2 eq.). Therefore, EVs utilization costs almost 80 EUR more because more emissions are generated during the EV's battery utilization process.

According to the performed calculation, the additional costs of all cars are mostly made up of the purchase of a car (fig. 3). Car utilization accounts for the smallest part of additional costs. The highest total additional costs are for a new EV and lower for a five-year-old gasoline car. The cost of the new EV is 2 558 EUR higher than for new diesel and 4 558 EUR higher than for new gasoline cars. For 5-year-old cars, the difference between EV and fossil fuel cars is lower.

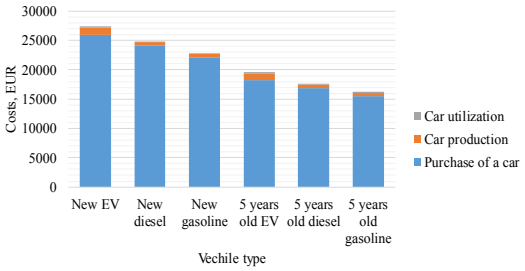


Fig. 3. Additional car costs.

The total vehicle's cumulative cost was calculated for the period of 10 years of operation for each car. In the first year of operation, car purchase and production costs were also included. Figure 4 shows that because EVs are currently more expensive than internal combustion engines cars, the costs are higher in the first year, but in 10 years the total cumulative costs for the new diesel car are 27.8 % higher than for the new EV. A 5-year-old diesel serving you for 10 years will cost 22.3 % more than a 5-year-old EV. For a gasoline car, a new will cost 30% more expensive than a new EV, and a 5-year-old EV will cost 19.2% less in 10 years. Comparing the costs of a new EV and a 5-year-old EV, the cost of the new EV is 7000 EUR higher, which is due to the high price of the purchase of a new EV. The cost of a new diesel and gasoline car is 5000-6000 EUR higher in 10 years, which could also be related to the high price of the new car purchase. Also, it can be noted that although a new gasoline car costs less in the first year, after 10 years of operation it will cost more than a diesel car due to higher fuel consumption and fuel price, while a 5-year-old gasoline car after 10 years of operation will cost as much as a 5-year-old diesel.

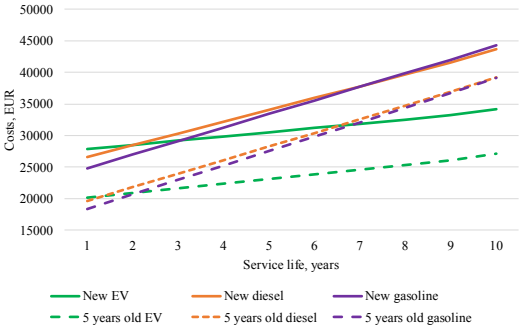


Fig. 4. Total cumulative costs.

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Sensitivity analysis was done to determine which of the selected factors, mileage during the year, fuel (including electricity) prices and changes in CO_2 prices have the greatest impact on the total cost over the life of the car. The performed calculation shows that this factor is the mileage per year. By varying the mileage from 70 % to 130 % the increase in the total cost of a 5-year-old gasoline car is 5209 EUR, the increase in the total cost of a 5-year-old diesel car is 4877 EUR, and the increase in the total cost of a 5-year-old EV is 2449 EUR. The changes for new cars are 4781 EUR for a gasoline car, 3618 EUR for a diesel car and 1981 EUR for an EV.

IV. CONCLUSIONS

An in-depth cost-benefit analysis was performed over the lifetime of the new and 5-year-old EV, diesel and gasoline vehicles. The operating costs of different cars were compared, and their influence on the total costs during their lifetime was determined. The total costs for 10 years of operation were also compared, including car purchase, fuel production, operation and utilization. It was determined that a new EV's usage would cost 27.8 % less than a new diesel car and 30 % less than a new gasoline car. A 5-year-old EV will cost 22.3 % less than a 5-year-old diesel and 19.2 % less than a 5-year-old gasoline car. Social and environmental costs for the EV exploitation period are significantly lower in comparison with internal combustion engine cars.

The results show that there are significant benefits to using EVs technologies, which will lead to both energy and money savings. Thus, the use of EVs can contribute to the achievement of the set goals in the transport sector in terms of increasing the share of renewable energy sources, as well as reducing the total energy consumption.

A more active increase of EV number in Latvia can be achieved by the implementation of the support mechanisms. Based on European country experience most effective instruments are subsidies for the purchase of a new EV, exemption from the registration fee and operating tax and development of charging station infrastructure. The cost-saving from EV usage in comparison with classic diesel and gasoline vehicle can be used as financial resources for the support mechanisms implementation.

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Linking Sustainable Mobility Criteria to Policymaking: Results of Multi-Criteria Analysis

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Abstract

With increasing emissions from the transport sector, the need to reduce emissions is becoming increasingly acute. The EC's Climate Law aims to re-duce emissions by 55% by 2030, while the growing transport sector is the slowest to meet these targets. Only a few European Union (EU) countries met the 2020 renewable energy source target in the transport sector, which indicates that major changes are needed to meet the new EU requirements. As each country has limited financial resources, it is necessary to assess the impact of the policy before its implementation. In this study, a survey of 19 industry experts was conducted to identify the most promising policy in-struments for reducing emissions in the road transport sector, as well as to identify the most promising fuels for which more resources should be devoted. In this publication, data analysis was performed by the combined Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology. The obtained data can be further used for in-depth analysis such as cost-benefit analysis or complex system dynamics analysis for later use in sustainable policy formulation.

Keywords: Transport, policy, survey, TOPSIS.

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1. Introduction

The transport sector is one of the most important sectors, which in 2018 was the second-largest source of greenhouse gas (GHG) emissions in Latvia and generated 28.5% of the total annual emissions [1]. Statistical data on GHG emissions also shows that emissions in the transport sector continue to increase, reaching 1.096 Mt CO2ekv in 2018 [2]. The data also show that actual GHG emissions exceed projected levels [2]. In the transport sector, the European Green Deal aims to cut emissions by 90% by 2050 by delivering a smart, competitive, safe, accessible, and affordable transport system, while the European Climate Law sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels [3], [4]. To reduce emissions in the transport sector, the European Union is-sued the revised renewable energy directive 2018/2001/EU (RED II) which entered force in December 2018 [5]. According to RED II, Latvia, like the other Member States, is entitled to determine its contribution within the framework of integrated national energy and climate plans [5]. Latvia's goals for renewable energy source (RES) integration in the energy sector are defined in the Latvian National Energy and Climate Plan 2021–2030. (NECP) [6]. Latvia's NECP sets the following main objectives in the transport sector [6]:

- to ensure at least a 14% share of RES in Latvia's final transport energy consumption by 2030;
- to ensure at least 3.5% of the share of modern biofuels in the final transport energy consumption of Latvia by 2030;
- to reduce the share of first-generation biofuels below 7% in RES by 2030;
- the share of first-generation or biofuels produced from food and feed crops may not exceed the share of such biofuels in Latvia by more than 1% in 2020 by 2030;
- Between 2023 and 2030, the use of biofuels with a high risk of indirect land-use change, the cultivation of which is associated with a significant expansion of production areas on high-carbon land, and the level of consumption of such biofuels must be completely abandoned and shall not be higher than in 2019 by 2030.

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Latvia's NECP identifies three main issues in the Latvian transport sector: An old car fleet dominated by diesel and petrol vehicles; Insignificant RES and electricity consumption in transport; and increasing the use of private vehicles and declining public transport [6].
To achieve the goals set by the NECP, Latvia needs to introduce policy instruments that would address the issues set by the NECP: to reduce the average age of vehicles in the country, which was 12.6 years in 2018; to increase the share of RES in the transport sector, which in 2019 amounted to only about 4%; to increase the use of electric vehicles (EV) in transport, which in 2019 accounted for only 0.07% of the total number of registered vehicles in technical order; as well as to reduce the use of private vehicles and to increase the popularity of public transport and active transport modes.
Before investing in the implementation of policy instruments, it is necessary to evaluate different policy instruments to determine the most effective ones. This publication offers a methodology based on expert surveys and data analysis with the combined Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

2. Literature analysis

2.1. Identification of policy instruments

To determine which policy instruments should be evaluated, an analysis of the policy instruments used in other European Union countries was performed. The countries which were chosen for the analysis were Sweden, Norway, Finland, the Netherlands, and Austria because these countries have the biggest share of the RES in the transport sector which in 2019 was 30.3%, 27.3%, 21.3%, 12.5%, and 9.8% respectfully. [7] The policy of the Baltic States (Lithuania and Estonia) was also analyzed, as they are closer to Latvia, as well as the adopted policy decisions in Latvia were examined.
A tax system based on CO_2 emissions has been introduced in three leading countries (Sweden, Norway and Finland) at the beginning of the 21st century as well as other initiatives that support environmentally friendly vehicles. For example, in Norway, EV has been exempting from VAT since 2001. Other countries have similar policy instruments in place that were introduced later, such as incentives to purchase low-emission vehicles, countries set operating tax costs based on emissions, and low-emission or zero-emission vehicles receive tax exemptions. For example, such vehicles are exempt from registration tax in the Netherlands, Austria, Lithuania and Latvia, and electric cars receive registration tax relief in Norway and Finland.
Other financial benefits for owners of more environmentally friendly cars include subsidies for low-emission cars. In Lithuania, for example, a newly introduced bonus of EUR 1,000 is available for scrapping an old polluting vehicle.
Alternative fuel vehicles also require new infrastructure, which is also subsidized in all these countries. Another policy instrument implemented in all these countries is green public procurement. To increase the share of RES with the existing fleet of internal combustion engines, countries set a mandatory share of biofuel blends.
The table below summarizes the application of the considered policy instruments in the different countries.

Table 1. Application of policy instruments in selected countries.

	Sweden	Norway	Finland	Netherlands	Austria	Estonia	Lithuania	Latvia
Exemption from registration tax		X	X	X	X		X	X
Exemption from operating tax		X		X			X	X
VAT relief		X						
Company tax relief	X				X	X	X	X
Subsidizing the purchase of vehicles	X	X	X	X	X	X	X	X
Green public procurement	X	X	X	X	X	X	X	X

States, where the number of EVs is not that high, also offer local bonuses such as the abolition of parking fees in cities, as well as the possibility of using bus lanes for electric vehicles.

2.2. Use of TOPSIS methodology in decision making

Mankind has long been interested in decision-making methods, as we often encounter the description of complicated problems, where the best option is often not obvious. The multicriteria approach makes it possible to identify a wide range of views to structure the decision-making process in terms of stakeholder preferences and a huge range of criteria, taking into account several aspects - economic, social, environmental, quality, ethical, etc. [8]. Multiple-criteria decision analysis (MCDA) is a general term for all the methods that exist to help people make decisions, even if the problem is complex or there are several conflicting criteria [8]. The application of the MCDA allows to make an informed decision, even if the criteria are contradictory [8].

The MCDA provides an opportunity to add weight to individual criteria that give different criteria different relative importance. This makes it possible to differentiate the contribution of different criteria in choosing the optimal alternative [8]. However, the weighting given to the criteria is to some extent subjective. One of the possible steps in the MCDA is to carry out a survey of specialists, which considers both the required criteria and their compliance with the final decision. Using a group of experts instead of one allows for a more objective assessment [8]. In this case, the risk of personal error is reduced. This makes it possible to differentiate the contribution of different criteria in choosing the optimal alternative [8].

One of the popular MCDA methods is TOPSIS, which was first used by Yoon and Hwang in his work "Multiple Attribute Decision-Making Methods and Applications. A State-of-the-Art Survey" [9]. The TOPSIS method is based on determining the shortest distance to the ideal solution from the geometric point of view (in the Euclidean space). The TOPSIS was used to analyze survey data and the TOPSIS algorithm will be described in more detail in section 3.2.

The TOPSIS method has several advantages that make it suitable for finding different solutions [10]:

- TOPSIS allows explicit trade-offs and interactions among attributes.
- The result can be a preferential assessment of alternatives with a numerical value that provides a better understanding of the differences and similarities between the alternatives.
- Pair comparisons are not allowed
- Unlimited range of criteria and performance attributes
- It can include a set of weighting coefficients for different attributes.
- Relatively simple calculation process,
- No special program required
- The method is perfectly suitable for connection to computer databases dealing with material selection.

The following TOPSIS features allow this method to be used in a variety of fields [11]. For example, Elzbieta Broniewicz and Karolina Ogrodnik identified the TOPSIS method, alongside the AHP method, as the most common decision-making process for The Strategic Environmental Assessment and Environmental Impact Assessment, which are important legal instruments for EU environmental policy which allows the identification, prediction, prevention and mitigation of the negative effects on the environment [12]. For example, Roman Vavrek and Jana Chovancová used TOPSIS to evaluate the energy economic and environmental performance of the EU countries where the breakdowns of energy indicators for sustainable development were separated into 3 dimensions – social, economical and environmental [13]. Xiuxia Zhang et.al. used the structural entropy-TOPSIS model for the evaluation of urban public transport priority performance in the city of Wuhan from 2006 to 2015 [14]. TOPSIS methodology was also used in the assessment of 2nd generation biofuels by Martina Haase et.al. and to determine barriers for sustainable development of renewable energy in Pakistan by Yasir Ahmed Solangi [15], [16]. The TOPSIS methodology was used to evaluate the efficiency of rail sections [17]. In Farhad Samaie et.al. study fuzzy TOPSIS methodology was used in evaluating various policies affecting the development of EVs in Tehran [18]. Gustavo Piresda Ponte et. al. used TOPSIS in their study where eighteen criteria were assessed, and ten specialists were interviewed to determine suggestions of public policies to stimulate the use of environmentally friendly energy sources at off-grid places in Brazil [19].

3. Methodology

3.1. Survey structure

The proposed methodology involves surveying experts to obtain their assessment of various policy instruments. 19 experts from different sectors (public administration, research or industry) were surveyed. Before the survey, respondents must provide information on the sector represented - public administration, research or industry.

In the first part of the survey, respondents had to evaluate each of the policy instruments according to the given criteria on a scale from 1 to 10. Policy instruments are evaluated according to 4 criteria: (i) required investments (P1), where 1 - the implementation of the measure does not require financial investment, and 10 - the implementation of the measure requires significant financial investments.; (ii) a monitoring mechanism (P2), where 1 - the implementation and monitoring of the measure is simple, and 10 - the implementation and monitoring of the measure is difficult; (iii) RES promotion potential (P3), where 1 - the measure has minimal or no effect on the increase of the share of RES, and 10 - the measure significantly affects the increase of the share of RES, and (IV) public support (P4), where 1 - the measure has no support or there is (is expected) minimal support in society, and 10 - the event has (is expected) high public support.

The following policy instruments were put forward, selected according to examples of good practice from the NECP and other countries:

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.

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.
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.
10A. Subsidization of biofuel production, including biomethane.
10B. Subsidizing the capital costs of biofuel plants, including biomethane.
10C. Facilitated conditions for biomethane injection into the natural gas grid.
10D. Proofs of origin for biomethane.
11A. Free parking for zero-emission and low-emission vehicles.
11B. Permitting the use of public transport lanes for zero-emission and low-emission vehicles.
11C. Increasing parking fees for vehicles using conventional fuels.
12. Introduction of low-emission zones in cities to reduce car traffic.
13. Electrification of the railway network.
14A. Renewal of the public transport fleet
14B. Reduction of the public transport ticket price

In the second part of the survey, respondents were invited to evaluate the potential of electric vehicles (EV), natural gas vehicles (CNG), biomethane vehicles (CBG), biofuel vehicles (BIO-F) and hydrogen (H2) vehicles in Latvia. The evaluation of the potential was given on a scale from 1 to 5, considering the relevant aspects:

- Social aspect (F1), where 1- support for the given technology will not promote the creation of social new jobs, 5 - the support of the identified RES will promote the creation of many jobs.
- Environmental aspect (F2), where 1- the identified RES support will contribute to a small negative impact on the environment, 5 - the identified RES support will promote a large negative impact on the environment.
- Technological aspect (F3), where 1- certain RES technologies are not developed, 5 - certain RES technologies are highly developed.
- Economical aspect (F4), where 1- certain RES technologies will not cost much, 5 - certain RES technologies have high costs.

In the last section of the survey, respondents assess the weight of the criteria mentioned in the first part (required investments; a monitoring mechanism; RES promotion potential and public support) and the aspects mentioned in the second part (social, environmental, and technological). The higher the weight, the more important the indicator. The sum of the weights is equal to 1. Weighing is required for further data processing.

3.2. TOPSIS methodology

According to A. Shanian, O. Savadogo and Yoon and Hwang, the TOPSIS solution method consists of the following steps [10], [11]:

1. Normalize the decision matrix. The normalization of the decision matrix is done using the following transformation:

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r^2{}_{ij}}}; j = 1,2,\dots,n; i = 1,2,\dots,m \quad (1)$$

2. Multiply the columns of the normalized decision matrix by the associated weights. The weighted and normalized decision matrix is obtained as:

$$V_{ij} = n_{ij} w'_j; j = 1,2,\dots,n; i = 1,2,\dots,m \quad (2)$$

Where w'_j represents the weight of the jth attribute.

3. Determine the ideal and nadir ideal solutions. The ideal and the nadir value sets are determined, respectively, as follows:

$$\{V_1{}^+, V_2{}^+, \dots, V_n{}^+\} = \left\{\left(\max_i V_{ij}\ Ij \in K\right), \left(\min_i V_{ij}\ Ij \in K'\right) Ii = 1,2,\dots,m\right\} \quad (3\text{-}1)$$

$$\{V_1{}^-, V_2{}^-, \dots, V_n{}^-\} = \left\{\left(\min_i V_{ij}\ Ij \in K\right), \left(\max_i V_{ij}\ Ij \in K'\right) Ii = 1,2,\dots,m\right\} \quad (3\text{-}2)$$

where K is the index set of benefit criteria and K' is the index set of cost criteria.

4. Measure distances from the ideal and nadir solutions. The two Euclidean distances for each alternative are, respectively, calculated as:

$$S_i^+ = \left\{\sum_{j=1}^{n} \left(V_{ij} - V_j^+\right)^2\right\}^{0,5}; j = 1,2,\dots,n; i = 1,2,\dots,m \quad (4\text{-}1)$$

$$S_i^- = \left\{\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2\right\}^{0,5}; j = 1,2,\dots,n; i = 1,2,\dots,m \quad (4\text{-}2)$$

Remark: In the so-called 'block TOPSIS' method, the two distances are obtained as:

$$S_i^+ = \sum_{j=1}^{n} \quad V_{ij} \quad (4\text{-}3)$$

5. Calculate the relative closeness to the ideal solution. The relative closeness to the ideal solution can be defined as:

$$C_i = \frac{S_i}{S_i^+ + S_i}; i = 1,2,\dots,m; 0 \le C_i \le 1 \quad (5)$$

The higher the closeness means the better the rank. The methods for assessing the relative importance of criteria must be well defined. In the proposed methodology, the relative importance of criteria is clarified in an expert survey.

4. Results

4.1. Identifying the most effective policy instruments

Summarizing the obtained results, the following criteria weights were determined: required investments - 0.33, a monitoring mechanism - 0.19, RES promotion potential - 0.25, public support - 0.23. Table 2 shows the five highest-rated policy instruments for each criterion.

Table 1. The five highest-rated policy instruments by each criterion

Criteria (criterion weight)	Political instrument	Score	Criteria (criterion weight)	Political instrument	Score
P1 - required investments * (0.33)	11B	1.95	P2 - RES promotion potential (0.25)	5A	7.42
	1A	2.68		6	7.42
	1B	3.00		5C	7.11
	2A	3.42		5B	7.14
	10D	3.42		13	6.63
P3 - a monitoring mechanism (0.19)	10A	7.05	P4 - public support (0.23)	5A	9.16
	10B	6.79		5B	8.95
	10C	6.57		5C	1.89
	13	6.57		14A	7.89
	7	5.84		14B	7.89

** As the most favourable case is when costs approach 0, the table shows the lowest or cheapest rated policy instruments, while the inverse values were used in the calculations.*

The results show that there is no single policy instrument that is valued equally high for all 4 criteria and that the instruments rated higher for each criterion are different, apart from vehicle purchase support policies (5A, 5B, 5C), which were rated higher in the RES promotion potential and public support, as well as in the electrification of the railway network (13), which were rated higher in the RES promotion potential and monitoring mechanism. The TOPSIS method was used to summarize the results of the first part of the survey with the previously determined weights. The results of the TOPSIS method are summarized in Fig.1.

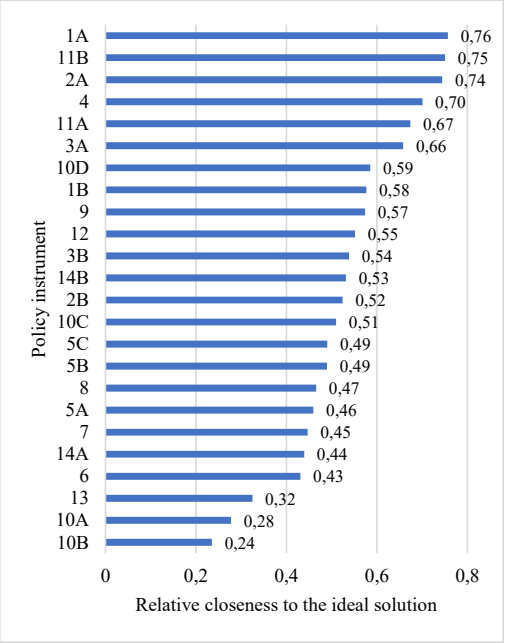


Figure 1. Relative closeness to the ideal solution of political instruments

Results show that the most influential political instruments are exemption from registration tax for zero-emission and low-emission vehicles (1A), permitting the use of public transport lanes for zero-emission and low-emission vehicles (11B) and exemption from operating tax for zero-emission and low-emission vehicles (2A) followed by tax incentives for zero-emission and low-emission vehicles owned by companies (4), free parking for zero-emission and low-emission vehicles(11A) and reduction of excise duty on alternative fuels (3A).

The results indicate that those policy instruments that require less cost were rated higher, which can be explained by the high weight given to the required investment criteria.

4.2. Identifying the most promising type of fuel

In the second part of the survey, respondents had to assess the potential of multi-fuel vehicles on four criteria. During the survey, the following weights were determined for each criterion: social aspects (impact on employment, welfare, health) - 0.22; total costs - 0.31; environmental impact - 0.25; technology development potential - 0.21.

The evaluation of each fuel type according to each criterion is shown in Fig. 2.

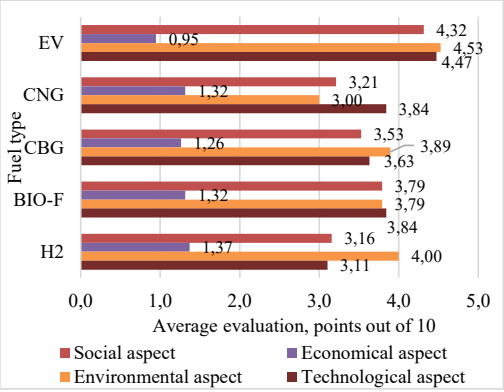


Figure 2. Evaluation of each fuel type according to given criteria.

Figure 2 shows that, according to experts, EV has the lowest costs, and EV has a greater positive impact in other respects as well. In terms of environmental impact, hydrogen-powered vehicles were assessed immediately after EV, which were also assessed as the most expensive fuel. In turn, according to the technological potential, natural gas took second place immediately after EV. The second place in social terms was the wider use of biofuel vehicles. The relative proximity of each fuel type to the ideal result is shown in Figure 3.

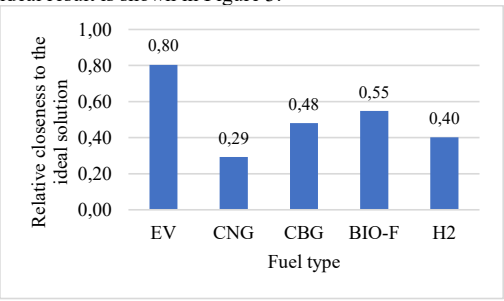


Figure 3. Relative closeness to the ideal solution of each selected fuel type

The results indicate that, according to experts, the biggest benefit in the country could be achieved by developing EV. Biofuels, biomethane and hydrogen were rated lower, while natural gas was rated the lowest, mostly due to the negative impact on the environment.

4.3. Sensitivity analysis

As the expert survey is subjective, a sensitivity analysis was performed to assess the significance of the weights identified in the expert survey. To check the effect of attribute distribution on the results of the TOPSIS method for evaluation of the fuels, the significance of attributes of the same size is selected. The chosen unitary variation ratio was 0.01, 0.5, 1.0, 1.5, 2.0, 3.0. Table 3 shows how the evaluation of policy instruments changes as the weight of the criterion increases. The results show how the assessment of policy instruments changes as the weight of each criterion increases.

Table 2. Changes in policy instruments' rank as the weight of each criterion increases.

	P1	P2	P3	P4
Criteria	Required investments	A monitoring mechanism	RES promotion potential	Public support
1A	I	I	D	I
1B	I	I	D	D
2A	I	I	D	I
2B	I	I	D	D
3A	I	I	D	I
3B	I	I	D	D
4	I	D	D	I
5A	D	D	I	I
5B	D	D	I	I
5C	D	I	I	I
6	D	D	I	I
7	D	D	I	I
8	D	D	D	I
9	I	D	I	D
10A	I	D	I	D
10B	D	D	I	I
10C	I	D	D	D
10D	I	D	D	D
11A	I	I	D	I
11B	I	I	D	D
12	I	D	D	D
13	D	D	I	I
14A	D	D	I	I
14B	D	D	D	I

**Increases – I; Decreases – D*

The data in the table show that most policy instruments (20 out of 24 policy instruments) show opposite results for the "P1" and "P3" criteria. In other words, policy instruments that decrease with increasing "P1" criteria, increase with increasing "P3" criterion and, conversely, increase with increasing "P1" criterion and decrease with increasing "P3" criterion. Similarly, the trend in the evaluation of policy instruments was the opposite of criteria "P2" and "P3" for 17 of the 24 trends in policy

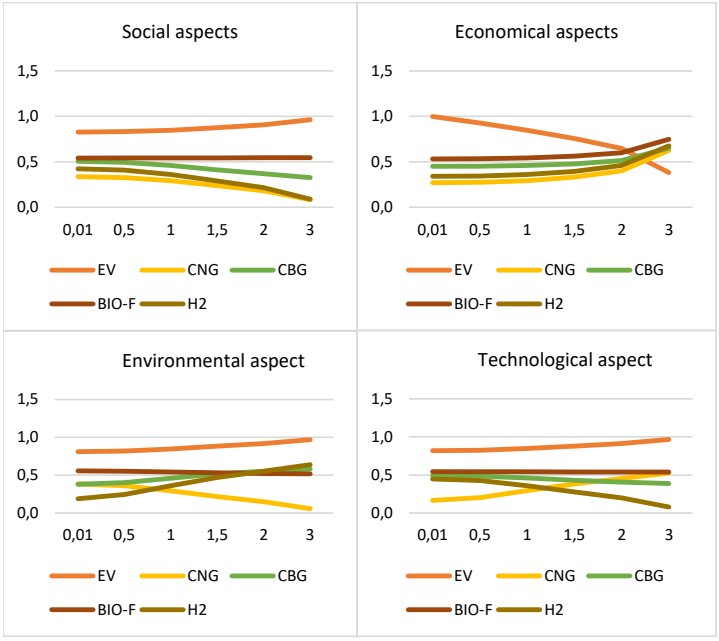


Figure 4. Sensitivity analysis for fuel evaluation

instrument change. In turn, the tendency of evaluation of policy instruments coincided with the criteria "P1" and "P2" (coincided with 17 out of 24 trends in changes in policy instruments), as well as with the criteria "P3" and "P4" (coincided with 15 out of 24 trends in changes in policy instruments).

This shows that 1) the most effective policy instruments in terms of RES promotion usually are the priciest, 2) instruments, which require less investments are easier to monitor and 3) policies that are effective in terms of RES promotion are more likely to be accepted by the public. Figure 4 shows how the evaluation of policy instruments changes as the weight of the criterion changes.

From the graphs, it can be concluded that EV receives the highest ratings in all cases, except when the importance of economic aspects increases, then the rating of other fuels increases with biofuels in the lead. The rating of biofuels does not change so drastically as the importance of other aspects changes. The rating of hydrogen fuel also increases with increasing environmental aspect role but decreases with increasing social and technological aspects. The rating of natural gas fuels also increases with the increasing role of the technological aspect but decreases with the increasing social and environmental aspects.

It should be noted that the opinions of experts were very volatile. The relative error, which was calculated with a probability of 95% for the weights of the evaluation criteria and fuel evaluation aspects of the policy instruments, is shown in Table 4.

Table 3. Relative error of determined weights of evaluation criteria/aspects.

Name of criteria/aspect		Weight of criteria/aspect	Relative error, %
Criteria for evaluating policy instruments	P1 - required investments	0.33 ±0.09	26.72%
	P2 - RES promotion potential	0.19 ±0.08	42.94%
	P3 - a monitoring mechanism	0.25 ±0.09	35.77%
	P4 - public support	0.23 ±0.08	33.59%
Aspects for fuel type evaluation	F1 - social aspect	0.22 ±0.09	41.08%
	F2 - economical aspect	0.31 ±0.07	22.38%
	F3 - environmental aspect	0.25 ±0.09	35.49%
	F4 - technological aspect	0.21 ±0.09	41.08%

Such a large relative error indicates an uncertainty characterized by differences of opinion between different experts. To obtain more accurate data, more industry experts from different representations should be interviewed.

5. Discussion

The study obtained results on the evaluation of policy instruments, as well as on the potential of different fuels in Latvia. An in-depth analysis of the highest-rated instruments is needed. This could be economic (cost-benefit analysis) or complex system dynamics analysis. For example, these data can be used further in modeling system dynamics in the transport sector, where the impact of different policy instruments is assessed.

6. Conclusions

Using the proposed methodology, several policy instruments were evaluated, which aim to increase the share of RES, not only in terms of RES promotion potential, but also in terms of necessary investments, monitoring mechanism, and public support, taking into account expert evaluation. According to the experts, the most promising political instruments are exemption from registration tax for zero-emission and low-emission vehicles, permitting the use of public transport lanes for zero-emission and low-emission vehicles and exemption from operating tax for zero-emission and low-emission vehicles;

The second part of the survey allows legislators and researchers to assess which fuel vehicles need more support. The results showed greater priority should be given to the development of electric transport, followed by biofuels and biomethane.

Sensitivity analysis showed that most policy instruments have a proportional link between the P1 and P2 criteria and between the P3 and P4 criteria, as well as an inversely proportional link between the P1 and P2 criteria.

The described methodology can be used in researches to identify the most promising support mechanisms that could be introduced by legislators to reduce the negative impact of the transport sector on the environment. The results obtained with this method can be used as a basis for further research, for example, in forecasting scenarios for the transport sector.

The disadvantage of the method is its possible subjectivity. Expert assessments varied widely, as indicated by the calculation of the relative error, which averaged around 35% in weighting. The influence of subjectivity can be avoided by interviewing more industry experts of various sectors, such as public administration representatives, researchers and entrepreneurs related to the transport sector. It is also important to address representatives of various associations, such as road transport, biogas, electric transport, fuel, and other associations' representatives as well as supporters of different types of alternative fuel vehicles (electricity, hydrogen biofuels, natural gas and bio-methane) have to be interviewed to get a broader view of the problem under study.

Acknowledgements.

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Renewable Transport Challenge: A Comprehensive Policy Assessment Model

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ABSTRACT

With the growth of the transport sector and its emissions, the European Union (EU) has obliged member states to increase the share of renewable energy sources. To understand which policies need to be pursued to achieve the objectives set by the EU, a system dynamics model was developed and applied to the case study of Latvia. The model considers the potential of the production and use of renewable fuels, the impact of policies on the development of renewable energies, and factors influencing population choice of transport mode.

Keywords: c

NONMENCLATURE

Abbreviations	
CO_2	Carbon dioxide
DTReM-LV	Dynamic TRansport emission Model for Latvia
EC	European Commission
EEA	European Energy Agency
EU	European Union
GHG	Greenhouse gas
RED	Renewable Energy Directive

1. INTRODUCTION

In 2017, the European Commission's Renewable Energy Progress Report concluded that transport is the only sector currently below aggregated national trajectories at the EU level [1]. The share of renewable energy is one of the primary indicators to measure progress in reducing fossil fuel emissions. In 2009, the Renewable Energy Directive (2009/28/EC) set the target that 10% of all energy used in transport should be from renewable sources by 2020. The latest EEA data indicated that in 2019 the share of renewables in transport in the EU was 8.4%. EEA also concluded that reaching the 10% goal by 2020 was unlikely at both country and EU levels because several countries were far from meeting the target. The following recast of the Renewable Energy Directive in 2018 (RED II) obliged fuel suppliers to ensure an increased 14% share of renewable energy in the final energy consumption of the transport sector [2]. This year, the Commission announced the "Fit for 55" package to provide a legislative framework for achieving the 55% greenhouse gas (GHG) emission reduction target by 3020 [3]. Among other proposals, the package also proposes new amendments to the Renewable Energy Directive.

The European Green Deal sets a very ambitious target of reducing GHG emissions from transport by 90% by 2050 compared to 1990 levels [4]. This envisages the development of alternative renewable transport fuels, including advanced biofuels, renewable liquid and gaseous transport fuels of non-biological origin, and renewable electricity in the transport sector.

This paper describes a newly developed modeling tool for comprehensive planning and continuous impact assessment of energy and climate policies in the transport sector. The model was approbated to the case study of Latvia.

2. MATERIALS AND METHODS

The structure of the proposed modeling tool is shown in Figure 1. The model is made in the Stella Architect software based on a previously developed DTReM-LV model (Dynamic TRansport emission Model for Latvia). The DTReM-LV model projects carbon dioxide (CO_2) emission trends in the Latvian transport sector by 2030 and evaluates the emission-saving potential of a broad set of policy measures [5]. Several substantial structural improvements were made to the initial model, including

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cross-sectoral interdependences with energy, agriculture & forestry and waste management sectors, and the inclusion of socio-economic impact and cost assessment of policies suggested.

The simulation takes place from 2017 to 2030. Modeling results reveal projections of energy demand, CO_2 emissions, and renewable energy share in the transport sector in Latvia and underlying factors influencing the projected development patterns.

The system dynamics modeling approach solves complex problems using the dynamic development research method [7]. This approach allows modelers to understand the behavioral patterns of complex systems (dynamic trends) and make changes in the system, which makes its parameters and structural changes flexible.

2.2 Structure of the model

The model is based on the relationship between the

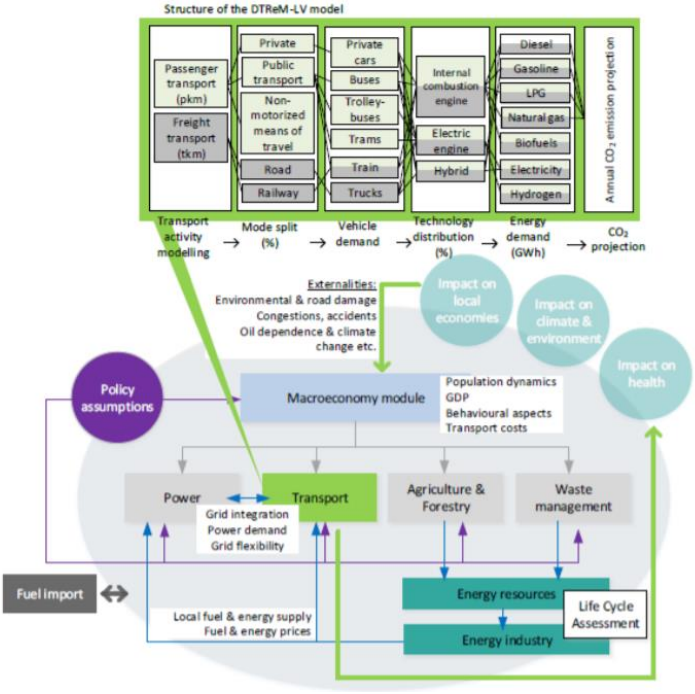


Fig. 1. The structure of the system dynamics model for sustainable transport policy analysis

2.1 System dynamics modeling

The proposed model is based on the system dynamics modeling approach. The analysis of the system structure is based on the concept of two-way causality or feedback. This concept involves linking decisions to information about the system's state or the environment, including the decision-maker himself. The goal is to make decisions based on which actions will change the state of the system. The changes introduced in the system affect future decision-making and thus also future changes. Each closed causal chain forms feedback; many links together form system dynamics models [6].

transport demand in passenger and freight transport, modality of transportation, technology distribution, and technology efficiency (fuel consumption). The model user can change assumptions about parameters such as transport demand, modal split, technology split, technology efficiency, resource prices, etc. The model allows analyzing changes in the CO_2 emissions balance based on assumptions made by the user. For example, what will be the effect of reducing the demand for passenger transport, which will be accompanied by an increase in the number of electric cars, more cycling or public transport, and so on. Based on modeling assumptions, results in terms of CO_2 emissions and renewable energy share are obtained.

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2.3 Scenario design & testing

Three main CO_2 reduction directions are considered in scenario runs following the "Avoid-Shift-Improve" sustainable mobility concept. Firstly, the "Avoid" strategies aim to improve the system's efficiency by reducing the need to travel. Secondly, the "Shift" strategies aim to enhance trip efficiency by shifting from private cars to more environmentally friendly modes of transport. Finally, the "Improve" strategies seek to improve vehicle efficiency by introducing alternative fuels and improving energy efficiency.

3. RESULTS

An innovative system-dynamics-based integrated modeling tool for comprehensive planning and continuous impact assessment of energy and climate policies in the transport sector in Latvia was designed, developed, and validated. Based on model results, improved policy formulation and evaluation analysis for elaborating coherent and comprehensive transport policies, emphasizing strategies for increasing renewable energy share. The pathways consider the co-existence of different technologies (both existing and new) and the need for national support mechanisms to accelerate the transition. The baseline scenario and policy scenarios with specific goals and achievable results were defined involving the following 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 & services policy;
- P9: Old vehicle scrappage scheme policy, and;
- P10: Fossil fuels tax policy.

First, the baseline scenario was simulated, and later the existing, expected, and new policies were designed across sectors. The policies were simulated in isolation at first and then in combination. This allows us to estimate the specific impact of each and whether current policies are creating any synergies or bottlenecks (side effects). Based on the modeling results, policy recommendations were developed to address environmental, social, and economic challenges the transport sector faces.

Modeling results showing CO_2 emission saving potential under each of the three emission reduction strategies are presented in Table 1. Policy measures to reduce the need to travel result in a 5-8% reduction in emissions compared to the baseline scenario. Policy measures aimed at shifting to more environmentally friendly modes of transport result in a 2-5% reduction in emissions compared to the baseline scenario. Policy measures aimed at improving the energy efficiency of transport lead to emission reductions of up to 8% compared to the baseline scenario. None of the analyzed policies implemented separately gives considerable effect on emission savings. However, when implemented in a combination, policy measures show the potential to reduce CO_2 emissions by around 30% in 2030.

Table 1. Modeling results: 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% Increased cycling share: < 2% Mode shift in freight transport: 2-4%	P5, P6
Improve efficiency	Increased alternative fuel share up to 10% of stock: 5-8% Improved energy efficiency: 6%	P1, P2, P3, P4, P7, P9

4. DISCUSSION

Well known optimization models applied in the transport sector include the TIMES model (e.g., for China and US transport sectors [8] and Denmark [9]), the MARKAL model (e.g., for India [10]), the LEAP model (e.g., for Korea [11]). These optimization models provide policymakers with insights on policy impacts and offer projections of significant variables and, in some cases, can provide insights on the interactions between macro-economic development and energy management, but rarely vice-versa. The conventional models are also poor at representing consumer behavior [9], which is critical when addressing transport challenges. E.g., the modal shift between transport modes in traditional energy-economy models is evaluated under "what if" scenarios by assessing the effect of exogenously assumed levels of modal shift. But from the policymaker's point of view, it is most interesting to understand how the mode shift can be achieved. The primary strength of the system

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dynamics modeling approach is its unique "systems" perspective and capability to address the fundamental structural causes of problems arising in complex dynamic socio-economic systems. This advantage is especially beneficial in the transport sector, represented by complex linkages between system elements, feedbacks, nonlinearities, and time delays. The "white box" modeling approach makes researching the existing causalities more efficient in the transport system and builds understanding and conference of the dynamic behavior generated by the existing system. Moreover, this approach allows further improvements in the structure of the model and assumptions used, thus ensuring the opportunity for accuracy improvement of the model and its use for transport system analysis from other perspectives or within the context of other country's case studies.

The proposed modeling tool extends the existing scientific knowledge in the field in the following ways: (i) by addressing the causal relationships within the transport system actors and processes that are usually replaced with exogenous assumptions in conventional energy-economy models; (ii) by including a comprehensive package of cross-sectoral policies that include the direct costs of policy implementation and the less obvious costs, net social costs avoided and benefits of policy implementation; (iii) by taking an integrative approach that combines not only technology solutions with regulatory framework conditions to minimize costs and maximize impacts but also the integration of behavioral aspects in techno-economic modeling, and (iv) by extending the traditional scenario modeling approaches with a cost-benefit analysis.

Modeling results are applicable by governmental stakeholders for assessment of both the existing and planned transport and energy policies, including answers to the following questions: Which sectors of the economy and society need interventions of the public powers? What are policy measures available for bringing the desired changes in the socio-economic context? What are the expected effects? What are the budgetary implications of the policy measure? Modeling results can be practically used for evaluation of the efficiency of existing policies against national targets and tracking progress, assessment of the potential pathways for changes in the transport sector, to foster the achievement of goals, and planning and producing strategy documents such as alternative transport energy strategy, low-carbon strategies, updates of Nationally Determined Contributions, etc.

The future development of the model will focus on long-term analysis, extending the modeling period until 2050 and looking for strategies on how to achieve ambitious Green Deal goals in life.

5. CONCLUSIONS

This paper describes a newly developed mathematical energy-economy simulation tool for national-level policy formulation in the transport sector, emphasizing renewable energy potential. The model was used to research the case study of Latvia. The research aims to find optimal solutions for achieving climate and energy policy goals by 2030 and beyond.

The results indicate that traditional policies can deliver CO_2 emission reductions up to 30% by 2030 compared to the baseline scenario if implemented collectively. However, this is not enough to be on track to meeting the ambitious goals of the European Green Deal. Further research is needed on the integration of new policy settings giving more significant effect and the topic of coupling of the transport and energy sectors through power-to-gas and vehicle-to-grid technologies, thus marking the role of transport not only as a provider of mobility but also by providing an energy storage and transformation function leading to improved overall energy use efficiency.

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Incorporating User Behaviour Into System Dynamics Modelling: A Case Study of Private vs. Public Transport in Latvia

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***Abstract* – In this paper, a newly developed dynamic simulation model for transport user behaviour analysis is presented. The study aims to evaluate the impact of various factors on human behavioural intentions, identify the inconvenience costs of public transport, and identify the necessary improvements to shift the demand for population mobility from private cars to public transport. The assessment of such aspects as travel time and travel cost is presented. Modelling assumptions are based on a specially designed public survey allowing to improve the reliability of the developed system dynamics model. Modelling results highlight the multiplicative effect of factors influencing mode shift.**

***Keywords* – Human behaviour; modelling; public transport; system dynamics**

1. INTRODUCTION

According to the Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (Renewable Energy Directive, RED II), EU Member States are obliged to reach at least 14 % renewable energy share in final transport energy consumption by 2030 but then allows member states to bring this target down if they have a lower limit on food-based biofuels [1]. The majority of countries face difficulties in achieving the target. In 2019 (latest data available) only 5 countries had reached the target of at least 10 % renewable energy share by 2020 set by the Renewable Energy Directive, namely Sweden (30.3 %), Norway (23.5 %), Finland (17.4 %), Netherlands (11.4 %), and Iceland (10.9 %) [2].

It is up to the Member States to decide how to achieve the goals set by RED II: they are developing alternative fuels, increasing vehicle efficiency and taking other measures to reduce energy consumption in the transport sector. Previous research outlines also the potential of the transition from private to public transport in decarbonizing the transport sector [3], [4]. By switching peoples' transport modes towards public transport which is run on alternative fuels, great results might be achieved in terms of greenhouse gas emission savings [5], [6].

However, the reality shows opposite development trends. The average per capita car ownership increases, meanwhile popularity of public transport decreases. Factors such as personal comfort, saving time and money play a role in favour of the car [7], [8], while the major drawbacks of public transportation are: longer travel time, crowding, low travel comfort, etc. [8], [9], [10].

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Several authors compile surveys of the population to better understand the current situation regarding the attitude of the population towards public transport, as well as to determine what improvements are needed. For example, Juan de Oña *et al.* surveyed 525 respondents who use public transport and 500 respondents who choose private transport to identify factors influencing the quality-of-service perceptions, satisfaction, and attitudes toward public transport [11]. The largest differences in the scores for the public transport of both groups were related to attitude towards lifestyle, travel time, and costs. Another finding was that to promote public transport, efforts should focus on developing policies to change the attitudes of private vehicle users towards public transport services, as well as their perceptions of proximity, speed and intermodality [11]. Other studies, that evaluated decision influencing factors concluded that the main efforts in policy planning should be put towards the improvement of a well-coordinated transportation environment as well as other service quality attributes [12], [13]. Regarding travel costs Owen Bull *et al*. study in Santiago, Chile showed an overall increase in travel by 12 % and an increase in the total number of trips by 23 % after the invention of fare-free public transport [14] while some studies showed that economic factors, such as fuel prices or public transport fares, are not very effective in terms of influencing people who intend to use public transport [15], [16]. The main research results indicate that the main focus should be put on service quality improvement as well as on psychological and behavioural interventions such as changing the attitudes to public transport and cars and breaking commuters' habits [17], [18].

To evaluate the transition potential from private cars to public transport in Latvia, a mathematical simulation model was developed using the system dynamics modelling approach. The model represents major human decision influencing factors related to the transition from private cars to public transport. Data assumptions regarding human behaviour aspects needed for the model were obtained with the help of a specially designed public survey. The major scientific novelty of the research is the attempt to integrate the social dimension of the transport system (results of the survey) with a mathematical modelling task. As transport users' behaviour is very important in this context, such an approach allows for increasing the reliability of the developed system dynamics model, as the assumptions used are based on the results of real survey data. The novelty of this work is the development of a methodology for modelling human behaviour and policy that would promote the switch from private car use towards public transport as well as the achievement of renewable energy sources (RES) goals in the transport sector in Latvia. In this paper, the first results are presented covering two of the five selected factors influencing mode shift - travel cost and travel time. This type of research in the Latvian context has not been performed before. The results obtained can be used in policy planning.

2. METHODOLOGY

An overall description of the research methodology is given in Fig. 1. It consisted of three successive phases. During the preparation phase, a scientific literature study about factors affecting transport mode choice was performed. Outcomes of the desk research were later presented in several group brainstorming events with colleagues and university students to collect first impressions and opinions about the topic. Based on the outcomes of the discussions, the first conceptual system dynamics model was developed and a survey questionnaire was designed.

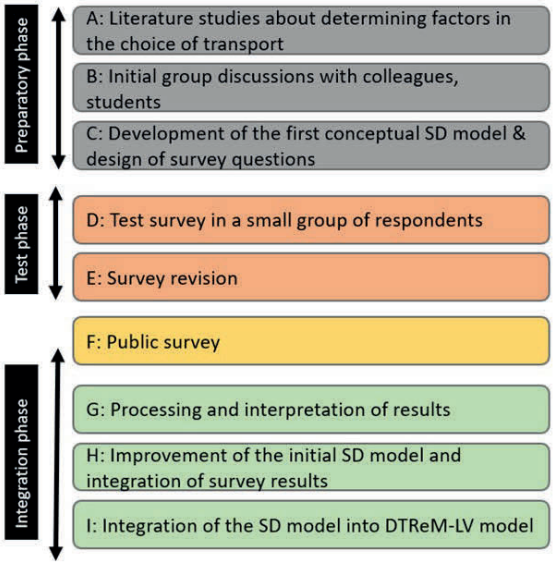


Fig. 1. Research methodology.

The second – test phase – was divided into two parts. At first, a test survey in a small group of five respondents was made. Their feedback showed that the first version of the survey was too long, as well they indicated a few survey questions that could be misunderstood and should be paraphrased. Changes were made accordingly to the feedback and the final version of the survey was shared via social media for two weeks for April–May, 2021.

The last phase of the research (still ongoing) involves processing and interpretation of the survey results, improvement of the initial conceptual system dynamics model and integration of survey results into the model. After the finalization of the private vs. public transport sub-module, it will be integrated into the whole transport system model for Latvia DTReM-LV (Dynamic Transport emission Model for Latvia) [19]. This study builds upon the previous work and aims to supplement the existing model to represent the inconvenience costs that are associated with public transport use.

3. Results and Discussion

3.1. Integration of survey results into the system dynamics model

To reduce carbon emissions in the transport sector, it is necessary to stimulate a change in human behaviour. Shifting human flows from private to public transport is influenced not only by the costs of the transport but also by the cost of inconveniences, such as travel time, travel comfort, congestion etc. [8], [20].

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 as 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 (Fig. 2). These results go along with a previously performed study in Poland about the main reasons for choosing a private car for daily commuting [20].

For the integration in the system dynamics model, factors influencing travel mode choice from the survey were grouped creating five major groups: (i) time, (ii) cost, (iii) infrastructure availability, (iv) comfort and (v) prestige (Fig. 3).

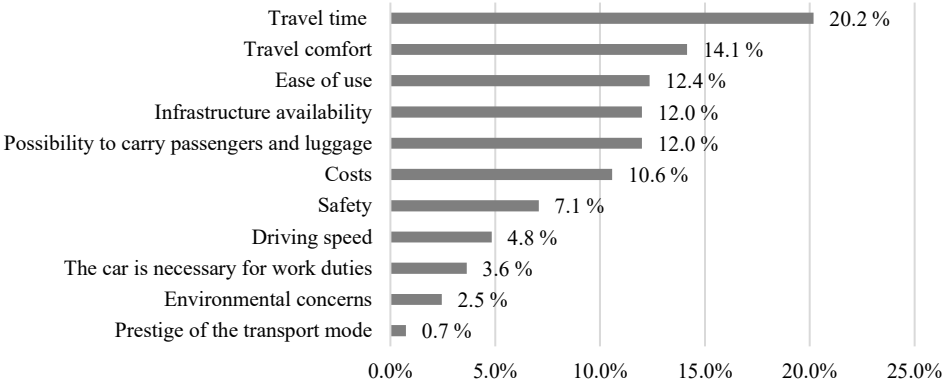


Fig. 2. Answers to the question 'Which of these factors do you find most important? (3–5 answers)'.

In the following sections step by step methodology and results are presented for two of the five factors, time and cost, namely. The effect of the time and travel cost on mode shift from private cars to public transport is modelled in a system dynamics model based on responses collected from the survey.

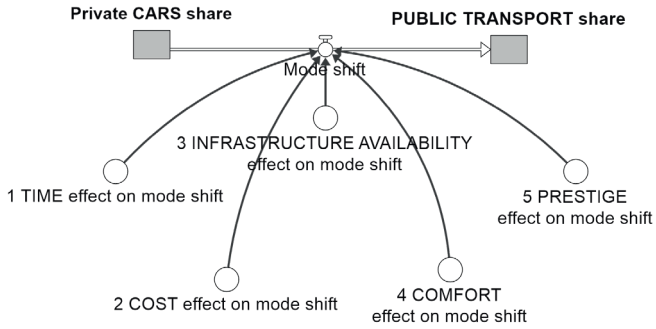


Fig. 3. Factors influencing mode shift included in the system dynamics model.

3.1.1. Travel time

As seen in Fig. 2 the highest-rated factor influencing the choice of transport mode is travel time. To determine the average travel time to be included in modelling assumptions, respondents were asked to indicate the average travel time from the moment of leaving home to reaching their destination (door-to-door) and to describe how this time would change if public transport was used instead of the private car. The average travel time was taken separately for respondents living in cities and for those living in regions and was compared with the time estimate provided by the respondents, which would be necessary to perform the same route by public transport. After comparing travel time for both transport modes results

show that on average trips by public transport take 133 % more time than by private car (median is 100 %) and only 10 out of 281 comparable responses (when respondents knew what is the travel time for both transport modes) or 3.6 % thinks that the trip by public transport could be faster than the trip by private car and 7.1 % believes that it would take the same time. Results for travel time compared by residence (urban or regional) are given in Table 1.

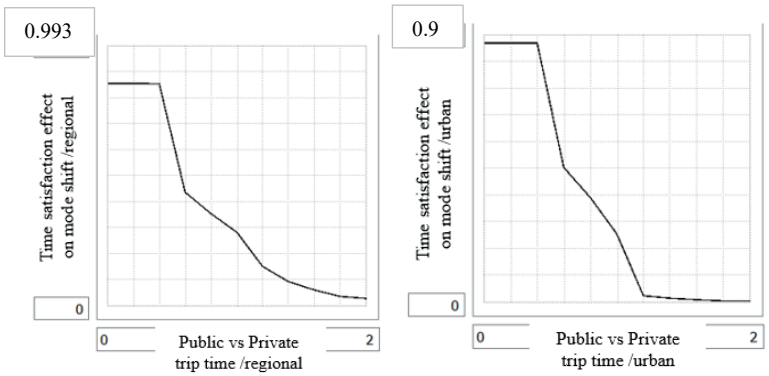
TABLE 1. TRAVEL TIME COMPARISON FOR THE URBAN AND REGIONAL AREA

	Urban area	**Regional area**
Average time spent travelling by car (door-to-door)	41.3 min	57.7 min
The average time that would be spent if the same distance was driven by public transport	78.5 min	82.6 min
Share of people who did not know the average time that would be spent if the same distance was driven by public transport	15.8 %	45.7 %
Average travel time difference (public vs private car) of respondents who could provide numerical answers about travel time	+132.2 %	+138.0 %

To include scenario analysis in the model allowing to project changes in transport mode, respondents were asked what travel time by public transport (compared to a private car) could motivate them to mode shift. The following options were offered:

- if it takes significantly less time than driving a private car;
- if it takes less time than driving a private car;
- if it takes about as much time as driving a private car;
- the journey time by public transport can be longer than by the car if I can do something useful during this time, and;
- I use the car for work which is not possible with public transport.

Based on obtained results, the key functions for the variable '1 Time effect on mode shift' (Fig. 3) were developed. In Fig. 4, the graph functions of the time satisfaction effect on mode shift are presented based on survey results. The x-axis shows the part of the population that is satisfied with the travel time, while the y-axis shows the travel time (up to 2 h). E.g. when the public vs. private travel time is equal (x-axis value is 1), the time satisfaction effect on mode shift is around 25–28 % (y-axis), i.e. around 28 % of the population is considered as willing to do the mode shift in case of regional travellers (Fig. 4(a)) and around 25 % – in case of urban travellers (Fig. 4(b)).



(a) (b)

Fig. 4. Time satisfaction effect on mode shift (a - regional, b - urban).

To understand the impact of the policies which could reduce the total public transport travel time, the following question was asked – 'Let's imagine that as a result of various improvements, the journey by public transport takes significantly less time than by private car. How many of the 10 car journeys would you be willing to replace by public transport?'. The results for this question are presented in Table 2 regarding the place of residence of respondents.

TABLE 2. NUMBER OF TRIPS REPLACED WITH PUBLIC TRANSPORT IF TRAVEL TIME BY PUBLIC TRANSPORT SIGNIFICANTLY DECREASES

Number of trips replaced with public transport	All answers	Urban residence	Regional residence
Share of respondents	100 %	86.86 %	13.14 %
Mean	4.84	4.87	4.61
Median	5.00	5.00	5.00
Std. deviation	3.00	3.03	2.84

Most people chose to replace 5 trips if the travel time by public transport decreased significantly. The total time effect on mode shift is then calculated using formula 1:

$$E_{\text{time}} = T_{\text{r time}} \cdot S_{\text{r time}} \cdot R_{\text{r time}} + T_{\text{u time}} \cdot S_{\text{u time}} \cdot R_{\text{u time}}, \quad (1)$$

where

E_{time} Time effect on mode shift;
$T_{\text{r time}}$ Share of trips for income group out of all trips in regions of total trips;
$S_{\text{r time}}$ Share of users who would switch to public transport in regions;
$R_{\text{r time}}$ Share of car trips replaced in regions;
$T_{\text{u time}}$ Share of trips in the urban area of total trips;
$S_{\text{u time}}$ Share of users who would switch to public transport in the urban area;
$R_{\text{u time}}$ Share of car trips replaced in the urban area.

3.1.2. Travel costs

The second factor influencing the mode shift from private cars to public transport presented in this paper is the cost. Cost is one of the factors that can be determined easier as it is not based on the inner feelings of the population. To determine the cost effect on the travel mode choice respondents were divided into three groups based on monthly income:

- up to 750 EUR per household member;
- 750–1500 EUR per household member, and;
- above 1500 EUR per household member.

Similarly to average travel time, respondents were asked about monthly average household expenditures on a vehicle, as well as how much should the monthly cost of using a private car increase to give up a private vehicle. Results show that the majority of the respondents (49.4 %) spend 50–150 EUR per month on a private car. The indication of the average monthly expenditure that would make respondents switch from the usage of a private car in daily commuting to public transport showed that 43.4 % will not abandon using a private car no matter the expenditures. The results showed that people who have a monthly income of up to 750 EUR per person in the household on average are setting the maximally allowed price for the car by 128.9 % and people who earn 751–1500 EUR per month on a person in the household are willing to pay by 207.8 % more. Interestingly but people who earn more than 1500 EUR per month per person in the household are willing to pay less than those who earn 751–1500 EUR per month (144.3 % increase).

To understand the mode shift potential due to the cost factor, respondents were asked about their travel mode choices in case the private car costs reach an unbearable amount. The results show that 11.4 % will continue to use a private car without changes, 45.4 % would reduce the number of car trips, and 2.6 % would drive with fellow passengers. Only 4 % would be ready to switch to public transport and 25.7 % would be ready to use it in combination with walking and cycling. The results also show that people with kids are slightly more open to walking and taking public transport and less towards travelling by bicycle. They are also more willing to combine walking, cycling and public transport. They are not willing to pay more than people without kids because fewer people chose to not change anything as well as they are less open to the idea to drive a private car with fellow passengers. Based on survey outcomes, the key functions for the variable '2 Cost effect on mode shift' (Fig. 3) were developed. In Fig. 5, the graph functions of the cost satisfaction effect on mode shift in each income group are presented based on survey results. The x-axis shows the part of the population that is satisfied with the cost of travel, while the y-axis shows the travel cost per one trip (up to 15.67 times more than the current expenses).

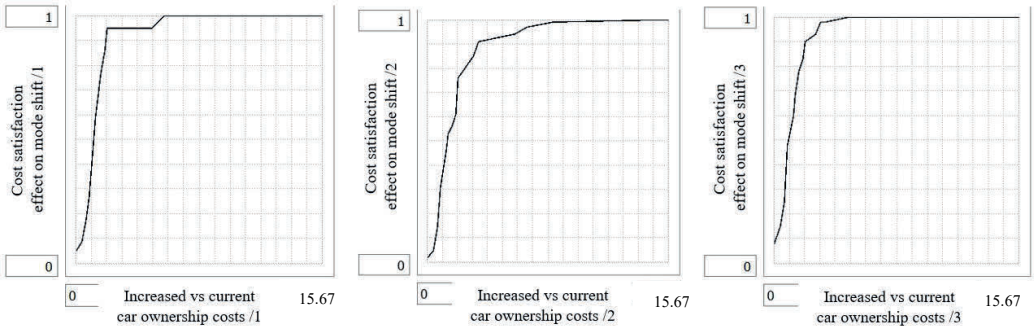


Fig. 5. The cost satisfaction effect on mode shift for different income groups: (a) income up to 750 EUR on a household member; (b) 750–1500 EUR on a household member; (c) more than 1500 EUR on a household member.

The share of people who would switch to public transport was calculated using formula (2):

$$S_{\text{cost},i} = SE_{\text{cost},i} \cdot M_{\text{cost},i}\,, \tag{2}$$

where

$S_{\text{cost},i}$ The share of people who would switch to public transport;
$SE_{\text{cost},i}$ Cost satisfaction effect on mode shift;
$M_{\text{cost},i}$ Maximal population accepting public transport alternative;
i Income group.

The total cost effect on mode shift is calculated according to formula 3:

$$E_{\text{cost}} = T_{\text{cost},i1} \cdot S_{\text{cost},i1} \cdot R_{\text{cost},i1} + T_{\text{cost},i2} \cdot S_{\text{cost},i2} \cdot R_{\text{cost},i2} + T_{\text{cost},i3} \cdot S_{\text{cost},i2} \cdot R_{\text{cost},i3}\,, \tag{3}$$

where

E_{cost} Cost effect on mode shift;
$T_{\text{cost},i}$ Share of trips for income group out of all trips of each income group;
$S_{\text{cost},i}$ Share of users who would switch to public transport of each income group;
$\text{R}_{\text{cost},i}$ Share of car trips replaced by each income group;
$i1$ Income group up to 750 EUR per household member;
$i2$ Income group 750–1500 EUR per household member;

*i*3 Income group above 1500 EUR per household member.

It was assumed that the share of the urban trips was 68 % while the share for the regional trips is 32 % according to the statistics. The share of the car trips that should be potentially replaced was taken from the survey results.

3.1.3. Mode shift model with time and cost factors

To get the total impact of travel cost and travel time effect on mode shift both previously described sub-models were put together. Representation of the developed system dynamics model in *Stella Architect* software is shown in Fig. 6.

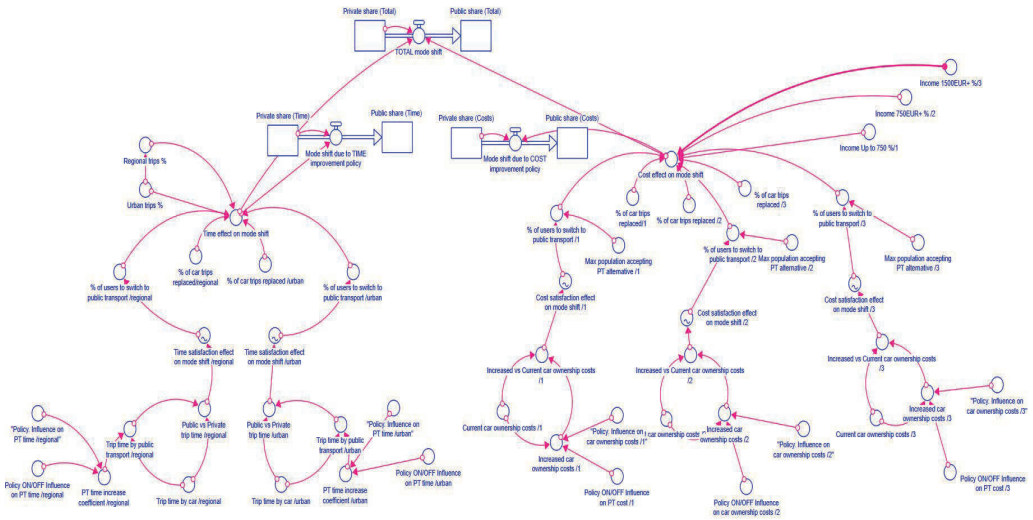


Fig. 5. Total effect on mode shift in the system dynamics modelling software Stella Architect.

The total mode shift is calculated using the formula 4:

$$\text{Total mode shift, \%} = \text{Private}_{\text{share}} \cdot E_{\text{time}} \cdot E_{\text{cost}}\,, \tag{4}$$

where

Total mode shift — Rate of share change of people who uses public transport;
$\text{Private}_{\text{share}}$ — Share of people who uses private cars;
E_{time} — Time effect on mode shift;
E_{cost} — Cost effect on mode shift.

Lastly, public transport share is calculated by using formula 5:

$$\text{Public transport}_{y} = \text{Public transport}_{(y-1)} + \text{Total mode shift}\,, \tag{5}$$

where

Public transport — Public transport users at a year y;
$\text{Public transport}_{(y-1)}$ — Public transport users in the previous year (in 2020 = 0.18);
Total mode shift — Rate of share change of people who uses public transport;
y — Year.

3.2. Sensitivity analysis

The modelling results are presented in three previously described modes: (i) travel time effect on mode shift, (ii) travel cost effect on mode shift and (iii) combination of travel time effect and travel cost effect.

3.2.1. Baseline scenario

The baseline scenario describes the situation when no additional policies are being added to the current situation. In the baseline scenario, it is assumed that the share of people who are using the private car in 2020 is 82 % while the share of people who are using public transport equals 18 %. The results about travel cost impact show that if the only concern which is stopping people from public transport use would be travel costs, an increase in the public transport sector by 57.3 % reaching 75.3 % share of public transport users would happen by 2030. This is due to the lower costs that public transport is offering in comparison with the increased car costs. This trend shows, that if the only important factor was car costs more people would switch to public transport. Results show that if the only parameter that would be taken in the count was travel time (which is different in urban and rural areas accordingly to the survey data), 24.1 % of people (an increase of 6.1 %) would use public transport. This shows that if the only factor influencing transport mode choice was travel cost then the public transport share would be much higher in comparison with the situation when only travel time is important. This highlights that when talking about human behaviour it is important to consider different parameters influencing it at once. After the multiplication of both previously mentioned factors, the switch to public transport use increases only by 0.6 % reaching 18.6 % public transport mode share. This shows the importance of considering as many influencing parameters as possible to get more precise results, as the total impact can drastically change after adding new multiplicators.

3.2.2. Policy testing

To see what the changes would be if the travel time and travel cost decreased, policy testing has been presented.

Several scenarios were developed, to see each aspect's influence if it was the only important aspect for travel mode choice and to see each aspect's influence on public transport share if it is combined with the second aspect. Three scenarios are presented:

- Travel time matters scenario (travel time is the only important aspect);
- Travel costs matter scenario (travel cost is the only important aspect);
- Both matter scenario (the combination of travel time and travel cost impact).

The impact of the travel time changes was assessed. The impact of the place of residence was taken into account, as road conditions inside and outside the cities are different and would require different policy instruments to reduce public transport time. Results show that if the 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 of 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, as it was described previously, despite travel time there are many other aspects influencing transport mode choice. In this scenario, the same tendency is visible however the values of the mode shift are much smaller. Results show that if the travel time is considered together with travel costs then getting travel time for public transport to be the same as private transport travel time would lead to an increase of public transport share for up to only 27.1 %

while 40.1 % of public transport share could be achieved by decreasing public transport's travel time by half in comparison to private cars.

Similarly, an assessment of the travel costs is presented. In this scenario, a great mode shift is achieved by increasing travel expenditures for private cars. Thus 81.5 % share of public transport could be reached just by increasing average monthly car costs by 50 EUR, while 90.0 % public transport share mark is passed when costs increase by 150 EUR. In the 'Both matter scenario' the maximal share of public transport that could be achieved is smaller by 74.6 % and reaches only 19.2 % if the monthly car costs increase by 500 EUR. 18.7 % share of public transport is achieved when an additional 50 EUR are added to the average monthly car costs while 19.0 % are achieved by increasing costs by 150 EUR. For a better understanding of travel time and travel cost impact on the total mode shift 'Both matter' scenario was divided into smaller parts. The combinations considered are shown in Fig.6.

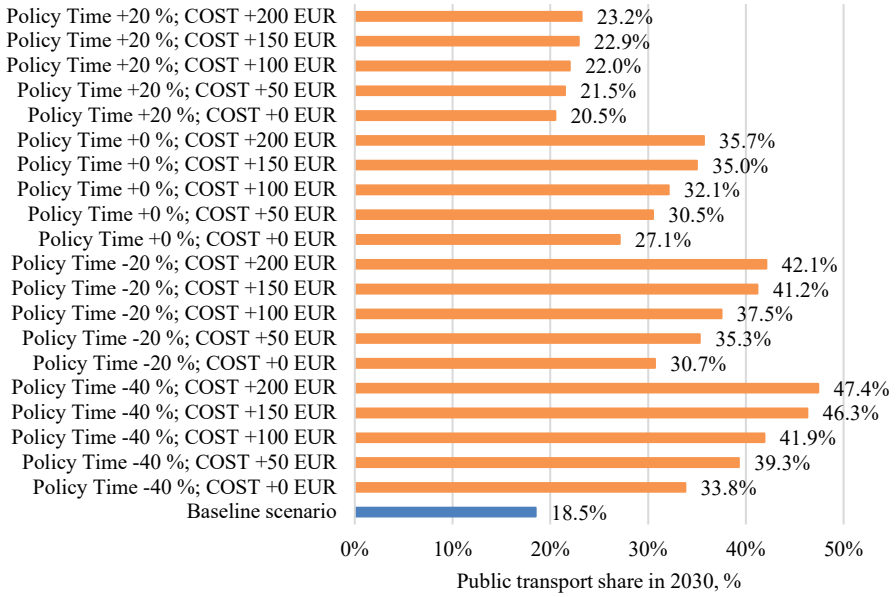


Fig. 6. The total effect on public transport share in 2030 (Both matters scenario).

The results show what rates of improvement give the biggest impact on public transport share increase. The best results were achieved by combining the biggest values of both policies (40 % travel time reduction and increase in travel costs by 200 EUR per month). This shows that for better results improvements have to be made in several sectors.

Results also show that there are several ways how to get similar public transport share:

- 'Time-40 %: COST+100 EUR' (41.9 %) and 'Time-20 %, COST+200 EUR' (42.1 %);
- 'Time-20 %: COST+50 EUR' (35.3 %) and 'Time+0 %, COST+150 EUR' (+35.0 %);
- 'Time+0 %: COST+50 EUR' (30.5 %) and 'Time-20 %, COST+0 EUR' (30.7 %).

This indicates the need for further cost and benefit assessment that has to be applied to determine which measures would be the most efficient and most cost-effective.

The travel time required for public transport can be reduced by redesigning existing public transport networks, introducing more bus lanes, as well as expanding micro-mobility opportunities, thus solving the first-mile and last-mile problems. It is also possible to use

other policies that would extend the journey time by private transport. Measures to make private transport more expensive could be tax increases, the proceeds of which could be used to purchase more environmentally friendly public transport, build infrastructure and improve the urban environment. An assessment of the impact of policy instruments needs to be established.

4. CONCLUSIONS

This paper aims to evaluate the impact of various factors on human behavioural intentions, identify the inconvenience cost of public transport, and identify the necessary improvements to shift the demand for population mobility to public transport.

To explore the attitude of private car users towards public transport in Latvia, a preference survey was carried out which included 350 respondents. The survey's results were in line with previous studies and showed that such aspects as travel time, travel comfort, ease of use, availability and the possibility to carry other passengers and luggage were rated higher as the most important aspects of transport mode choice than travel costs. Within the framework of the study, 2 out of 5 factors influencing transport mode choice, which were defined by the survey as important for transport users, were considered for the further integration of the survey results into the system dynamic model. The integration of other factors into the system dynamics model will be continued within the framework of the 4muLATe project until the end of 2021. Independent sub-models have been developed for the considered behavioural factors.

Results of the modelling showed that when considering only one factor (travel time or travel costs) a great achievement can be reached in terms of public share increase, however as soon as these factors are multiplied their impact on the switch to public transport drastically decreases. This shows the importance of considering several decision-influencing factors at once. Policy analysis indicated that the same results in terms of public transport share increase can be achieved by the combination of different policies, which indicates the need for further cost and benefit assessment that has to be applied to determine which measures would be the most efficient and most cost-effective. An assessment of the impact of policy instruments needs to be established to determine how to get such travel time reduction or private car cost increase most cost-effectively. It is recommended to use Statgraph or similar software to present an even more detailed analysis of the variables such as household size, number of kids, education level, etc. For more precise results more answers for the same survey are needed. At present, the analysis does not take into account possible changes over time, how the importance of the defined factors could change (for example, as wealth increases, the importance of costs decreases even more, but something else increases). Thanks to the open structure of the developed model, these shortcomings can be improved in the future, as well as it this methodology could be used for further planning of the development of the transport sector not only in Latvia but in other countries too if used parameters are adjusted to the local context.

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sustainability

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Review

Hydrogen Horizons: A Bibliometric Review of Trends in Diverse Emission Sectors

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Abstract: Recognizing the future and present challenges facing humanity, the United Nations has developed 17 Sustainable Development Goals. To achieve these goals, it is necessary to understand energy sources and the origin of their raw materials. Therefore, the role of hydrogen in the future energy balance is being discussed more and more frequently. The aim of this study is to use bibliometric analysis to determine the effectiveness of hydrogen use in different sectors to achieve sustainable development goals. This work identifies the most cited articles, as well as the most productive journals, countries, and institutions. This work provides insight into the current state of hydrogen sustainability research in six different areas. The reviewed sectors include energy, industry, transport, agriculture, commercial, and residential. The results show that the energy sector shows the greatest interest in sustainable development, followed by industry and transport.

Keywords: hydrogen; bibliometric analysis; SDG; sustainable development goals

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1. Introduction

The problem of global warming was first raised in the 1980s, when it was determined that carbon dioxide increases in the Earth's atmosphere, which, in turn, contributes to climate change [1]. At present, the negative impact of human activity is becoming more and more visible, prompting us to both change our habits and look for better solutions in the usual systems. The improvement in people's quality of life, together with the overall population growth, also contributes to the greater consumption of resources, including in the energy sector [2]. Future research on energy system planning will increasingly assess the possible contribution of hydrogen to decarbonization goals.

Global energy consumption has grown exponentially in recent decades, from 8,588.9 million tons (Mtoe) in 1995 to 13,147.3 Mtoe in 2015 [3]. The total world demand for primary energy is expected to be 17,487 Mtoe in 2040 [4] compared with the global primary energy consumption in 2021 of 595.15 EJ or 14,214.9 Mtoe [5].

Green hydrogen and sustainable biomass are significant decarbonization options for businesses looking to reduce carbon emissions while contributing to energy security. Concerns over energy security, particularly in Europe, are putting pressure on policymakers to speed up the deployment of alternative energy sources, with renewables, energy efficiency, and hydrogen at the top of the list [6].

According to the findings, the possible range of global hydrogen consumption is increasing, with estimates ranging from 73 to 158 Mt in 2030, 300 Mt in 2040, and 568 Mt in 2050, depending on the scenario provided [7].

The United Nations 2030 Agenda for Sustainable Development, approved by all UN member states in 2015, presents a shared blueprint for peace and prosperity for people and the planet, both today and in the future. The 17 sustainable development goals (SDGs), which are further broken into 169 specific targets that can be used to accomplish the various SDGs, are depicted in Figure 1. Clean energy is one of the key drivers of the SDGs. As

an energy vector and one of the cleanest energy carriers, hydrogen may also be directly related to the different SDGs [8].



Figure 1. Sustainable development goals of the United Nations.

The goal of this research is to apply bibliometric analysis to establish how well sustainable development goals can be reached through the use of hydrogen and how sustainability is discussed in different sectors.

1.1. Previous Research

The search for the title ("hydrogen OR h2" AND SDG OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") resulted in 5180 publications in the time period from 1975 to 2023 (August 15th) in the SCOPUS database, while adding keywords (Bibliometr* OR "Bibliometric Analysis" OR "Bibliometric map" OR "Research Trends" AND sector*) to the SCOPUS database to find similar studies resulted in eight publications. The selection process involved choosing results that were written in the English language, with a focus on articles and review papers. Table 1 presents a comprehensive overview of the articles that were identified.

Three out of the eight discussed research topics mostly related to the mobility sector. Md. Sazal Miah et al. conducted a bibliometric analysis and investigation of optimized energy management schemes (EMSs) for electric vehicle (EV) applications [9]. The researchers emphasized the various challenges and issues associated with EMSs in EVs. These challenges include power distribution concerns, thermal management problems related to batteries, battery storage life cycle and aging issues, policy and regulation challenges, power electronics controller and converter issues, such as switching loss, high ripple current, voltage stress, high voltage gain, high impedance, optimization integration, and complex control techniques. The discourse brought attention to the annual shortfall in achieving the SDGs in the transportation industry, as well as the related apprehensions regarding the environmental consequences and human welfare. Another study regarding hydrogen mobility was presented by Davide Calandra et al. [11]. The authors presented a comprehensive scientific roadmap outlining key concerns for managers and policymakers aiming to expand the utilization of hydrogen in the transportation sector. Their roadmap was constructed based on an analysis of 233 papers sourced from the SCOPUS database, all of which were focused on the subject matter at hand. The primary issues identified were those pertaining to expenses, specifically high costs, insufficient investments, and

the absence of well-defined business models. The authors of the study underscored the importance of fostering strategic alliances to facilitate collaborative efforts beyond the realm of public transportation. Additionally, the authors advocated for the dissemination of public education initiatives aiming to enhance awareness and acceptance of hydrogen technology among the general populace.

Table 1. A summary of the prior review articles.

Title	Year	Sectors Discussed	SDGs Mapped by SCOPUS	Source
Optimized energy management schemes for electric vehicle applications: A bibliometric analysis towards future trends	2021	Mainly transport, power sector	7, 9, 13, 17	[9]
Selected aspects of sustainable mobility reveals implementable approaches and conceivable actions	2021	Mainly transport, power sector	7, 8, 11, 13	[10]
Management of hydrogen mobility challenges: A systematic literature review	2023	Mainly transport, power sector, commerce sector	9, 11, 17	[11]
Global research trends on anaerobic digestion and biogas production from cassava wastewater: A bibliometric analysis	2022	Mainly industry, agriculture	6, 7, 8, 9, 17	[12]
Applications of P-graph to carbon management: A mini-review	2022	Industry, power sector, agriculture	7, 9, 13, 17	[13]
Analysis of the scientific production on the green hydrogen theme published in scientific journals indexed by EBSCO	2023	Power sector, industry, transport	7, 8, 9, 17	[14]
Use of patents as a tool to map the technological development involving the hydrogen economy	2019	Transport, industry	7, 13	[15]
A systematic review on green hydrogen for off-grid communities—technologies, advantages, and limitations	2023	Power sector, industry	7, 17	[16]

Suprava Chakraborty et al. examined studies about sustainable mobility in the last two decades [10]. Their article explores the role of sustainable mobility in relation to the attainment of the SDGs. One of the main concerns raised in this context is the diversity of interests and expectations among various stakeholders. The authors believe that all parties must have a shared understanding of the larger goal of creating a transportation system that is intended for the future. Additionally, they recognize the necessity of achieving this goal. Furthermore, this bibliometric study elucidates the need to advocate for transportation services that are efficient, safe, and convenient. They also highlight the importance of reducing car traffic in metropolitan areas and encouraging a low transportation demand. According to the authors, the limited supply of resources for battery production has caused people to think about hydrogen as a possible fuel for environmentally friendly transportation.

Amanda L.M. dos Santos et al. conducted a review analysis aiming to investigate global scientific research trends in the anaerobic treatment of wastewater resulting from cassava processing, one of the world's most consumed vegetable roots [12]. Although the study did not explicitly address SDGs, it did show an increasing interest in this process, including the recovery of by-products such as hydrogen. However, their results noted that cassava's circular economy production chain is still limited to large-scale companies, and that further research into this subject, including economic–financial, and environmental viability analyses, is required.

Migo-Sumagang M.V. et al. used the P-graph framework and presented a bibliometric analysis of decarbonization and carbon management networks including biohydrogen and

carbon capture and storage technologies in their research [13]. The growing interest in biohydrogen was observed in the work.

Henrique César Melo Ribeiro and Rosany Corrêa, in their review, discussed green hydrogen production and how this topic was described in scientific journals indexed by EBSCO. This study presents and verifies that green hydrogen offers opportunities for economic growth and job creation [14]. Juan P. Viteri's research concerned the potential of hydrogen to serve as an affordable, dependable, and sustainable form of energy for the world's poorest and presented an extensive bibliometric analysis of green hydrogen to address SDG 7: affordable and green energy [16].

Tiago Sinigaglia et al. conducted a patent-based review study to ascertain the technological evolution of the hydrogen economy. The majority of patents were found to be related to the mobility sector, specifically vehicle and fuel cell technologies. Fuel station-related patents were followed by hydrogen production- and storage-related patents. The number of patent licenses has decreased since 2012; this might be due to a loss of interest among scientists. Based on research, Toyota and Honda are clearly leading in the car industry [15].

1.2. Research Outline

Examining the issue of hydrogen sustainability in different sectors, we rigorously adhere to the organized literature review process. First, we state our research question in Section 1. Then, in Section 2, we outline the literature review protocol and present the research sample. Finally, we pair critical analysis and the identification of future research directions in Sections 3–5.

2. Materials and Methods

Nees Jan Van Eck and Ludo Waltman, two scientometric experts at Leiden University in the Netherlands, developed a scientometric and knowledge graph analysis tool called VOSviewer [17,18], which was used in this study to assess publications in the field of hydrogen sustainability in different sectors. In recent years, VOSviewer has been widely recognized and used in the fields of scientometrics and knowledge graphs because of its extremely simple, user-friendly interface design and trustworthy results.

VOSviewer provides a mapping method that is similar to the multidimensional scaling method, with a more explicit representation of the results. The objective function of VOSviewer is expressed in mathematical notation by Equation (1) [19].

$$V(x_1 \ldots x_n) = \sum s_{ij} \left\| x_i - x_j \right\|^2 \quad (1)$$

where x_i denotes the position of node i and $\left\| x_i - x_j \right\|$ denotes the Euclidean distance between nodes i and j in a two-dimensional space, and s_{ij} represents the similarity between two nodes, i and j, which is multiplied by dividing the number of times that nodes i and j appear at the same time by the number of times that nodes i and j appear. The constraint of Equation (2) is

$$\frac{2}{n \times (n-1)} \sum_{i<j} \left\| x_i - x_j \right\| = 1 \quad (2)$$

where n represents the total number of nodes in the network. VOSviewer specifically provides a method for visualizing knowledge graph density graphs, which is the most distinctive feature compared with other knowledge graphs. The density map $D(x)$ for node $x = (x_1, x_2)$ is calculated as follows:

$$D(x) = \sum_{i=1}^{n} w_i K \frac{\left\| x_i - x_j \right\|}{\bar{d}h} \quad (3)$$

$$\bar{d} = \frac{2}{n \times (n-1)} \sum_{i<j} \left\| x_i - x_j \right\| \quad (4)$$

where $K : [0, \infty) \rightarrow [0, \infty)$ denotes the kernel function, which is nonincreasing and is represented using the Gaussian function $K(t) = \exp(-t^2)$, h denotes kernel width, and $\overline{d}$ denotes the point density, that is, the average distance between two nodes [18,20].

A good literature review is the basis for knowledge development, so extensive survey research was carried out to provide the content. A thorough approach was used to analyze and gather the most trusted and relevant papers for the study. This study examined hydrogen sustainability in six key sectors: energy, transportation, industry, agriculture, residential, and commercial, as shown in Figure 2.

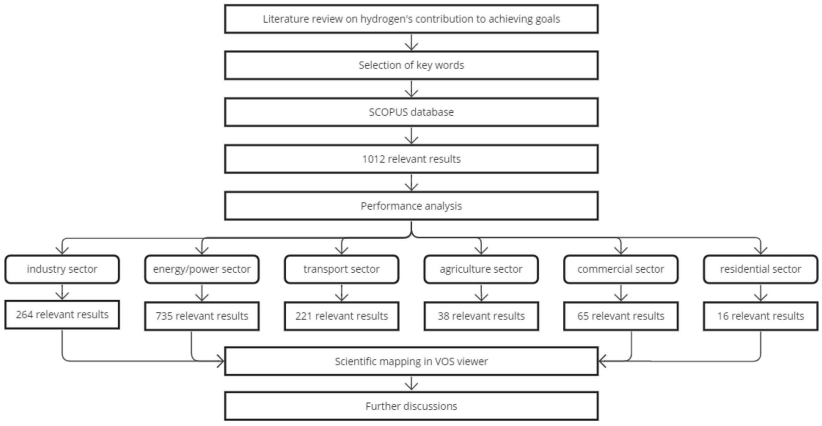


Figure 2. Flowchart for systematic research methodology.

Performance analysis included an analysis of the number of publications, the number of citations, types and research areas, and highly cited publication analysis. Scientific mapping analysis included citation, co-authorship, burst detection, co-occurrence, and timeline analysis. The discussion section includes an analysis of popular issues, trends, and challenges.

The SCOPUS database was used on 15 August 2023, to investigate how sustainable development goals can be achieved through the use of hydrogen energy in various sectors. The SCOPUS database was chosen as the data source because it provides access to a huge number of indexed articles and is a powerful database with extensive sorting, ranking, and refinement options [21]. To understand how different sectors are researching the impact of hydrogen on the SDGs, we looked at the energy/power, industrial, transport, agriculture, commercial, and residential sectors (Section 3.4). The following request was used to obtain common insights: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems" AND TITLE-ABS-KEY (sector AND industry) OR TITLE-ABS-KEY (sector AND power OR energy) OR TITLE-ABS-KEY (sector AND transport) OR TITLE-ABS-KEY (sector AND agriculture) OR TITLE-ABS-KEY (sector AND commercial) OR TITLE-ABS-KEY (sector AND residential)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re) OR LIMIT-TO (DOCTYPE, cp)) AND (LIMIT-TO (LANGUAGE, English)).

Consistent with the literature [22,23], the search string adopted Boolean operators in addition to pertinent terms such as "Bibliometr*", which includes the words "bibliometric" and "bibliometry".

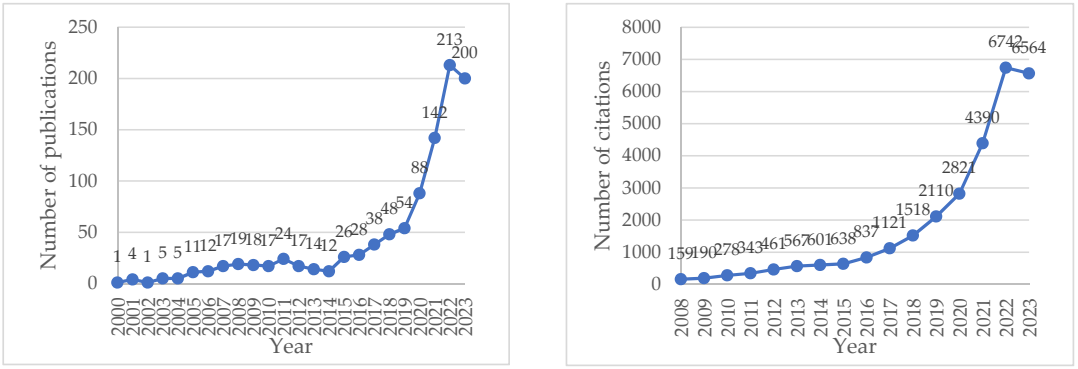
3. Results

3.1. Performance Analysis

This section analyzes the performance of publications in terms of annual indicators, publication types, research fields, and highly cited articles.

3.1.1. Annual Indicators of Publications

Figure 3a,b display the annual publication and citation of hydrogen sustainability research, respectively. As shown in Figure 3a, the first related publication, entitled "Prospects for sustainable energy in Atlantic Canada", was published in 1991. In addition to this publication, three more publications were published in the 20th century, two of them in 1997 and one in 1999. The number of publications is generally on the rise but fluctuates slightly. Before 2010, there were less than 20 research papers per year on the sustainable development of hydrogen energy in different sectors. Since then, this field of research has gained considerable importance. The number of publications increased more than 12 times from 2011 to 2022, and over the past five years it has grown from 54 publications in 2019 to 213 publications in 2022. The number of publications in the middle of 2023 almost reached the total number of publications in 2022, an indicator of growing interest.



(**a**) (**b**)

Figure 3. Annual publication and citation rates: (**a**) the average number of publications; (**b**) the average number of citations.

Similarly, a growing trend is visible in Figure 3b regarding the number of citations in the last 15 years. The first citation of research on this study topic appeared in 1997. Figure 3b shows that, since 2008, citation numbers grew relatively slowly before 2016. In the time between 2016 and 2019, growth was moderate but, since 2019, the number of citations rapidly increased, from 2110 in 2019 to 6742 in 2022. It is evident that the hydrogen sustainability topic has received increasing scholarly attention in recent years.

3.1.2. Types and Research Areas of Publications

In the SCOPUS database, all publications can be classified according to their different types. It should be noted that some documents are of two or more types.

Most (605 or 59.4%) of the obtained publications were articles, followed by review articles (214 or 21.0%) and proceedings papers (199 or 19.5%). Each publication covers at least one subject area. Figure 4 presents the top 10 research areas.

As can be seen from Figure 4, the most popular fields of study are energy (28.2%), engineering (16.8%), and environmental science (13.5%), followed by fields such as social sciences, physics and astronomy, chemistry, computer science, mathematics, business administration, management, and accounting.

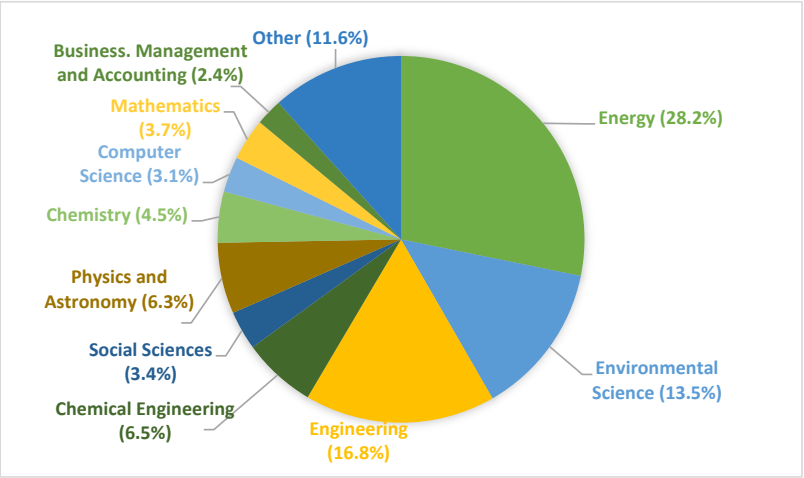


Figure 4. Distribution of publications by the most popular research areas.

3.1.3. Highly Cited Publications

A publication's citation count is a key metric for assessing its impact because it shows that the publication is well-known and relevant. Table 2 shows the 10 most cited works in descending order of citation count. The "SDG" column shows which sustainable development goals are covered in the most cited publications according to the Elsevier SDG data mapping. This mapping was built by Elsevier data science teams and uses extensive keyword queries, supplemented by machine learning, which, in turn, provides document mapping to SDGs with very high precision. It is available on the SCOPUS website under the description of each article in the "Sustainable Development Goals 2023" section.

Table 2. The 10 most cited works in descending order of citation count.

Author/Authors	Title, Year	Cited by	SDG	Source
Alonso, David Martin; Bond, Jesse Q.; Dumesic, James A.	Catalytic conversion of biomass to biofuels, 2010	1912	7	[24]
Hosseini, Seyed Ehsan Hosseini S.E.; Wahid, Mazlan Abdul	Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development, 2016	1296	7, 13	[25]
Preuster, Patrick; Papp, Christian; Wasserscheid, Peter	Liquid organic hydrogen carriers (LOHCs): Toward a hydrogen-free hydrogen economy, 2017	531	7, 8, 13	[26]
Serrano, Elena; Rus, Guillermo; García-Martínez, Javier	Nanotechnology for sustainable energy, 2009	444	7	[27]
Singh, Sonal; Jain, Shikha; Ps, Venkateswaran; Tiwari, Avanish K.; Nouni, Mansa R.; Pandey, Jitendra K.; Goel, Sanket	Hydrogen: A sustainable fuel for future of the transport sector, 2015	407	7, 9, 12, 13	[28]
Tabbi Wilberforce; A. Alaswad; A. Palumbo; M. Dassisti; A.G. Olabi	Advances in stationary and portable fuel cell applications, 2016	391	7, 8, 9, 13	[29]
Mari Voldsund; Kristin Jordal; Rahul Anantharaman	Hydrogen production with CO_2 capture, 2016	313	7, 13	[30]
Puga A.V.	Photocatalytic production of hydrogen from bio-mass-derived feedstocks, 2016	308	7, 9, 11, 13	[31]
Kovač, Ankica; Paranos, Matej; Marciuš, Doria	Hydrogen in energy transition: A review, 2021	285	7, 9, 13, 17	[32]
Nicoletti, Giovanni; Arcuri, Natale; Nicoletti, Gerardo; Bruno, Roberto	A technical and environmental comparison between hydrogen and some fossil fuels, 2015	285	7	[33]

The most cited study, by David Martin A. et al., covers catalytic methods for the production of biofuels from aqueous carbohydrates separated by biomass pretreatment and hydrolysis. This study discusses the importance of hydrogen in biorefining and explores numerous methods for effectively controlling its usage to promote a shift from the dependency on fossil fuels [24]. The study authored by Seyed Ehsan Hosseini et al. provides a comprehensive examination of contemporary hydrogen manufacturing methodologies that use renewable and sustainable energy sources. The researchers concluded that the primary obstacles hindering the broad commercialization of solar-based hydrogen generation are the poor efficiency of the solar-to-hydrogen system and the high cost of photovoltaic cells. They concluded that since electricity costs affect hydrogen pricing, solar and wind energy should be four times cheaper than commercial power prices for the manufacture of carbon-free hydrogen at a competitive price with fossil fuels [25].

The study of P. Preuste et al. discusses the importance of hydrogen in the field of biorefining and investigates numerous techniques for efficiently controlling its use, fostering a shift from the dependency on fossil fuels. They found that technological readiness varies according to field. For stationary energy storage systems, liquid organic hydrogen carrier (LOHC) technology has been demonstrated to be feasible in commercial demonstrations, and cost will determine its commercial viability. Other interesting solutions, such as supplying hydrogen to hydrogen filling stations or direct-LOHC-fuel cell applications, require extensive basic and applied research [26]. Serrano E. et al. presented a review of the most recent advances in nanotechnology for sustainable energy production, storage, and use, concluding that solar, hydrogen, and new-generation batteries and supercapacitors are the most significant examples of nanotechnology's contributions to the energy sector [27]. According to Singh S. et al., practically any energy source may be used to make hydrogen, and hydrogen can be used as fuel for almost any application that uses fossil fuel. Their paper studies current breakthroughs in the fields of hydrogen generation, storage, transport, and delivery, as well as the environmental and safety concerns associated with its usage as an energy carrier. Onboard hydrogen storage was identified as one of the major technological challenges related to the use of hydrogen as a vehicle fuel and political–economic strategies and money allocation were mentioned in the article as the most necessary tools to promote hydrogen energy use in daily life [28]. Wilberforce T. et al. also presented an overview, focusing on the use of hydrogen in fuel cell technologies, and emphasizing the advantages and disadvantages of these technologies [29]. M. Voldusnd et al. presented an overview of technologies for hydrogen production from fossil fuels with CO_2 capture technologies, concluding that, at the stage of transition technology, hydrogen production with CO_2 capture could be a promising solution [30]. Kovač A. et al. also addressed the energy transition problem, concluding that hydrogen plays an important role in this process. In their work, they point to positive examples in other countries and highlight the barriers that stand in the way of the development of hydrogen technologies [32]. Puga A.V.'s article views photocatalytic hydrogen production as a sustainable, viable, and efficient process, with particular emphasis on the role of biorefinery products, agricultural residues, and industrial or municipal waste in hydrogen production [31]. Giovanni N. et al., in their 2014 article, compared the technical and environmental indicators of hydrogen with those of fossil fuels and concluded that renewable hydrogen, as a low-emission fuel, has a low environmental impact, which would positively affect the global environment in the long term. Technical deficiencies and barriers were identified [33].

Figure 5 shows a summary of the SDGs mapped in the top ten most cited publications. The results show that all the most cited publications discuss solutions that could achieve Goal 7 (affordable and clean energy). Behind this SDG is Goal 13 (climate protection) and Goal 9 (industry, innovation, and infrastructure). Other SDGs mentioned included Goal 8 (decent work and economic growth), Goal 11 (sustainable cities and communities), Goal 12 (responsible consumption and production), and Goal 17 (partnering for the goals).

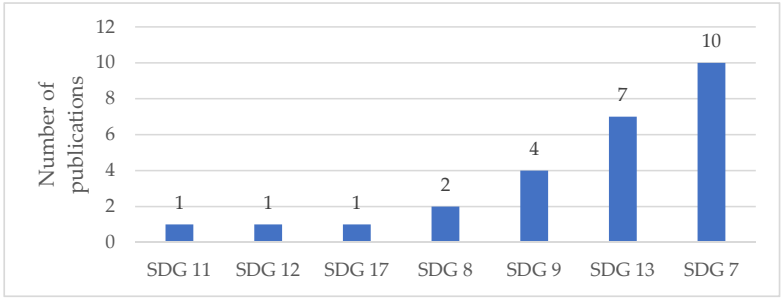


Figure 5. SDGs mapped in the top 10 most cited publications.

In Table 3, the 10 journals are ranked according to number of publications. As can be seen, the most productive journal is the International Journal of Hydrogen Energy, with 91 relevant publications, followed by Energies and Renewable and Sustainable Energy Reviews. The journal with the most citations (945) and the highest number of average citations per publication (67.5) is Renewable and Sustainable Energy Reviews, with four publications.

Table 3. Top 12 most-productive journals that study the application of hydrogen to achieve the SDGs in particular emission sectors.

Rank	Source	NP	NC	ANC
1	International Journal of Hydrogen Energy	91	4692	51.56
2	Energies	55	970	17.67
3	Renewable And Sustainable Energy Reviews	33	4165	123.19
4	Journal Of Cleaner Production	31	1563	50.42
5	Sustainability (Switzerland)	27	332	12.30
6	Energy Conversion and Management	26	1132	43.54
7	Applied Energy	21	683	32.52
8	Fuel	13	458	35.23
9	Energy	12	97	8.08
10	SAE Technical papers	12	27	2.25
11	Science Of the Total Environment	11	559	5.81
12	Energy Policy	10	391	39.10

NP: the number of publications; NC: the number of citations; ANC: the average number of citations per publication.

3.2. Analysis of the Countries/Regions, Institutions, and Authors

This section evaluates publications from three perspectives: author, institution, and country. First, a citation analysis identifies the most important institutions, countries, and authors. The analysis also considers the most productive countries, the most productive institutions, and a collaborative analysis by the authors.

Citation Analysis

Table 4 lists the top 10 most cited countries/regions, institutions, and authors of publications and is sorted in ascending order by the number of citations.

Table 4 demonstrates that the United States, India, and Germany are the countries that show the highest levels of interest in this subject, because each of these countries produced more than 100 publications. On the other hand, comparing the citation data, it can be seen that the most influential countries with the highest citation rates are the U.S., Italy, India, and the United Kingdom. Figure 6 displays co-authorship among the 29 nations where at least 15 articles were produced.

Table 4. The top 10 most cited countries/regions/institutions/authors of publications by the number of publications.

Rank	Country/Region	NP	NC	Institution	NP	Author	NP
1	U.S.	137	5975	Yildiz Technical University	5	Dincer, I.	12
2	India	131	3281	Purdue University	4	Agrawal, R.	8
3	Germany	108	2711	Technologico de Monterrey	4	Delgass, W.N.	6
4	UK	99	3208	University of Cassino and Southern Lazio	4	Ribeiro, F.H.	6
5	Italy	92	3316	Centre for Process System Engineering	4	Bartolucci, L.	5
6	China	69	2148	National Renewable Energy Laboratory	3	Breyer, C.	5
7	Spain	64	2382	Clean Energy Research Laboratory, Ontario	3	Cordiner, S.	5
8	Canada	57	1829	Aston University	3	Iqbal, H.M.N.	5
9	Australia	37	1609	University of Naples Parthenope	3	Mulone, V.	5
10	Netherlands	36	1598	University of Rome Tor Vergata	3	Singh, N.R.	5
						Stolten, D.	5

NP: the number of publications; NC: the number of citations.

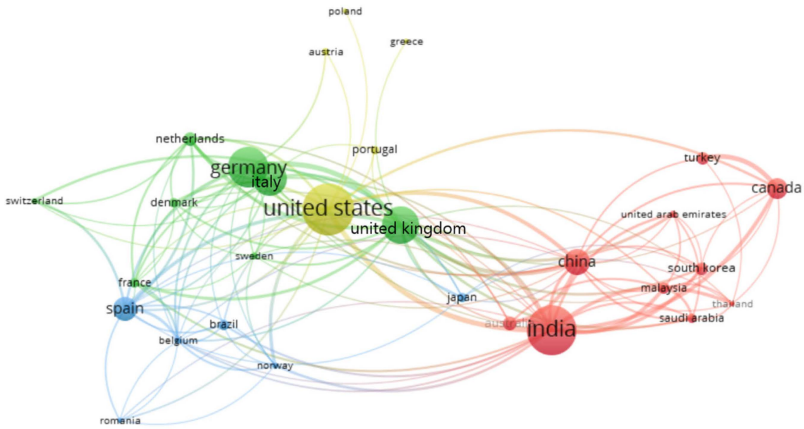


Figure 6. Co-authorship among the 29 nations where at least 15 articles were produced.

As shown in Table 4, Yildiz Technical University contributed the most research on this topic, with five retrieved articles. Research on this topic is arguably institutionally fragmented, as the institutions with the most publications account for only a small fraction of all publications. The most influential authors are Dincer, I., who contributed twelve articles, followed by Agrawal, R. (eight articles), Delgass, W.N. (six articles), and Ribeiro, F.H. (six articles).

3.3. Keyword Analysis

Keyword analysis helps identify key themes and topics, trends, and patterns, as well as knowledge gaps. To locate research hotspots, boundaries, and trends, this part conducts co-occurrence analysis, the burst detection analysis of keywords, and timeline visualization. This process uses the VOSviewer visualization tool.

3.3.1. Co-Occurrence Analysis

The examination of terms' co-occurrences makes it easier to comprehend the research hotspots in each topic. Using VOSviewer, this section analyzes the co-occurrence of keywords in publications. A keyword must appear at least 23 times before it is considered present (out of 8589 keywords, 111 did so). Figure 7 displays the network of keywords' co-occurrences. Two connected nodes indicate that two keywords appear in the same publication. Nodes are used to represent keywords. The more frequently the keyword

appears, the larger the node. The number of keyword co-occurrences increases with link width.

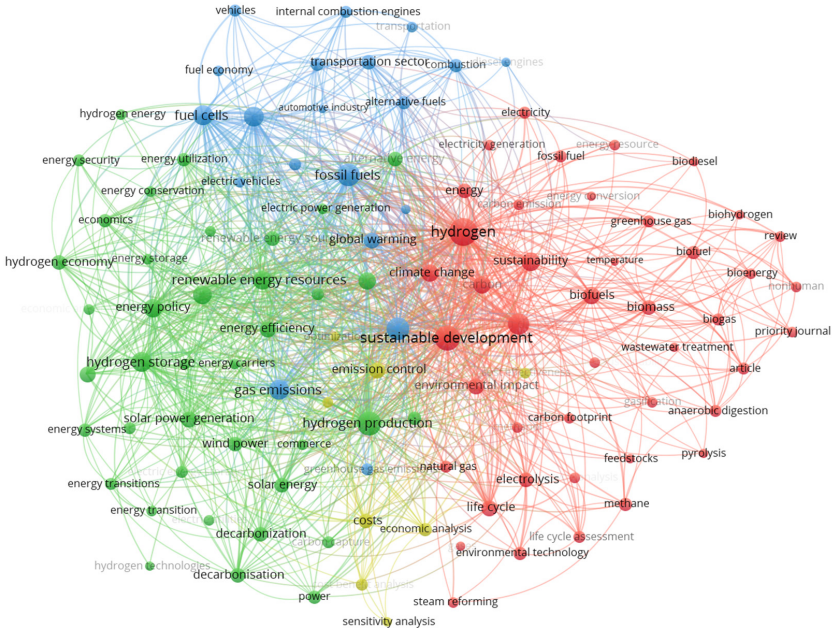


Figure 7. The network of keywords that appeared at least 23 times.

Information about each cluster and its top five keywords, ranked by the total link strength, is shown in Table 5.

Table 5. Cluster information summary list.

Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
1 (red)	44	2017.4	Hydrogen
		2017.9	Sustainable development
		2018.5	Carbon dioxide
		2019.0	Sustainability
		2018.8	Climate change
2 (green)	39	2019.9	Hydrogen production
		2020.0	Hydrogen storage
		2018.5	Renewable energy resources
		2018.9	Energy policy
		2020.0	Renewable energies
3 (blue)	20	2019.5	Greenhouse gases
		2019.3	Fossil fuels
		2017.1	Fuel cells
		2018.9	Gas emissions
		2018.0	Hydrogen fuels
4 (yellow)	8	2019.9	Emission control
		2018.3	Costs
		2018.8	Economic analysis
		2020.6	Cost benefit analysis
		2018.8	Decision making

Cluster analysis shows that the keywords can be divided into four clusters. The first (red) includes terms that describe various raw materials and fuels (e.g., biomass, bioenergy, fossil fuel, biogas, biodiesel), hydrogen production technologies (e.g., gasification, electrolysis, steam reforming), and keywords characterizing the climate (e.g., climate change, greenhouse gas, carbon dioxide). The second (green) cluster describes keywords related to the use of hydrogen (e.g., hydrogen technologies, hydrogen storage, commerce), policy-related keywords (e.g., energy policy, energy security, decarbonization, hydrogen economy, economic and social effects, investments). The third (blue) cluster largely affects mobility (transportation sector, fuel economy, fuel cells, combustion engines, etc.). The fourth (yellow) cluster includes keywords related to analysis (cost–benefit analysis, economic analysis, decision-making).

3.3.2. Timeline Visualization

Topics and keywords evolve over time, and research in related fields is constantly changing. Timeline visualizations show the development of research topics and published results over time. The co-occurrence overlay of keywords is shown in Figure 8. This shows the temporal distribution of keywords in different clusters, where the average publication year of a keyword determines its color shade. The darker the color, the earlier the average year of publication.

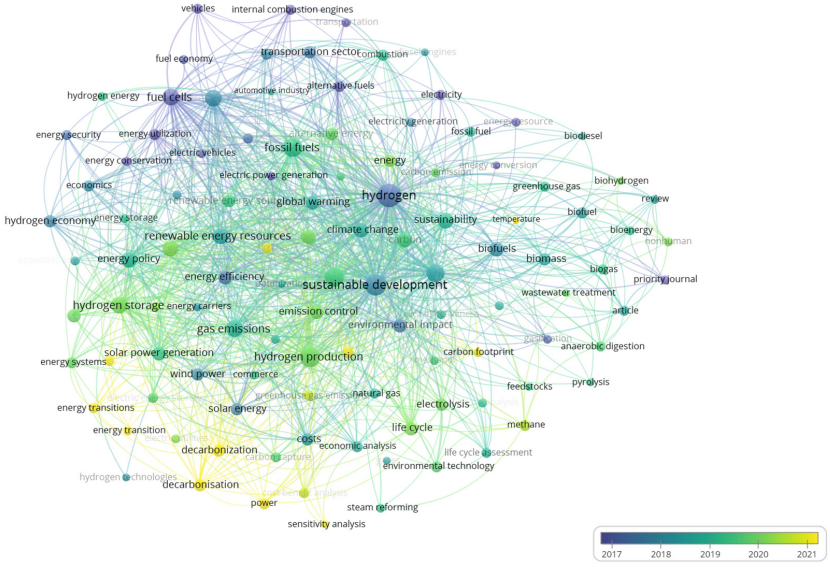


Figure 8. The overlay of keywords that appeared at least 15 times.

Notably, the keywords with an average publication year later than 2021 are "decarbonisation" (2021.97), "decarbonization" (2021.92), "power" (2021.86), "energy transitions" (2021.83), "energy transition" (2021.75), and "current" (2021.97). These results demonstrate that scientists are addressing the challenges of decarbonization and exploring innovative solutions to energy transitions, including hydrogen utilization, for a sustainable future.

The top 15 keywords with the highest co-occurrence rate are shown in Figure 9. As can be seen from the figure, although hydrogen is a long-studied topic, the issue of hydrogen storage is a hot topic at present, alongside energy discussions.

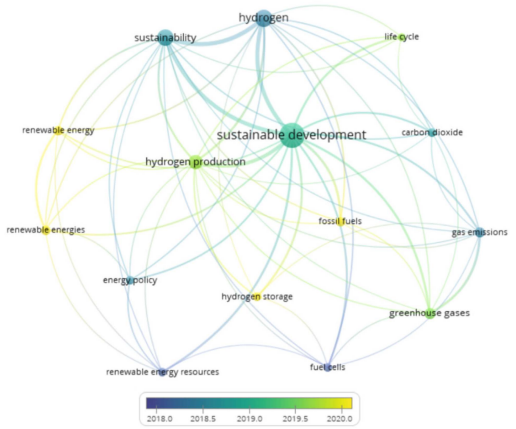


Figure 9. The overlay visualization of the top 15 keywords with the strongest citation bursts.

In addition, the top 15 keywords with the most occurrences are depicted in Table 6. These keywords are related to the sustainability topic ("sustainable development" and "sustainability"), hydrogen technologies ("hydrogen", "hydrogen production", "hydrogen storage", "fuel cells"), emissions ("greenhouse gasses", "gas emissions", "carbon dioxide"), and energy sources ("fossil fuels", "renewable energy", "renewable energies", "renewable energy sources", "hydrogen fuels"), as well as energy policy, showing the measures that should be taken for hydrogen development.

Table 6. The top 15 keywords with the biggest total link strength.

Rank	Keyword	Mean (Year)	Total Link Strength
1	Hydrogen	2017.4	2486
2	Sustainable development	2017.9	2048
3	Hydrogen production	2019.5	1743
4	Greenhouse gases	2019.1	1521
5	Fossil fuels	2019.3	1434
6	Carbon dioxide	2018.5	1380
7	Fuel cells	2017.1	1218
8	Hydrogen storage	2020.0	1149
9	Gas emissions	2018.6	1143
10	Hydrogen fuels	2018.0	1125
11	Renewable energy sources	2019.4	1038
12	Energy policy	2018.9	970
13	Renewable energies	2020.0	937
14	Sustainability	2019.0	889
15	Climate change	2018.8	806

The average publication year shows that hydrogen, as well as sustainability, have been discussed for some time. The most relevant of the top 15 keywords were related to renewable energy and hydrogen storage (Table 6).

3.3.3. Sustainability Topic Analysis

This section describes how the topic of sustainability is represented in the keywords' analysis. Among the determined keywords, the following keywords related to sustainability were identified: "sustainable development", "sustainability", "sustainable energy".

Figures 10 and 11 show how the found keywords relate to the topic of sustainability. Thus, it was determined that the keyword "sustainable development" is most associated with keywords describing emissions, such as "carbon dioxide" and "greenhouse gases",

as well as with the term "fossil fuels" and hydrogen-related keywords such as "hydrogen", "hydrogen fuels", "fuel cells". The keyword "sustainability" is most associated with energy-related keywords ("energy", "alternative energy", "renewable energy"), as well as with "hydrogen", "sustainable development", and "environmental impact". "Sustainable energy", however, is not only connected to the keywords "hydrogen", "sustainable development", and "hydrogen production", but also to "energy policy" and "energy conservation".

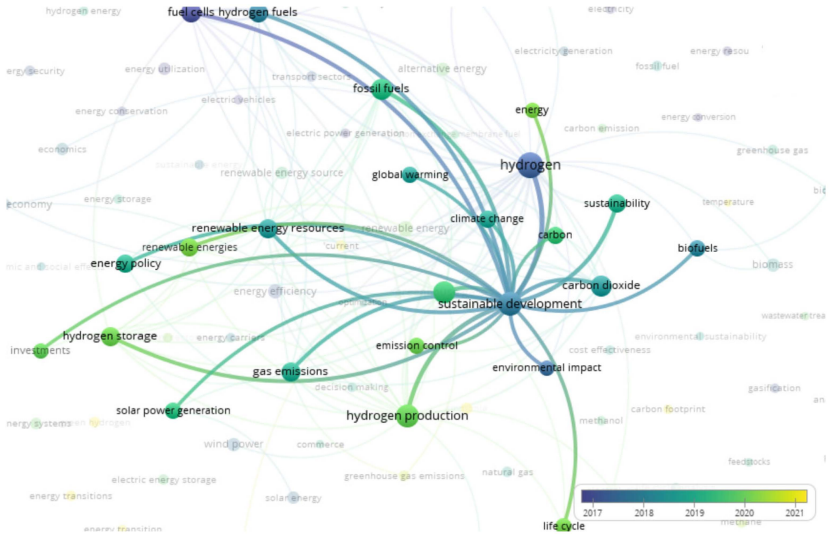
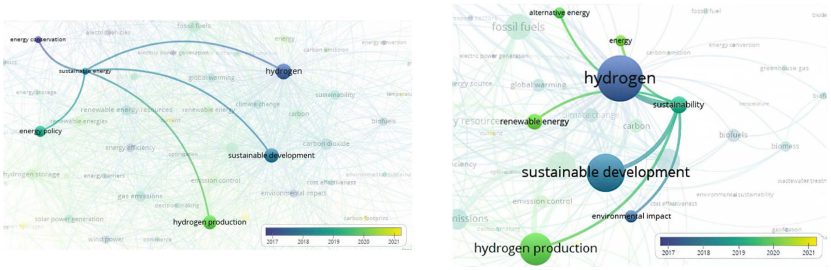


Figure 10. An overlay of the keyword "sustainable development" with the strongest links.

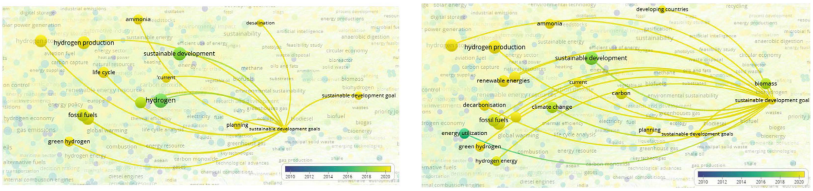


(**a**) (**b**)

Figure 11. An overlay of keywords (**a**) "sustainable energy" and (**b**) "sustainability" with the strongest links.

Terms related to sustainability are mostly associated with concepts such as "hydrogen", "hydrogen production", "energy", and "energy policy". With these settings, the term "SDG" does not appear in the keyword list. To determine the co-occurrence network of keywords related to SDG, 4000 most used keywords were taken. Figure 12 shows the results obtained by setting the number of allowed line connections to the maximum (10,000).

The analysis of keywords showed that, when talking about SDGs, the most frequently mentioned words are "green hydrogen", "biomass", and "ammonia", which also appeared in Figure 11.



(**a**) (**b**)

Figure 12. The overlay visualization of keywords (**a**) "sustainable development goals" and (**b**) "sustainable development goal" with the strongest links.

3.4. Sector Analysis

This section will compare the results for six sectors, power, industry, transport, agriculture, commercial, and residential, by analyzing the co-occurrence of keywords in publications and timeline visualization using VOSviewer.

3.4.1. Power Sector

To gain insight into the stage of hydrogen development in the energy sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (SDG OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND energy OR power)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

This request corresponded to 735 publications (23 August 2020). The condition was set that keywords must appear at least 18 times. Out of 6505 keywords, 104 keywords corresponded to this request. Figures 13 and 14 show the visualization of keyword co-occurrence.

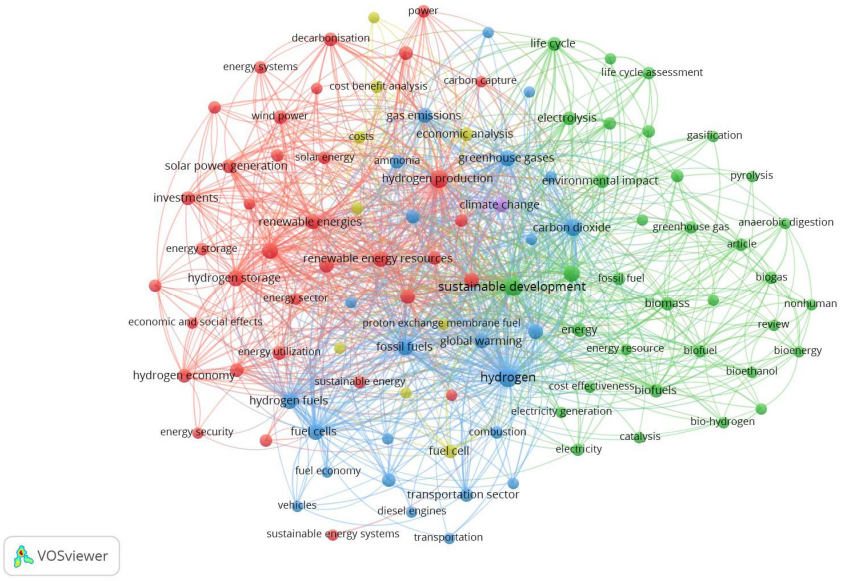


Figure 13. Co-occurrence network generated by VOSviewer in the power sector. Cluster analysis.

According to Figure 13, keywords were divided into six different clusters. A summary list of their information is shown in Table 7.

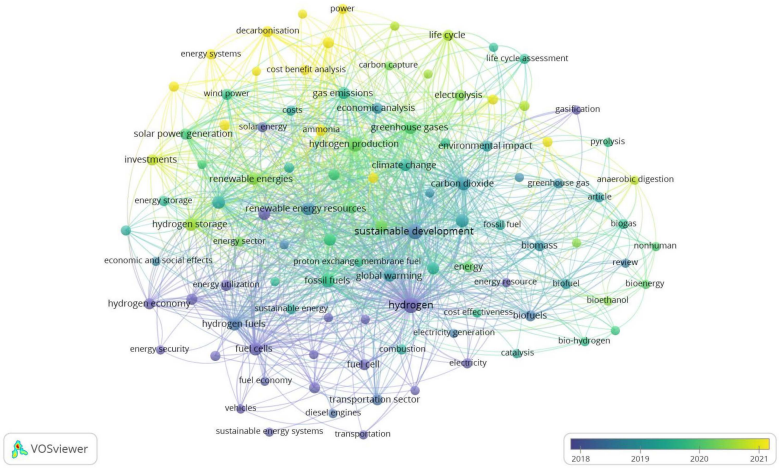


Figure 14. Co-occurrence network generated by VOSviewer in the power sector. Time trend analysis.

Table 7. Power sector cluster information summary list.

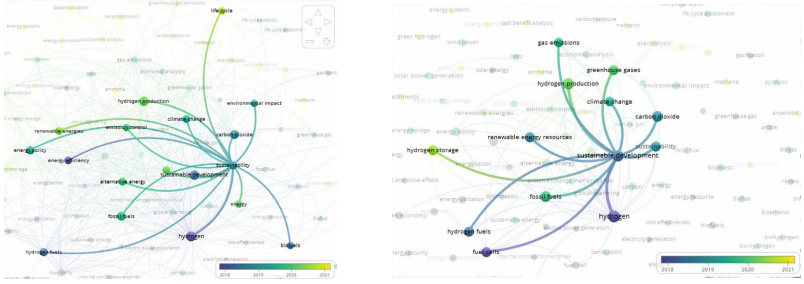
Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
Power	P1 (red)	36	2020.2	Hydrogen production
			2019.3	Energy policy
			2020.5	Hydrogen storage
			2018.7	Renewable energy resources
			2020.3	Renewable energies
	P2 (blue)	34	2017.8	Hydrogen
			2019.7	Fossil fuels
			2020.0	Greenhouse gases
			2018.9	Carbon dioxide
			2019.5	Gas emissions
	P3 (green)	16	2018.5	Sustainable development
			2019.0	Sustainability
			2020.6	Life cycle
			2018.9	Biomass
			2018.5	Biofuels
	P4 (yellow)	15	2018.8	Economic analysis
			2017.9	Fuel cell
			2019.2	Costs
			2021.2	Cost benefit analysis
			2019.4	Decision making

These findings show that research focusing on hydrogen sustainability is diverse in the power sector. This includes research into hydrogen production and storage, its role as a clean energy carrier, and its potential use in fuel cells and power generation. Thus, from the keywords used, it can be concluded that such topics as sustainable development, climate change mitigation, greenhouse gas emissions reduction, and a transition away from fossil fuels are very prominent in the power sector, and hydrogen's contribution to solving these problems is actively being studied. According to Figure 13 and Table 7, the most relevant clusters with the highest mean years are P1 and P4, which describe hydrogen production, storage, renewable energies (P1), and decision-making-describing keywords (P4).

Nine out of ten of the most cited publications are described in Section 3.1.3. Apart from the articles described above, the most citations about the power sector were found in

articles that performed technical analyses of the available renewable alternatives, including hydrogen [34–36], as well as many articles that were focused on the connection between the power sector and the transport sector [35,37,38].

The theme of sustainable development appears in the following keywords: "sustainable development", "sustainable energy", "sustainability", "sustainable energy", and "sustainable energy systems". The most frequently mentioned keywords, with 1541 and 100 mentions, were "sustainable development" and "sustainability", respectively (see Figure 15).



(**a**) (**b**)

Figure 15. Keywords that are connected to (**a**) "sustainability" and (**b**) "sustainable development" in the power sector.

Similar to 3.3.3, the term "SDG" does not show up in the keyword list in the section containing these parameters. To determine the co-occurrence network of keywords related to SDGs, all the found keywords were taken. Figures 16 and 17 show the results obtained by setting the number of allowed line connections to the maximum (10,000).

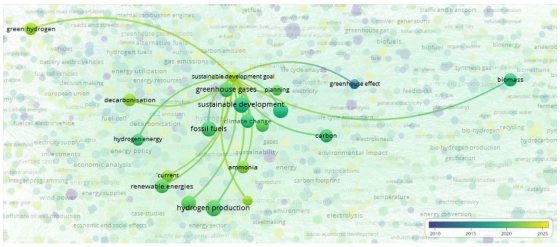


Figure 16. The overlay visualization of the keyword "sustainable development goal" (power sector).

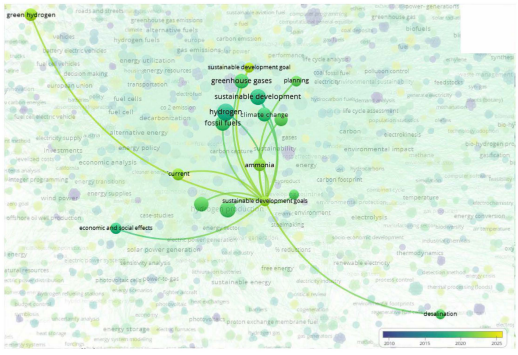


Figure 17. The overlay visualization of the keyword "sustainable development goals" (power sector).

3.4.2. Industry Sector

To gain an insight into the stage of hydrogen development in the industry sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND industry)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

This request corresponded to 264 publications (23 August 2020). The condition was set that keywords must appear at least eight times; out of 3357 keywords, 91 keywords corresponded to this request. Figures 18 and 19 show the co-occurrence of keywords.

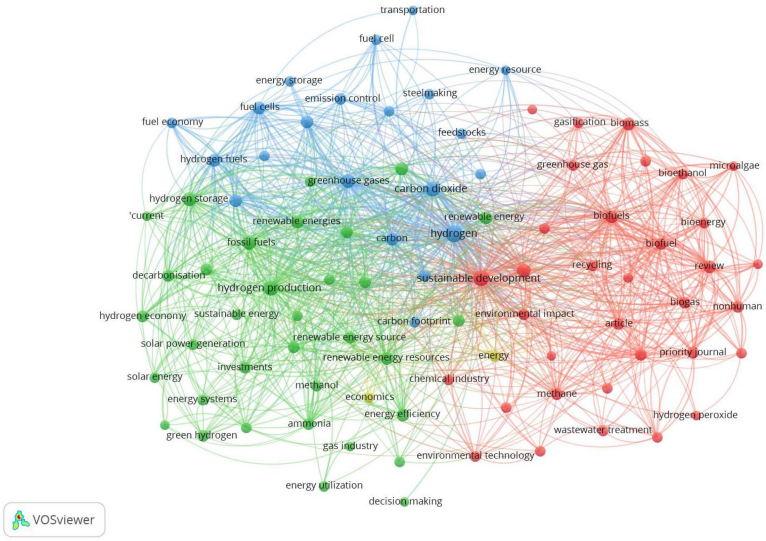


Figure 18. Co-occurrence network generated by VOSviewer in the industry sector. Cluster analysis.

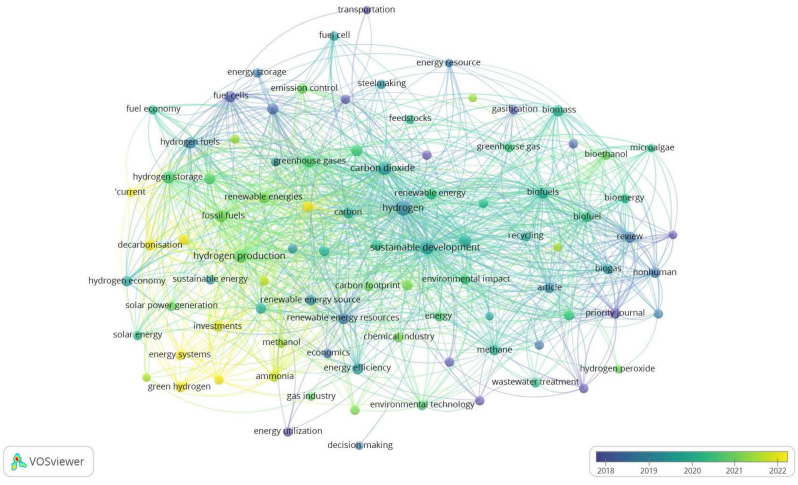


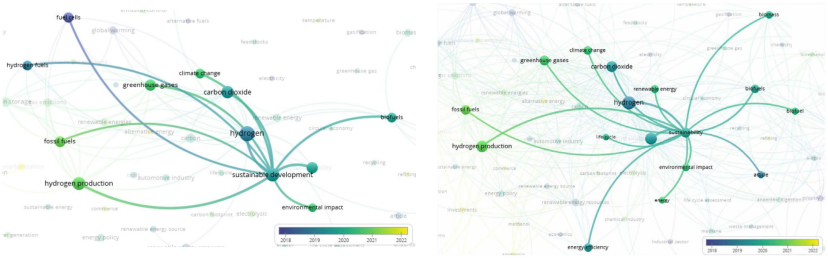
Figure 19. Co-occurrence network generated by VOSviewer in the industry sector. Time trend analysis.

In Figure 18, keywords are divided into five different clusters. A summary list of their information is shown in Table 8.

Table 8. Industry sector cluster information summary list.

Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
Industry	I1 (red)	36	2019.5	Sustainable development
			2019.8	Sustainability
			2019.8	Biofuels
			2020.3	Biofuel
			2020.0	Biomass
	I2 (blue)	34	2019.0	Hydrogen
			2019.5	Carbon dioxide
			2020.6	Greenhouse gases
			2020.6	Gas emissions
			2019.8	Carbon
	I3 (green)	21	2020.8	Hydrogen production
			2020.9	Fossil fuels
			2020.6	Hydrogen storage
			2018.7	Renewable energy resources
			2020.5	Climate change

As shown above, each cluster represents a specific aspect of research related to sustainable development and bioenergy, emissions, hydrogen technologies, and climate change. From Figure 19, it can be concluded that most keywords whose average year is prior to 2022 are depicted in yellow color and include the keywords "decarbonization", "energy systems", and "green hydrogen". The concept of sustainability was evident through the usage of terms such as "sustainability", "sustainable development", and "sustainable energy". The initial pair of keywords exhibited greater total link strength values (304 and 520, respectively), indicating a more detailed representation in Figure 20.



(**a**) (**b**)

Figure 20. Keywords that are connected to (**a**) "sustainable development" and (**b**) "sustainability" in the industry sector.

Based on the analysis of Figure 18, it is clear there is a significant overlap between the two mentioned keywords. Furthermore, these keywords also exhibit a substantial degree of overlap with emission-characterizing keywords, as well as fossil and renewable fuels, and hydrogen and its production. The co-occurrence network was expanded to include all discovered keywords to analyze "SDG" and "SDGs" keyword co-occurrences (Figures 21 and 22).

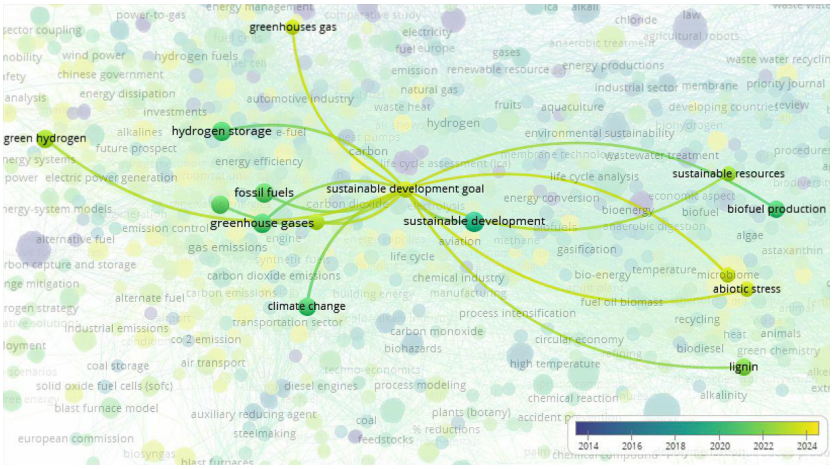


Figure 21. The overlay visualization of the keyword "sustainable development goal", along with the strongest links (industry sector).

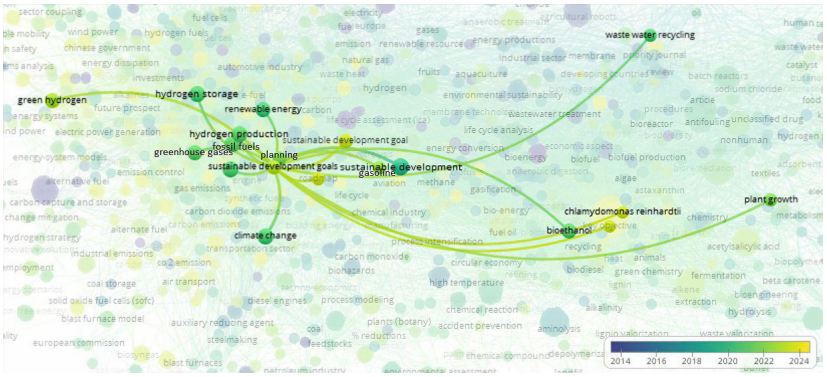


Figure 22. The overlay visualization of the keyword "sustainable development goals" (industry sector).

3.4.3. Transport Sector

To gain an insight into the stage of hydrogen development in the transport sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND transport)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

This request corresponded to 221 publications (23 August 2020). The condition was set that keywords must appear at least seven times; out of 2505 keywords, 103 keywords corresponded to this request. Figures 23 and 24 show the keywords' co-occurrence.

In Figure 23, the found keywords are divided into five different clusters. A summary list of their information is shown in Table 9.

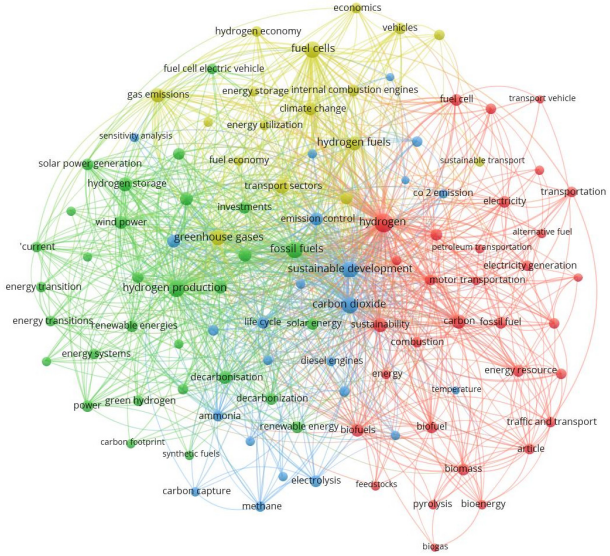


Figure 23. Co-occurrence network generated by VOSviewer in the transport sector. Cluster analysis.

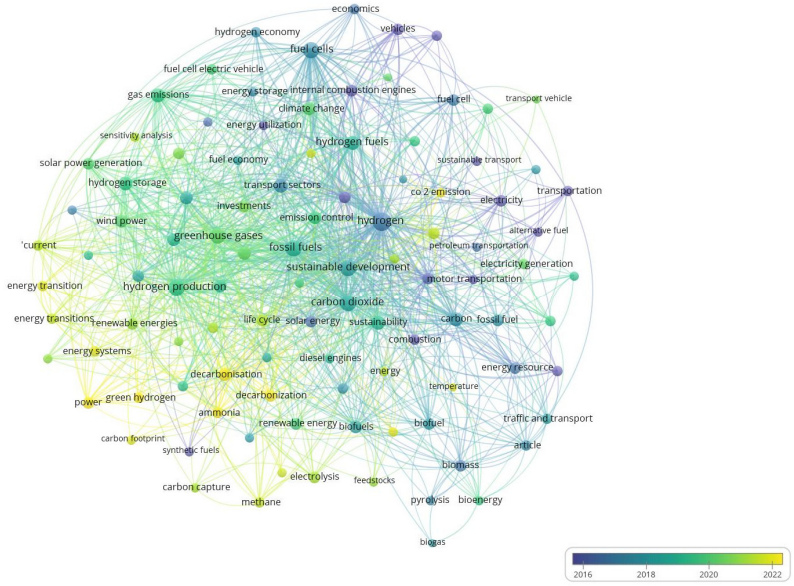


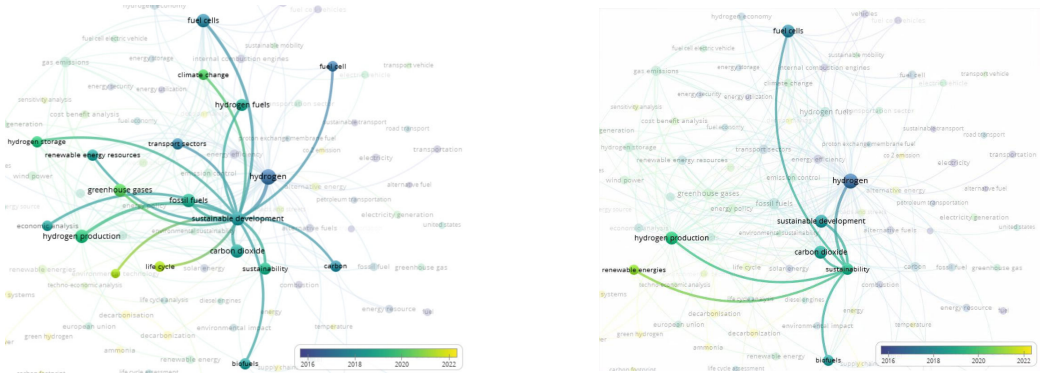
Figure 24. Co-occurrence network generated by VOSviewer in the transport sector. Time trend analysis.

The most cited papers not only focused on hydrogen as a solution to decarbonizing the transport sector [29,31,32,39] but also discussed the current state of the art and the deployment of hydrogen fueling stations [40,41], examined the existing International Energy Agency Hydrogen Agreement support program for hydrogen development [42], compared fuel cell technologies with other alternatives [43–46], and examined hydrogen fuel sustainability [47,48].

Table 9. Transport sector cluster information summary list.

Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
Transport	T1 (red)	32	2016.94	Hydrogen
			2019.07	Sustainability
			2017.67	Carbon
			2018.25	Biofuels
			2017.05	Fuel cell
	T2 (green)	30	2019.51	Hydrogen production
			2018.84	Fossil fuels
			2019.55	Hydrogen storage
			2020.20	Energy policy
			2018.33	Renewable energy resources
	T3 (blue)	24	2018.13	Sustainable development
			2018.46	Carbon dioxide
			2019.58	Emission control
			2019.12	Global warming
			202.13	Life cycle
	T4 (yellow)	17	2017.55	Fuel cells
			2020.17	Greenhouse gases
			2018.72	Hydrogen fuels
			2019.52	Gas emissions
			2017.43	Transport sectors

In this section, under the selected conditions, SDGs do not appear as keywords, but the theme of sustainability appears in the keywords "sustainable development", "sustainable transport", "sustainable mobility", and "sustainability". The connection between the keywords "sustainable development" and "sustainability" and other keywords is shown in Figure 25.



(**a**) (**b**)

Figure 25. Keywords that are connected to (**a**) "sustainable development" and (**b**) "sustainability" in the transport sector.

In the transport sector, the keywords "sustainability" and "sustainable development" are largely related to fuel cells, and they appear together with the use of terms "renewable resources", "hydrogen production", and keywords describing emissions (e.g., carbon dioxide, greenhouse gases).

A co-occurrence network was built using all keywords and 10,000 connecting lines to examine the linkages that are shown to be in contact with the SDGs (Figure 26). The

terms "sustainable development goal" and "sustainable development goals", both of which featured in two articles and had a total link strength of 24, were discovered when publishing such a network (for comparison, the keyword total link strength shown in Table 9 varied from 510 to 2206).



(**a**) (**b**)

Figure 26. The overlay visualization of keywords (**a**) "sustainable development goals" and (**b**) "sustainable development goal" in the transport sector.

According to Figure 26, the terms "fossil fuels", "sustainable development", "hydrogen storage", and "decarbonization" have the strongest relationships with the terms "sustainable development goals" and "sustainable development aim". The terms "sustainable development aim", "current", "environmental effect", and "energy source" are also related to the term "sustainable development goal". The attainment of SDGs in the transport industry just lately began to be considered, as seen by the fairly recent (2023.0) average publication date of both keywords.

3.4.4. Agriculture Sector

To gain an insight into the stage of hydrogen development in the agriculture sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND agriculture)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

This request corresponded to 38 publications (23 August 2020). The condition was set that keywords must appear at least three times; out of 1050 keywords, 65 keywords corresponded to this request. Figures 27 and 28 show a visualization of keyword co-occurrence.

According to Figure 27, keywords were divided into four different clusters. A summary list of their information is shown in Table 10.

An analysis of the most cited articles showed that the article that was cited the most focused on the utilization of biogas and renewable hydrogen as catalysts for sustainable development [49]. It delved into an analysis of existing and potential sources of feedstock for the generation of these gases, with particular emphasis on agricultural waste and wastewater. Other highly cited publications discussed biofuel production and the importance of alternative fuels in future transport systems [46], as well as discussing energy generation and hydrogen production via the gasification process [50].

The most recent works discussed the contribution to ecology and the achievement of SDGs by microalgae and the hydrogen produced by these [51,52], as well as plant-growth-promoting endophytic bacterium and how they were further tested for other plant-growth-promoting attributes, such as hydrogen cyanide [53]. The role of biogas in achieving a hydrogen economy was also investigated [54].

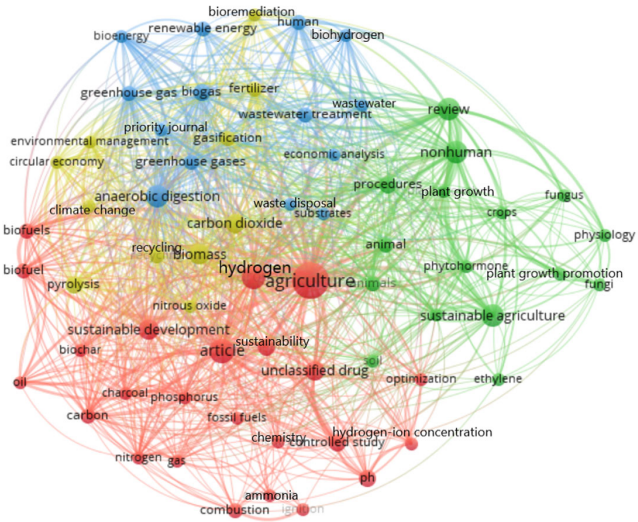


Figure 27. Co-occurrence network generated by VOSviewer in the agriculture sector. Cluster analysis.

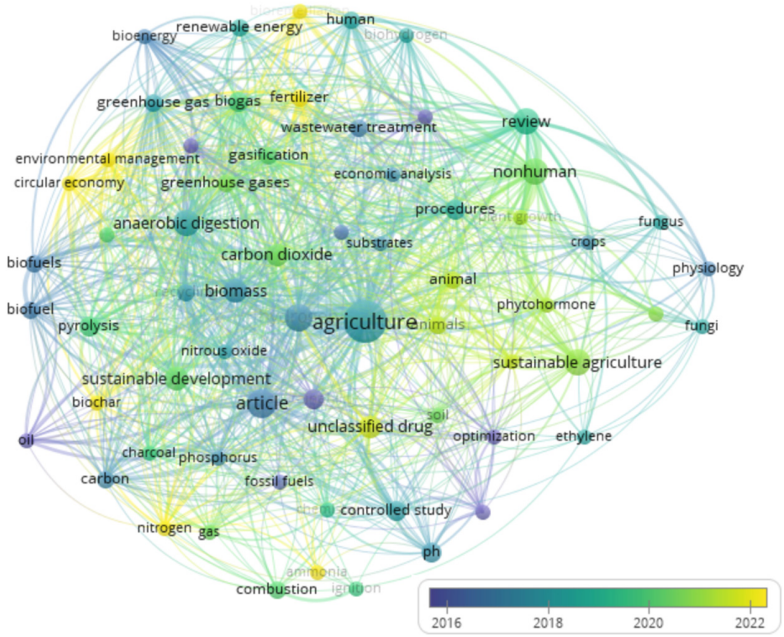


Figure 28. Co-occurrence network generated by VOSviewer in the agriculture sector. Time trend analysis.

In this section, under the selected conditions, SDGs do not appear as keywords, but the theme of sustainability appears in the keywords "sustainable development" and "sustainability". The connection between these keywords with other keywords is shown in Figure 29.

Table 10. Agriculture sector cluster information summary list.

Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
Agriculture	A1 (red)	24	2017.9	Agriculture
			2022.0	Article
			2020.1	Sustainable development
			2017.3	Hydrogen
			2017.3	Carbon
	A2 (green)	16	2020.4	Nonhuman
			2019.3	Review
			2018.6	Procedures
			2020.8	Sustainable agriculture
			2021.3	Animals
	A3 (blue)	14	2018.1	Anaerobic digestion
			2019.8	Biogas
			2018.0	Greenhouse gas
			2020.5	Greenhouse gases
			2017.0	Bioenergy
	A4 (yellow)	11	2017.6	Biomass
			2020.3	Carbon dioxide
			2019.8	Pyrolysis
			2017.8	Recycling
			2022.8	Fertilizer



(**a**) (**b**)

Figure 29. Keywords that are connected to (**a**) "sustainable development" and (**b**) "sustainable agriculture" in the agriculture sector.

Remarkably, within the realm of agriculture, the term "hydrogen" does not emerge as one of the most prominent keywords in conjunction with the term "sustainable development". However, the discussion includes ideas such as the circular economy, recycling, and bioenergy. Based on these findings, it can be inferred that "sustainable agriculture" exhibits a stronger correlation with biomass as compared with hydrogen. It is important to acknowledge that a particularly robust association exists between the keyword in question and the term "nonhuman".

A co-occurrence network made up of all keywords and 10,000 link lines was developed to study the connections that are seen in relation to SDGs (Figure 30). The terms "sustainable development aim" and "sustainable development goals" were discovered when building such a network; they both appeared in two articles and had total link strengths of 153 and 97, respectively (for comparison, the keyword total link strength shown in Table 10 varied from 188 to 864).

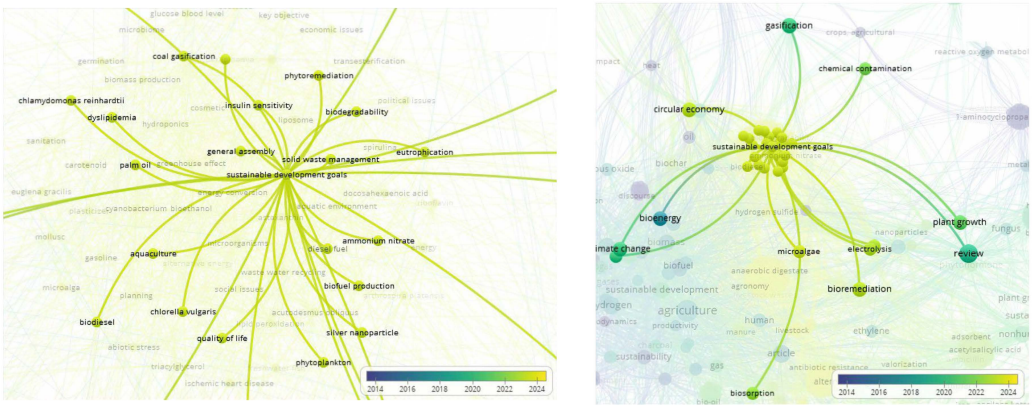


Figure 30. Overlay visualization of the keyword "sustainable development goals" in the agriculture sector.

Figure 31 shows that the keyword "sustainable development goal" has the strongest connection with the keywords "circular economy", "chemical contamination", "bioenergy", "nitrogen", "biodegradability", "alternative energy", and "biofuel production". On the other hand, the keyword "sustainable development goals" has the strongest connection with the keywords "biosorption", "bioremediation", "bioenergy", "biodiesel", "biodegradability", "ammonium nitrate", "biofuel production", and "aquaculture".

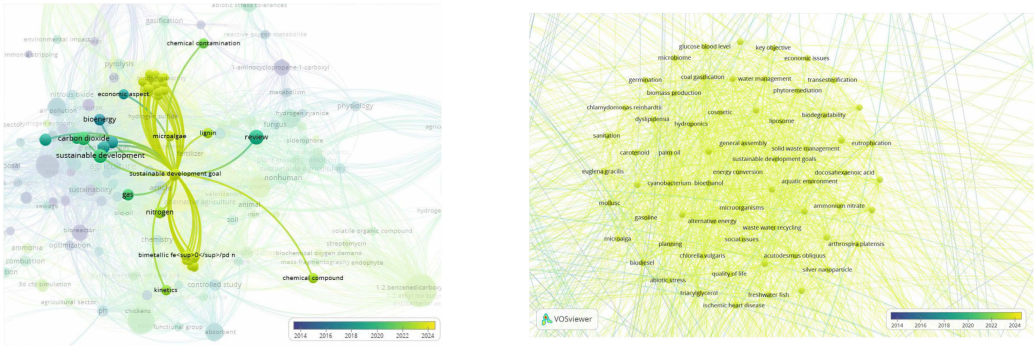


Figure 31. Overlay visualization of the keyword "sustainable development goal" in the agriculture sector.

3.4.5. Commercial Sector

To gain insight into the stage of hydrogen development in the commercial sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND commercial)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

This request corresponded to only 65 publications (23 August 2020). The condition was set that keywords must appear at least three times; out of 997 keywords, 74 keywords corresponded to this request. Figures 32 and 33 show a visualization of keyword co-occurrence.

In Figure 32, keywords are divided into five different clusters. A summary list of their information is shown in Table 11.

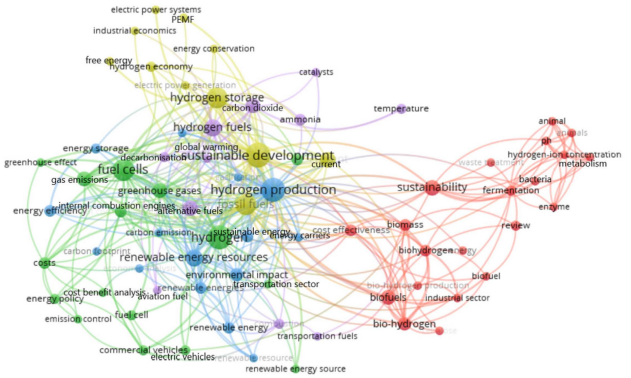


Figure 32. Co-occurrence network generated by VOSviewer in the commerce sector. Cluster analysis.

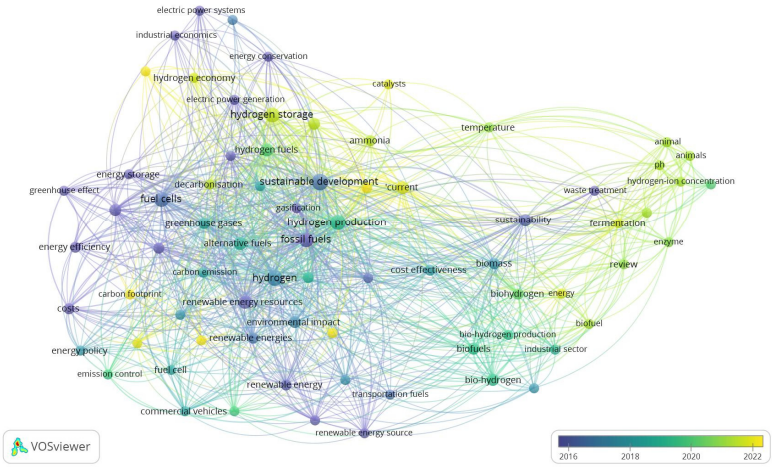


Figure 33. Co-occurrence network generated by VOSviewer in the commerce sector. Time trend analysis.

Table 11. Commercial sector cluster information summary list.

Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
Commercial	C1 (red)	21	2016.3	Sustainability
			2019.3	Bio-hydrogen
			2018.0	Cost effectiveness
			2019.3	Biofuels
			2020.2	Biohydrogen
	C2 (blue)	15	2019.2	Hydrogen production
			2016.1	Renewable energy resources
			2016.8	Renewable energies
			2016.2	Renewable energy
			2017.3	Environmental impact
	C3 (green)	16	2017.4	Hydrogen
			2016.6	Fuel cells
			2018.3	Greenhouse gases
			2015.4	Gas emissions
			2012.0	Internal combustion engines

Table 11. *Cont.*

Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
	C4 (yellow)	11	2016.0	Fossil fuels
			2016.8	Sustainable development
			2021.3	Hydrogen storage
			2021.6	Current
			2021.5	Hydrogen economy
	C5 (purple)	11	2020.0	Hydrogen fuels
			2018.8	Alternative fuels
			2021.3	Carbon dioxide
			2021.3	Decarbonisation
			2017.5	Combustion

The results show that keywords from the second cluster were used most recently, and the most relevant keywords related to hydrogen are "hydrogen storage" and "hydrogen economy" (see Figure 33).

In C1 and C2, the topic of sustainability appears in the keywords with the strongest total link strength, with "sustainable development" in cluster C1 and "sustainability" in cluster C2. Sustainable development goals do not appear to be one of the keywords with applicable conditions. Figure 34 shows the keywords associated with sustainable development in the commerce sector.

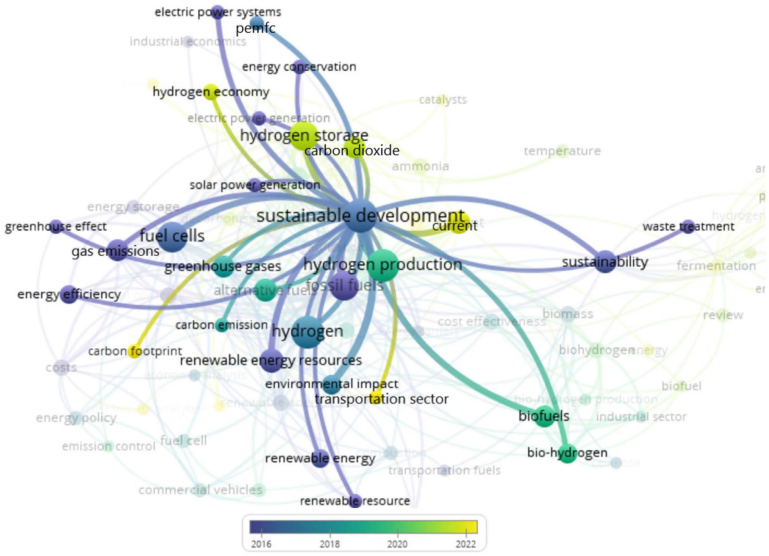


Figure 34. Keywords that are connected to the keyword "sustainable development" in the commerce sector.

In order to investigate the connections observed in contact with SDGs, a co-occurrence network was created, which consisted of all keywords and represented 10,000 connection lines (Figure 35). When creating such a network, the keyword "sustainable development goal" was found, the total link strength of which was 41 (for comparison, the total link strength of the keyword shown in Table 11 varied up to 426).



Figure 35. Overlay visualization of the keyword "sustainable development goal" in the commercial sector.

In the commercial sector, there was only one article with the keyword "sustainable development goal". Dang B.T. et al.'s article investigated the current application of seaweed waste for composting and biochar production. Hydrogen was mentioned in the article as a potential use of biochar, as biochar may have been used for hydrogen storage purposes.

3.4.6. Residential Sector

To gain an insight into the stage of hydrogen development in the residential sector, the following request was used: (TITLE-ABS-KEY (hydrogen OR h2) AND TITLE-ABS-KEY (sdg OR "sustainable development goal*" OR sustainability OR sustainable OR "sustainable development" OR "sustainability assessment" OR "sustainable energy" OR "sustainable energy systems") AND TITLE-ABS-KEY (sector AND residential)) AND (LIMIT-TO (DOCTYPE, ar) OR LIMIT-TO (DOCTYPE, re)) AND (LIMIT-TO (LANGUAGE, English)).

This request corresponded to only 16 publications (23 August 2020). The condition was set that keywords must appear at least two times; out of 33 keywords, 221 keywords corresponded to this request. Figures 36 and 37 show a visualization of keyword co-occurrence.

In Figure 36, keywords are divided into four different clusters. The summary list of their information is shown in Table 12.

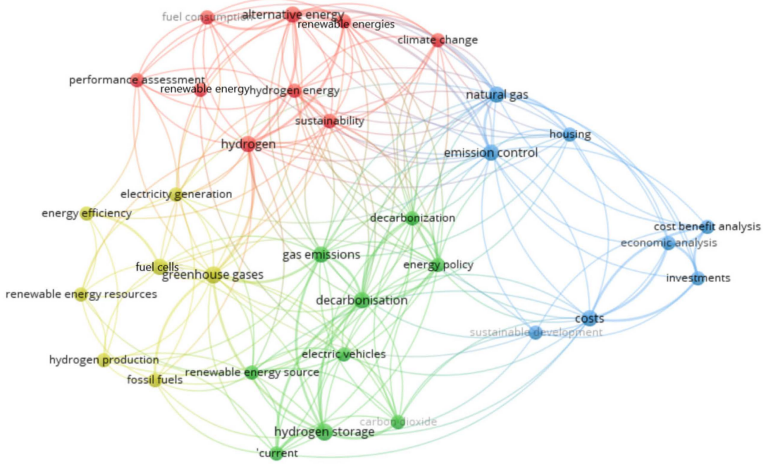


Figure 36. Co-occurrence network generated by VOSviewer in the residential sector. Cluster analysis.

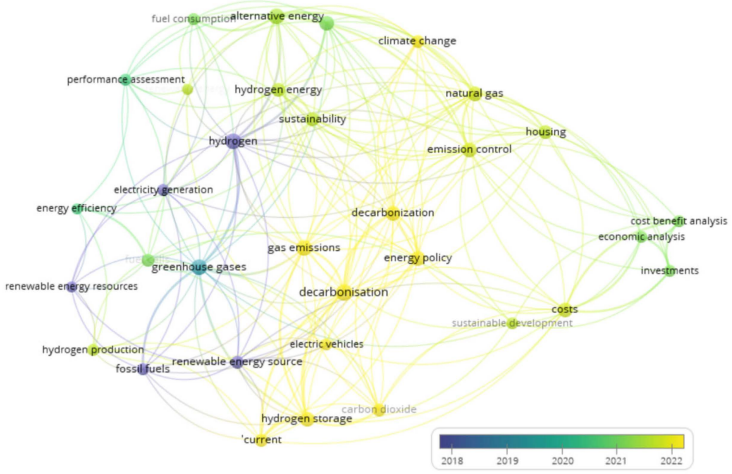


Figure 37. Co-occurrence network generated by VOSviewer in the residential sector. Time trend analysis.

Table 12. Residential sector cluster information summary list.

Sector	Cluster ID	Size	Mean (Year)	Top 5 Keywords Ranked by Total Link Strength
Residential	R1 (red)	9	2018.0	Hydrogen
			20213	Alternative energy
			2021.0	Renewable energies
			2021.5	Hydrogen energy
			2021.5	Sustainability
	R2 (blue)	8	2021.67	Emission control
			2021.67	Natural gas
			2021.67	Costs
			2021.50	Housing
			2021.50	Sustainable development
	R3 (green)	9	2022.67	Decarbonisation
			2022.33	Gas emissions
			2022.50	Decarbonization
			2022.50	Energy policy
			2022.75	Hydrogen storage
	R4 (yellow)	4	2019.25	Greenhouse gases
			2021.00	Fuel cells
			2017.50	Fossil fuels
			2021.50	Hydrogen production
			2017.00	Electricity generation

This study shows that there are very few targeted residential area studies on the application of hydrogen. Like other industries, after analyzing the timeline of keywords (Figure 37), it can be concluded that "gas emissions" and "hydrogen storage" are the most relevant topics, the mean year of which corresponds to 2023. Similarly, it can be concluded that topics of decarbonization, electric vehicles, and climate change are currently the most topical.

The theme of sustainable development appears in the keywords "sustainable development" and "sustainability", which are shown in Figure 38.



(**a**) (**b**)

Figure 38. Keywords that are connected to (**a**) "sustainable development" and (**b**) "sustainability" in the residential sector.

As in other sectors, "sustainable development" is mostly associated with "hydrogen storage", "greenhouse gases", "fuel cells", and "gas emissions". In this sector, the economic sector is prominently divided, which describes keywords such as "costs", "investments", "economic analysis", and "cost benefit analysis". However, the keyword "sustainability" is most associated with keywords such as "hydrogen", "greenhouse gases", "fuel cells", "climate change", "housing", "emission control", and "performance assessment". Of all the obtained keywords, it was found that the individual term SDG or SDGs does not appear in a string of other keywords.

4. Discussion

By identifying important areas of research interest and the connections between them, this keyword analysis aids in presenting a thorough overview of the major themes in a particular dataset. The results show a rapid increase in interest in this topic, which increased more than 12 times in the period from 2011 to 2022. A similarly rapid increase in citations was also observed.

The sustainability of hydrogen is most popular in the energy, environmental science, and engineering research areas. The most productive journal on the discussed topic is the International Journal of Hydrogen Energy, followed by Energies and Renewable and Sustainable Energy Reviews. The last one showed the most productive results when comparing the average number of citations per publication.

Most articles on this topic were written in the US, India, and Germany, while an analysis of institutions indicated that, despite the fact that Yildiz Technical University contributed the most research to this topic, with five articles retrieved, it corresponds to only 0.5% of all publications, which indicates that the study of sustainability is decentralized. The most influential authors are Dincer, I., who contributed twelve articles, followed by Agrawal, R. (eight articles), Delgass, W.N. (six articles), and Ribeiro, F.H. (six articles).

A comparison of studies on sustainable development by sector concluded that the energy sector was the most discussed sector, followed by industry and transport. The number of publications that met the selected conditions in the agriculture, commercial and residential sectors was small, at—38, 65, and 16, respectively. The keywords "sustainable development goal" or "sustainable development goals" appeared much less often than the keywords "sustainable development" or "sustainability", which indicates that although the topic of sustainability is widely studied, the number of studies that analyze the achievement of the SDGs is not too high. Both keywords ("SDG" and "SDGs") are relatively young, as their average publication date was after 2022.

In the general performance analysis (Section 3.3), it was determined that keywords can be grouped into the following groups that describe various raw materials and fuels (e.g., biomass, bioenergy, fossil fuel, biogas, biodiesel):

- Hydrogen production technologies (e.g., gasification, electrolysis, steam reforming).
- Keywords characterizing the climate (e.g., climate change, greenhouse gas, carbon dioxide).
- Keywords related to the use of hydrogen (e.g., hydrogen technologies, hydrogen storage, commerce).
- Policy-related keywords (e.g., energy policy, energy security, decarbonization, hydrogen economy, economic and social effects, investments).
- Mobility sector (transportation sector, fuel economy, fuel cells, combustion engines, etc.)
- Keywords related to analysis (cost benefit analysis, economic analysis, decision-making).

These keywords also appeared, to an extent, in the finer comparison of industries.

The time trend analysis showed that "the youngest" keywords with the most current average publication year are "decarbonization", "gas emissions", "energy systems", "energy transitions", "power", "green hydrogen", and "hydrogen storage". This indicates that the issue of decarbonization is likely becoming more and more relevant, which could also contribute to the increase in interest in the field of energy transition. The issue of hydrogen energy storage remains very relevant.

Overall, this paper shows that the use of hydrogen is being explored to achieve sustainable development goals and, despite the relatively limited number of publications, interest in the field is growing rapidly and there is no reason to believe it will decline soon. This study can provide researchers who are new to the topic of hydrogen sustainability with a quick overview of the research status and trends.

5. Conclusions

In response to the anticipated and existing difficulties confronting humanity, the United Nations has formulated a set of 17 sustainable development goals. In order to attain these objectives, it is important to comprehend the energy sources and the provenance of their primary constituents. There is growing debate regarding the possible contribution of hydrogen to the future energy balance. The aim of this study is to provide a bibliometric analysis assessing the effectiveness of the use of hydrogen in different sectors in achieving the SDGs and to provide an overview of how sustainability is discussed in different sectors. This study identifies the most cited publications, as well as the most productive journals, countries, and organizations. This study analyzes the current state of research on hydrogen sustainability in six sectors. The areas of study include energy, industry, transport, agriculture, commercial and residential sectors. The results show that the energy sector shows the greatest interest in sustainable development, followed by industry and transport.

The work has several limitations; for example, it is known that to obtain a more accurate understanding of research reviews, it is important to explore ways to combine data from different databases. The limitations of the work include the fact that only the SCOPUS database was examined. Researching other databases could provide additional insight into the researched topic. Another limitation is that the topic of SDGs and sustainability can also be discussed in other publications that are not tied to any specific sector. Another limitation is that, due to the diverse range of techniques employed in the production of green hydrogen, it is likely that many scientific papers related to this topic may not incorporate the particular terms "hydrogen" or "H2" within their abstract, title, or keywords. A potential increase in the number of articles might be achieved by supplementing the keywords with terms on all established techniques for the production of green hydrogen.

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Realizing a Green Hydrogen Economy: An Examination of Influencing Factors

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***Abstract* – The significance of hydrogen in the context of the ongoing energy transition is growing noticeably. This study presents a review of the literature on the factors that influence the development of a hydrogen economy. Based on an analysis of relevant studies, we suggest the factors that drive the growth of a hydrogen economy. Unlike traditional sector-based analyses, our approach is a comprehensive examination of the hydrogen value chain, incorporating stakeholder perspectives that are frequently overlooked in technical and economic research. Drawing on recent International Energy Agency assessments and extensive desk research, we identify barriers and propose solutions critical to the successful implementation of a hydrogen economy. The study then introduces a conceptual causal loop diagram and an illustrative framework that visually depict the intricate interconnections between stakeholders and influencing factors. The findings emphasize the importance of increased political support, particularly for addressing concerns about technological immaturity and economic viability, and strategic collaborations between private companies, academia, and government institutions. The proposed solutions, which include research and development support and the formulation of national hydrogen strategies, highlight the critical role of a well-defined policy framework in advancing the green hydrogen economy. This study significantly enriches both academic understanding and practical decision-making by providing valuable insights for long-term hydrogen development.**

***Keywords* – Energy systems analysis; energy transition; hydrogen economy; influencing factors.**

1. INTRODUCTION

Fighting climate change is a contemporary challenge of the global society. Global temperatures have already reached half the allowed 2 °C temperature increase relative to pre-industrialized levels, which, scientists warn, is the threshold by the end of the century beyond which the climate and the environment will encounter dangerous, catastrophic consequences [1]. Transitioning toward climate neutrality [2] requires society to reduce carbon emissions in less than 30 years to an extent no sector has yet achieved.

Efforts to mitigate climate change should be improved, and hydrogen is one of the considered solutions [1]. Hydrogen pathways in clean energy transition are being actively explored in case studies of various scales, such as studies in China [2], Italy [3], and Europe [4] and a global study [5]. Hydrogen currently accounts for less than 2.5 % of the global energy consumption [6]–[8], but this proportion can increase to 12 % by 2050 [6]. The

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primary rationale for using hydrogen is to shift from the current linear energy systems to integrated energy systems, where energy flows between users and producers, reducing wasted resources and money [7]. Sustainable hydrogen provides energy storage, sector connectivity, and emission reduction [8].

However, despite the contribution of hydrogen to the achievement of decarbonization, several challenges hinder the development of hydrogen. Industry stakeholders raise significant barriers that the technology must overcome, such as high costs, availability of fuelling infrastructure, and lack of experience and knowledge [9]. Other authors have added such factors as lack of an integrated national strategy and roadmap, lack of private-sector participation, low willingness to use hydrogen, and high dependence on fossil fuel revenues [10] and safety issues [11]. These examples indicate the complexity of a hydrogen economy, highlighting the different stakeholders, interests, and time-varying factors determining the development of such an economy along its value chain [12].

This paper is a literature review on the factors that influence the development of a hydrogen economy. The introduction gives background information about the present consumption of hydrogen, future development prospects, and emerging trends based on a recent International Energy Agency (IEA) assessment [13]. Additionally, desk research is conducted on the variables influencing the growth of a hydrogen economy. This paper enriches the field in various ways. First, we take a holistic approach, examining the hydrogen value chain rather than specific phases or sectors, as has been described previously (such as [14]–[17]). Second, we incorporate stakeholder analysis, elucidating the practical perspective of implementers and gaining insights that are often overlooked in conventional technical or economic research. Furthermore, for the growth and advancement of a hydrogen economy, the significance of public attitudes and information distribution should be considered in addition to technical and economic factors. This involves the development of public policies and the establishment of collaborative efforts among research institutions and nations, drawing upon successful models of implementation. Such measures will facilitate the exchange of knowledge among relevant stakeholders [12]. Third, given our desk research findings, we propose a conceptual causal loop diagram that illustrates the linkages identified in the literature review between the various stakeholders in a hydrogen economy and their interactions. Clarifying the connections between the various components and participants of the economy can facilitate the prediction of system behaviour and its associated effects. This approach will then enable the formulation of highly informed decisions aimed at reducing the carbon dependency of domestic economies. It will also help deepen the comprehension of the intricate hydrogen economy. By summarizing existing knowledge about the elements affecting the green hydrogen economy from a holistic perspective and identifying gaps in the current understanding of the subject, this study is practically significant not only as a decision-making guide but also as an academic resource.

1.1. Background Information

The latest IEA Global Hydrogen Review 2023 [13] distinguishes five sectors of hydrogen consumption: industry, refining, transport, buildings, and electricity generation. Below, we briefly provide background information about the current hydrogen developments in these sectors and expected future trends.

1. Industry. The industry sector is the largest consumer of hydrogen globally, using 53 Mt of hydrogen in 2022. Hydrogen is used to produce three major industrial commodities: ammonia (60 % of hydrogen demand in 2022), methanol (30 % of hydrogen demand in 2022), and steel (10 % of hydrogen demand in 2022). Considering current trends and announced policies, the IEA projects that the demand for hydrogen

will rise by approximately 20 % by 2030 relative to the 2021 level [18]. Virtually all hydrogen used in the industry sector is obtained from unabated natural gas or coal, producing 630 Mt of direct CO_2 emissions on a net basis (or 7 % of industrial CO_2 emissions) in 2021. Considering current policies and announced projects, by 2030, low-emission hydrogen production in the industrial sector is expected to reach 3 Mt and the hydrogen demand for oil refining, ammonia and methanol production, high-temperature heating, and production of primary steel is projected to grow by 7 %, 31 %, 9 %, and up to 14 %, respectively [19].

2. Refining. The global hydrogen demand of the oil refining sector exceeded 41 Mt in 2022 [13]. This demand is mainly influenced by the consumption of oil products, as hydrogen is used to remove impurities and upgrade heavy oil fractions into lighter products. Almost all hydrogen used in refineries is obtained from fossil fuels, resulting in 240–380 Mt of CO_2 emissions in 2022. New sources of hydrogen demand in refineries may include biofuel upgrades, the production of low-emission synthetic hydrocarbon fuels (synfuels), or high-temperature heating for various processes.
3. Transport. Hydrogen consumption in the transportation sector is rapidly growing. The total hydrogen demand of this sector exceeded 30 kt in 2021 and increased by approximately 45 % in 2022. Nonetheless, hydrogen consumption accounts for an insignificant part of the total transport energy consumption. Given their high annual mileage, trucks and buses are the biggest consumers, although the largest fleet in terms of the number of units is passenger cars (approximately 50 thousand). In 2022, the first fuel cell train fleet started operating in Germany [20]. Hydrogen's role in rail transport is expected to rise in the near term, as it is a substitute for diesel rail lines where electrification is difficult and the distances are too long to be covered by battery electric trains. Global hydrogen demand is expected to reach 0.7 Mt by 2030 in the Stated Policies Scenario and 8 Mt in the Announced Pledges Scenario [18]. Industry announcements indicate that the market for hydrogen-powered vehicles is poised to expand over the next decade in all road segments. China and Korea have had the largest increase in the number of hydrogen refuelling stations in stock since 2020, with Korea accounting for approximately two-thirds of the increase in the number of fuel cell vehicles in 2022. In terms of infrastructure, approximately 1,100 hydrogen refuelling stations are operating globally as of June 2023, with hundreds more planned. Hydrogen technology development is also occurring in off-road transport, shipping, and aviation. Ports are particularly well-suited to become hydrogen hubs, and some are beginning to integrate hydrogen infrastructure to support heavy-duty trucks, cargo handling equipment, and other port equipment and maritime vessels. The European Union (EU) established the FuelEU Maritime regulation in July 2023 to encourage the use of low-carbon fuels in shipping, offering additional incentives for the use of nonbiological fuels, such as low-carbon hydrogen [21].
4. Buildings. Hydrogen accounts for a negligible share of energy demand of the building sector, with no significant increase from the previous years. Currently, hydrogen cannot compete with traditional low-carbon alternatives, such as electricity, district heat, and distributed renewables. Hydrogen consumption will exceed 1 Mt by 2030, accounting for only 0.14 % of the overall energy demand of the industry. The main reason for this is the low energy extraction efficiency of buildings. However, opportunities for hydrogen applications may exist in buildings that already have natural gas infrastructure and where energy use is difficult to decarbonize. Hydrogen can provide building heat supply in several possible ways. Blending hydrogen with natural gas (blending ratio of 5–20 %) using existing gas infrastructure and equipment

is a simple, cost-effective way to reduce emissions [22]. However, natural gas combustion releases emissions. Nonetheless, this type of hydrogen use will help scale-up hydrogen production, thus reducing hydrogen production costs [23]. For instance, from 2023, part of the gas network of the United Kingdom (UK) will be ready to use up to 20 % hydrogen blends [24]. According to IEA forecasts, the hydrogen consumption of buildings will account for 0.1–0.2 % of the sector's energy consumption in 2030. The following are other ways to provide building heat supply using hydrogen: methane production from pure hydrogen, direct use of pure hydrogen, and use of fuel cells and cogeneration.

5. Electricity generation. Hydrogen accounts for less than 0.2 % of global electricity generation. Gas turbines and reciprocating engines can use hydrogen. In the short run, co-firing with hydrogen or ammonia can lower emissions in current coal- and gas-fired power plants. The long-term flexibility or large-scale seasonal storage offered by hydrogen and ammonia-fired power plants can aid in the integration of changing renewable energy sources. The utilization of hydrogen in fuel cells and the co-firing of ammonia in coal-fired power plants will account for approximately 10 % and 6 %, respectively, of the project pipeline capacity by 2030 worldwide. Considering current trends, the demand for hydrogen for electricity generation is expected to remain quite low, approximately 0.3 Mt, until 2030. In the Announced Pledges Scenario, the hydrogen demand of the power sector will reach 5 Mt by 2030 [18]. According to project announcements, the capacity of hydrogen and ammonia-fired power generation may surpass 5800 MW by 2030, primarily from hydrogen co-fired in combined-cycle gas turbines.

2. METHODOLOGY

The methodology comprises two parts. First, desk research is conducted on the discussed topic. In this step, scientific sources are used, such as studies and publications from indexed databases of scientific articles, reports of independent organizations and industries, policy papers, and statistical data. The desk research is divided into two parts. First, the stakeholders engaged in the development of a hydrogen economy are identified in the context of barriers to hydrogen economy growth and potential solutions. Then, a systematic overview of the economic, political, technological, and social elements influencing a hydrogen economy is presented.

Second, we synthesize the findings of the literature review and visualize the relationships between stakeholders and the many factors affecting a hydrogen economy, ensuring that hydrogen technologies are adopted in a way that benefits society, the economy, and the environment while addressing the challenges and risks associated with their deployment. The research method is illustrated in Fig. 1.

Large amounts of material about ongoing work on hydrogen economy development, problems between different stakeholders, and factors impacting the continued growth of a hydrogen economy can be examined feasibly using the desk research approach. The literature review covers the years 2003–2023, but most of the scientific papers (>66 %) cover the years 2019–2023, especially 2022–2023.

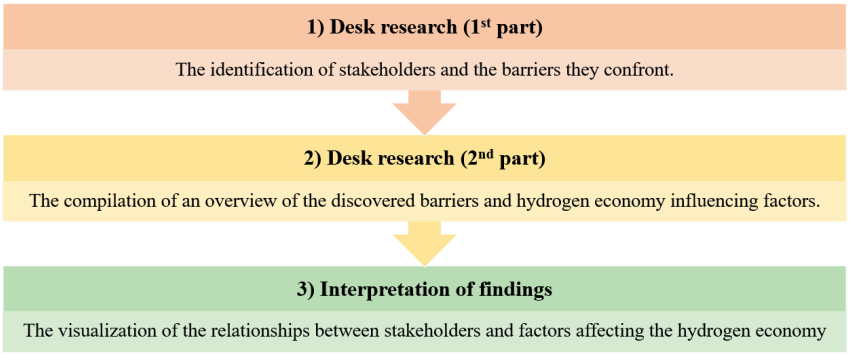


Fig. 1. Scheme of research method.

3. RESULTS

The introduction provides a brief overview of hydrogen use in several areas and potential developments. Based on the desk research results, this chapter provides a comprehensive, structured examination of the factors influencing hydrogen consumption.

3.1. Hydrogen Economy Stakeholders and Their Perception

Several studies have been published on the stakeholders involved in a hydrogen economy [25] and their different perspectives on the development of the hydrogen sector [9], [26], [27]. One of the most extensive studies on this subject was performed in Brazil. Chantre *et al.* distinguished five stakeholder groups: companies, public institutions, research centers, associations, and universities [9]. Based on a literature analysis and the results of interviews with 32 experts, they presented stakeholders' perspectives on the main barriers and needs of a hydrogen economy. Although opinions varied, economic viability was one of the most frequently mentioned barriers. The removal of hurdles for university and research centre stakeholders and the creation of incentives for scientific research were deemed critical. All respondents highlighted the significance of these institutions for generating knowledge and developing human resources. Interviewees from research centres and universities cited the absence of research and development (R&D) investments, political support, and incentives for infrastructure and market creation and enlargement as the main challenges in the development of a hydrogen economy. The study concludes that fostering a long-term policy framework will help increase the confidence of private investors. Furthermore, the maturity and market delivery of hydrogen technology can be accelerated by developing standards and regulations, increasing support for R&D, and removing barriers to market growth by creating dedicated funding programs [9].

Another stakeholder analysis through interviews was performed in Brazil by Aldara *et al.* [28]. They analysed the main routes and productive processes used in Brazil and the R&D of potential alternatives for fossil fuels, focusing on economic feasibility. The authors identified the following aspects of a hydrogen economy:

- Input and infrastructure (such as feedstock availability and infrastructure conditions for hydrogen storage and transport);
- Management (certification and standardization of products and processes involved in hydrogen production);

- Market and governance (the extent of the relationship of different hydrogen economy actors);
- Institutional environment (influence of sectoral policies), and technology (such as investments in R&D, technological maturity, and production costs).

Their results highlighted the value of funding R&D, innovation, and the spread of new technologies and the development of infrastructure for hydrogen production, distribution, storage, and transportation. Advances in the standardization and certification of hydrogen sectors and the initiation of relationships with established technology countries are required to build a national chain of component suppliers.

Stakeholder analysis related to a hydrogen economy was also conducted in Germany. In this study, 49 stakeholder groups were identified and analysed to determine the relationships, opportunities, and risks they perceive are crucial to a hydrogen market ramp-up. The paper also addresses the potential problems arising from the growth of a hydrogen economy in the fields of foreign policy, supply, consumption, and economics. The authors concluded that R&D, hydrogen technology providers, and electricity utilities are the most important stakeholder connections. R&D connects many otherwise unconnected groups and is therefore the most critical stakeholder group. Stakeholder groups from beyond the value chain, such as non-governmental organizations, energy service companies, public companies, and associations, can achieve a significant effect during market ramp-up [29]. Murray *et al.* also discussed the significance of R&D in the hydrogen field, concluding that a portfolio of demonstration projects should be created and that further obstacles are caused by a lack of demand for hydrogen in the end-use stage [30].

Denmark aims to foster a hydrogen economy by investing substantially in hydrogen research. Andreasen *et al.* identified Denmark's main stakeholders in a hydrogen economy and the conflicts between them [27]. They concluded that the path of hydrogen-related technologies toward maturity may be hindered by conflicts as stakeholders try to determine the direction of maturity [27]. Similar findings were obtained by a German study where approximately 30 % of respondents anticipated stakeholder conflict caused by technology preferences. One significant obstacle is a three-sided chicken-and-egg problem, which states that the future development of the hydrogen industry will be significantly slowed down by a lack of cooperation between the supply sector, customers, and infrastructure developers [29]. Nonetheless, Andreasen concluded that conflicts on the development of a hydrogen economy will compel stakeholders to find solutions that will satisfy all involved parties as much as possible, thus making the technology resilient and competitive [27].

The necessity of conducting various information campaigns that involve local officials, consumers, and other key stakeholders was covered by Gordon *et al.* [31]. They also discussed the importance of social acceptance challenges, such as the safety, cost, usability, convenience, and (thermal) comfort of hydrogen; the national and local contexts; the robustness of supply chains and skilled technicians; and the composition of stakeholder engagement. Additionally, the authors stated that investments in the R&D sector play a critical role in the scale-up of demonstration projects and that emerging supply chains are compromised by a lack of market confidence. Additionally, the paper underlines the necessity of public support and addresses society's lack of awareness regarding hydrogen technology.

3.2. Factors Influencing Hydrogen Demand

As the literature analysis reveals, the need for hydrogen varies by industry. Furthermore, hydrogen should be regarded not just as a feedstock for manufacturing and refining processes or as a transportation alternative to fossil fuels but also as an energy carrier in the context of

renewable energy storage (RES) power storage. The possibilities of energy accumulation using hydrogen are mostly related to energy transformation, which is closely related to the energy sector. Nevertheless, we highlight the possibility of using hydrogen separately, as the accumulated energy can be used in all sectors. Hydrogen is an efficient, cleanest, light fuel due to its high efficiency; thus, it is excellent for storing renewable energy, which is somewhat unpredictable due to seasonal or daily changes in solar and wind energies. Green hydrogen generation and utilization create RES prospects, hence broadening the use of renewable energy and boosting energy independence [32]. Hydrogen demand is important for determining not only future emission reduction but also the size of the necessary infrastructure and the required hydrogen supply volume [15].

Tao Ma *et al.* [15] were among the first to use system dynamics in the context of a hydrogen economy. Their developed model enables an analysis of China's medium- and long-term hydrogen demand against the economic sector's gross domestic product and energy consumption intensity. They concluded that the country's hydrogen demand is determined by factors that need to be studied besides the economic growth rate. In the second chapter of his book 'Solar Hydrogen Production', Benedetto Nastasi discusses the importance of the following deciding elements for the growth of a hydrogen economy [33]:

1. Market. Hydrogen price competitiveness is an important factor for demand increase. It may be influenced by demand stimulation, a higher CO_2 emission price, the development of hydrogen infrastructure, and assurance of long-term profitability, which can all be handled through political and regulatory initiatives;
2. R&D projects. The development of hydrogen alternatives, such as battery technology and technologies for large-scale storage, considerably influences the hydrogen demand potential. The growing market for renewable energy and the ability to accumulate the generated renewable (hydrogen) energy with relatively small losses are also vital. Thus, the rapid development of solar panels, wind power plants, and other renewable energy technologies also contributes to the demand for hydrogen [34]–[36];
3. Hydrogen policy. Large-scale energy system reforms require new hydrogen infrastructure and value chains, and regulation tools must be applied, such as government support and public funding [32], market-driven investments [37], confirmation of the origin of low-carbon hydrogen and evaluation of avoided carbon emissions [38], and limits for hydrogen blending in natural gas pipelines [39], [40].

The IEA-commissioned Global Hydrogen Review 2023 offers numerous ways to increase the demand for renewable hydrogen [13]. These options are divided into two categories; the first aims to increase the demand for existing hydrogen applications, and the second aims to create demand for new applications where other low-emission alternatives are limited and hydrogen can thus play a pivotal role in decarbonization. The review focuses on prices in the first category; it emphasizes the need to implement a carbon pricing market and supports the "polluter pays" concept and other support mechanisms that make the use of renewable hydrogen cheaper than the use of fossil hydrogen. This may be accomplished by promoting green hydrogen generation and raising taxes on fossil fuels, making ecologically friendly alternatives more competitive. About the use of hydrogen in new applications, the review underlines the importance of regulation, including the control of hydrogen use in new sectors and the development of standards. Moreover, it assesses the benefits of the rise of green hydrogen demand, which is affected by international collaboration and the establishment of national objectives [13].

In addition, the public's acceptance of hydrogen technology is an important variable in the growth of a hydrogen economy [41]. The following subsections cover the factors influencing hydrogen demand:

- Overall costs;
- Governmental institutions and their role in implementing hydrogen-related policies;
- Development of alternative technologies (primarily driven by the R&D industry);
- Level of public acceptability.

3.2.1. Cost Competitiveness

The most significant factor influencing hydrogen consumption is cost despite its wide-ranging ecological and social ramifications [31]. As hydrogen technologies become more cost competitive, so does the demand for hydrogen. The certainty of meeting the growing demand for hydrogen is based on many cost parameters, such as hydrogen technology costs (capital costs, operation and maintenance costs [OPEX], and raw material costs), infrastructure construction costs, the costs of other alternative fuels, fossil fuel prices, and CO_2 emission allowance prices [42]. The amount, source, and price of consumed electricity; the supply of photovoltaics and wind electricity; and investments in system components are the most crucial factors influencing the overall costs and environmental burdens of large-scale hydrogen production configurations [43]. The following subsections explain current costs in the hydrogen value chain and conclude with an overview of hydrogen cost competitiveness in the industries that contribute to hydrogen demand.

Hydrogen Production

The present costs of producing hydrogen using coal gasification and steam methane reformation are USD 0.90–2.11 and USD 0.75–3.49 per kilogram, respectively [44]. However, both methods do not produce hydrogen sustainably and require the use of carbon capture equipment. Some studies indicate that this technology raises the initial cost of hydrogen production by 7–18 %, but other studies indicate a price rise of up to 60 % [45], [46]. The capital cost of electrolysis technology, which can be used to produce renewable hydrogen, can vary significantly, ranging from USD 500 to USD 5,600 per kilowatt, depending on factors such as the electrolyser type and the associated installation expenses [13]. The primary factor influencing the production costs of green hydrogen is the substantial capital expenditure (CAPEX) related to the electrolyser, which entails a significant capital investment [31]. Therefore, the present cost of hydrogen production via electrolysis considerably varies, ranging from USD 0.98 to USD 23.27 per kilogram of H_2, with an average value of USD 6.62 per kilogram of H_2 [44].

Raw material prices affect hydrogen production, and electricity prices account for 60–80 % of green hydrogen costs, thus increasing the market volatility and investment risks of hydrogen production [47]. However, the availability and prices of coal and natural gas and CO_2 allowance prices considerably impact the future use of grey hydrogen (derived from fossil fuels) and blue hydrogen (derived from fossil fuels and pared with carbon capture and storage (CCS) technologies). The competitiveness of green hydrogen depends on reductions in electrolysis and renewable electricity costs and the availability of green hydrogen against the hydrogen demand; blue hydrogen costs depend on natural gas prices, residual emissions, carbon pricing, methane leakage, capture rates, and permanent CO_2 storage [48]. The future of blue hydrogen in a climate-neutral setting depends on the extent to which residual emissions can be avoided or compensated for via CO_2 removal and geological CO_2 storage.

Storage

Storing hydrogen is a substantial challenge with associated financial consequences apart from the costs involved in the production process. A hydrogen storage system's cost is greatly

impacted by several variables, such as the particular storage technology used, the mode of storage (onboard or offboard), the storage capacity, and the system's production volume. A 2007 study in India demonstrated that the levelized cost of underground storage was lower than those of other storage technologies, with the order being as follows: underground, compressed hydrogen, liquid hydrogen, and metal hydride [49]. Underground storage incurs low expenses due to its small capital costs and ability to accommodate bigger gas storage volumes over extended durations, resulting in lower costs per day. According to another study, the daily cost of storing hydrogen in salt caverns is approximately USD 0.14 per kilogram of H_2 [50]. By contrast, the levelized cost of small-scale hydrogen storage in the form of pressurized gas for a brief duration is approximately USD 0.19 per kg of H_2. This amount escalates by up to 10 times for extensive volume storage over longer seasonal periods. The use of metal hydride [49] for hydrogen storage incurs costs ranging from USD 0.4 to USD 4.0 per kilogram of H_2.

Transportation

Various methods can be used to transport hydrogen, among which pipeline transport is widely regarded as the most cost-effective means of large-scale gaseous hydrogen transportation due to its low maintenance expenses. Transporting liquid hydrogen via trucks and railways is viable, depending on the availability of these modes of transport [44]. Trucks are more cost-effective than trains for transporting gaseous hydrogen over short distances (less than 300 km) but are more costly over longer distances (more than 300 km) [51]. Due to the large capacity of trains, liquid hydrogen delivery by rail may be less expensive than trucking for large quantities of hydrogen. The influence of transit distance on gaseous hydrogen transport via pipelines is negligible. However, when the hydrogen flow rate is raised from 5 kg H_2/h to 45.4 kg H_2/h, the cost per kilogram of H_2 decreases considerably from USD 320.4 to only USD 0.1 [51]. Thus, gas pipelines can transmit hydrogen efficiently across short and long distances at a high flow rate [44]. The transportation costs of hydrogen in the UK were predicted to be USD 0.1–1, USD 0.5–2, USD 0.3–0.5, and USD 1.8–2 per kilogram of H_2 per 100 km for gaseous hydrogen via pipelines and gaseous hydrogen via tube trailers, trucks, and ships, respectively [44].

Infrastructure

The transportation industry has a huge potential for hydrogen usage. Infrastructure such as filling stations and the expenditures related to buying hydrogen-fuelled cars are also necessary for the use of hydrogen in the transportation industry. A hydrogen refuelling station's capital cost can range from USD 0.84 million to USD 7.84 million, depending on the infrastructure and configuration of the station, the type of vehicles to be refuelled, capacity (the mass and number of vehicles to be refuelled and the number of tube trailer connection points), operation conditions (temperature and pressure of delivery), and the installation country. According to estimates [44], the capital costs of refuelling stations in Europe are approximately USD 1.34 million for 150 kg/day capacity stations and USD 2.05 million for 700–1000 kg/day capacity stations. Due to low vehicle production, the unit manufacturing cost of fuel cell stacks is approximately EUR 175 per kW, which may be reduced by three times by increasing production to 100,000 units/year. The typical maintenance cost, such as that of battery electric cars, is roughly EUR 0.018 per km.

Future Perspective on Hydrogen Cost Competitiveness

Fast industrial development will occur when the costs of hydrogen become equal to or lower than those of current alternatives. In 2020, the Hydrogen Council published a paper titled

'Path to Hydrogen Competitiveness: A Cost Perspective' [52]. The report encompasses projections for the time frame in which renewable hydrogen is expected to achieve cost competitiveness. Furthermore, it provides a comprehensive analysis of the prevailing pricing of hydrogen technologies, categorized by segment [52]:

- According to the paper, hydrogen is now utilized as a feedstock in several industries where it is cost competitive, such as refining and ammonia and methanol production. Furthermore, hydrogen is expected to achieve cost competitiveness in steel manufacturing by 2030;
- In emerging hydrogen applications, the use of hydrogen has achieved competitiveness in the context of backup generation. However, hydrogen will shortly also attain competitiveness in simple cycle turbine usage. The forecasted trend suggests that hydrogen will experience enhanced competition in the domain of mid-grade heating beyond 2035. The usage of hydrogen in combined-cycle turbines and high-grade heating is projected to become more competitive around 2050;
- The report's data indicate that the use of hydrogen for building heat and power and its application in current and future networks (such as blending) will become economically viable by about 2030. The use of combined heating plants is expected to follow suit shortly after 2030;
- The transportation sector is expected to emerge as a rewarding hydrogen application. The use of hydrogen in regional trains, coaches, and heavy- and medium-duty vehicles can become cost competitive by the mid-2020s. Soon, the competitiveness of hydrogen use in various transportation sectors will improve. This competitiveness will initially (approximately within 2027–2030) be observed in applications such as taxis, long-distance buses, large passenger vehicles, sports utility vehicles, small ferries, and mid-sized long-range vehicles. Subsequently, between 2030 and 2035, the cost competitiveness of hydrogen will extend to include applications such as urban delivery vans, short-distance urban buses, large ferries, mid-sized short-range vehicles, and even synthetic fuels for aviation.

The least competitive applications of hydrogen include its use in small urban automobiles within the transportation sector and its use in distant power production for industrial purposes within the heat and power industry. Both applications will not achieve cost competitiveness by the year 2050 [52].

The predicted price decline induced by scale-up will drive the future growth of the use of hydrogen technology. The development of hydrogen technologies will boost demand, hence increasing manufacturing plant capacities while decreasing the OPEX [48], [52]. Supply chain scale-up will reduce the cost of hydrogen use for non-transportation applications by 90 %, whereas the manufacturing scale-up of end-use equipment will account for up to 70 % of cost reductions in transportation applications [52]. In terms of future costs, the Hydrogen Council predicts that a scale-up within five to ten years can reduce renewable hydrogen costs to approximately USD 1.0–1.5 per kg at optimal locations and to approximately USD 2–3 per kg under average conditions due to significant reductions in the electrolyser CAPEX (approximately 70–80 %) and renewables' levelized cost of energy [47]. The price of hydrogen fuel may be reduced by 60 % by 2030 due to future technical advancements [47].

Future price decreases will be influenced by learning curves/rates, which reflect technical development as a function of experience with the adopted technology [50], [53]. The acquisition of technical expertise will lower the required CAPEX. For example, in 2020, the total investment in projects related to hydrogen fuel cell vehicles was approximately USD 1,500 million, which is expected to increase in the coming years [44]. Nonetheless, far more financial resources are required. The availability of refuelling and distribution networks and

the cost differential between fuel cell tanks, hydrogen tanks, and low-carbon alternatives globally need an additional investment of USD 30 billion to overcome the economic gap [52]. Moreover, the cost differential between hydrogen and natural gas and the expenditures needed to develop or convert the first gas pipeline networks for hydrogen will total USD 17 billion by 2030 for buildings and industries; a total of 70 GW of electrolyser capacity must be installed to produce competitively renewable hydrogen via electrolysis, implying a cumulative amount of USD 20 billion needed with grey production [52].

The Hydrogen Council predicts that a scale-up will shortly lead to electrolyser learning rates for alkaline and proton exchange membrane technology of approximately 9 % and 13 %, respectively, whereas fuel cell stacks for passenger vehicles will have a learning rate of approximately 17 % [52]. Commercial vehicles will have lower learning rates, approximately 11 %, due to the lower volume of cars compared with private vehicles but will still benefit from a scale-up in other segments, which will considerably cut equipment prices across the hydrogen value chain. The total expenses for big passenger vehicles should fall by approximately 45 % by 2030 because of three major factors: reduced vehicle CAPEX, cheaper hydrogen distribution and retail, and lower hydrogen generation. Hydrogen distribution and retail costs account for most of the cost of hydrogen incurred by big passenger vehicle end users, accounting for approximately 60 % of the outlay. A value chain scale-up can result in an 11 % reduction in the total cost of ownership of a major passenger car. For example, increasing the utilization of hydrogen refuelling stations from 60 % to 80 % will reduce these stations' cost contribution by approximately 25 %.

Expenses also have associated risks. Market ramp-up risks and first-mover risks are expected, such as slow market dynamics, a low learning curve, and cost regression effects; uncertainty regarding demand and supply volumes, which was considered a risk by every fourth respondent in the study of David Schlund *et al.*, can be particularly problematic for stakeholders during hydrogen market ramp-up [29]. According to the same study, 54 % of stakeholders feel that the national government and economy should bear the risks associated with becoming a first-mover nation, which entails significant investments in R&D, facilities, and infrastructure [29]. Cost sharing during market ramp-up has also been highlighted in publications. For example, a study conducted in Poland found that the costs of CCS are unknown and may add to the challenges of CCS. This is why zero-emission coal-based power plants are deemed challenging, according to M. Luke Murray *et al.* study. The authors also underscored the uncertainty around the parties that will be responsible for paying for the CCS process, estimated plant costs, and transportation and sequestration problems [30].

Cost data suggest that green hydrogen is not yet competitive relative to other fuels and grey hydrogen. Assistance is required to end the current reliance of hydrogen consumption on fossil raw materials (which will continuously increase CO_2) considering the price difference between green and fossil hydrogen. Decision-makers should consider whether fiscal and regulatory policy tools may be used to influence price difference as soon as possible to limit the development of fossil hydrogen capacity. Supporting the development and use of renewable hydrogen and outlining the position to utilize this form of hydrogen in the future will help reduce the fossil hydrogen production capacity and accelerate the transition to renewable fuels.

3.2.2. Strength of Policy

Considering the current inability of green hydrogen to compete with other alternatives in many sectors and directions of use, policies must be developed for hydrogen technologies to be adopted by the market. The IEA's 'The Future of Hydrogen' report identifies five policy initiatives that are required by 2030: establishing long-term signals to foster investor

confidence; stimulating commercial demand for hydrogen in multiple applications; helping mitigate salient risks, such as value chain complexity; promoting R&D and knowledge sharing; and harmonizing standards and removing barriers [19].

Solutions for policy implementation have been explored on regional and national scales. A total of 41 nations, accounting for roughly 80 % of worldwide energy-related CO_2 emissions, are already implementing hydrogen plans [13]. The following outlines the objectives that the United States (US), South Korea, Japan, and the EU have set for the development of hydrogen technology, demonstrating the global diversity of this field.

One such example is the hydrogen development program of the US and the 'Road Map to a US Hydrogen Economy', which identifies four stages of hydrogen economy development and realistic goals:

- The 'immediate next steps' (2020–2022), or the establishment of reliable, technology-neutral decarbonization targets;
- The 'early scale-up' phase (2023–2025), which calls for the development of large-scale hydrogen production, thus reducing costs;
- The 'diversification' phase (2026–2030), which focuses on extending hydrogen use across different applications;
- Widespread deployment throughout the US after 2030. This approach emphasizes that hydrogen technologies are not yet common enough and, similar to other technologies, will also have to undergo the Rogers innovation diffusion curve [45] and associated challenges.

In general, the adoption of a proper policy framework significantly influences the development of new technologies, particularly during the implementation of research prototypes and the early stages of commercialization [54]. The effective use of incurred expenditures necessitates the formulation of an appropriate policy (strategy) for the hydrogenation of the economy, which includes public administration support, assurance of stable investment conditions, and the necessary regulatory conditions in addition to precisely defined long-term objectives [54].

Despite the absence of domestic clean hydrogen production in South Korea, where all 220 000 metric tons generated in 2020 were derived from fossil fuels (grey hydrogen), the country has set an ambitious target of supplying 27.9 million metric tons of hydrogen per year by 2050 [55]. This objective will be achieved through the production of 3 million metric tons of green hydrogen per year and 2 million metric tons of blue hydrogen per year alongside the importation of 22.9 million metric tons per year of green hydrogen from international sources. Notably, South Korea's hydrogen supply will exclusively consist of green and blue hydrogen [55]. By implementing this strategy, South Korea aims to obtain approximately one-third of its energy from hydrogen by 2050, therefore establishing hydrogen as the predominant energy source in the country.

Japan has also proposed strategies for the establishment of a 'hydrogen society,' wherein hydrogen plays a prominent role in the nation's secondary energy infrastructure, as outlined in its Strategic Energy Plan [56]. Japan's 6th Strategic Energy Plan aims to decrease hydrogen costs from the current JPY 100 /Nm^3 to JPY 30/Nm^3 in 2030 and to no more than JPY 20/Nm^3 in 2050; it also aims to increase hydrogen supply from the current approximately 2 million tons/year to a maximum of 3 million tons/year in 2030 and to 20 million tons/year in 2050 [57]. To implement this plan, Japan intends to:

- Increase the use of hydrogen on the demand side (power, transportation, industry, and consumer sectors);
- In the power generation sector, the demonstration of co-firing/single-fuel firing will be promoted, an environment will be prepared for the appropriate assessment of non-

fossil value, and a 1 % hydrogen/ammonia power generation mix is planned for the fiscal year 2030;
- In the transportation sector, the demonstration of co-firing/single-fuel firing will be promoted, and an environment will be prepared for the appropriate assessment of non-fossil value;
- The large-scale diversion of manufacturing processes, such as hydrogen-reduced iron making, and the technology development of burners and large, highly functional hydrogen-fired boilers will be addressed based on combustion characteristics;
- Technology development toward the cost reduction and expansion of stationary fuel cells, including pure hydrogen fuel cells, will be addressed in the industry sector [57].

A regional policy is evident within the EU framework. The EU adopted the European Hydrogen Strategy in 2020 [58]. The strategy outlines 20 key actions, including financial (such as the Clean Hydrogen Alliance Investment Platform), regulatory (taxonomy regulation, Fit for 55 package incentives, and the REPowerEU Plan), and research (such as the European Clean Hydrogen Innovation Partnership) initiatives. The European objective regarding hydrogen involves constructing 17.5 GW of electrolyzers by 2025 to supply energy to the EU industry sector by producing 10 Mt of renewable hydrogen domestically and importing an additional 10 Mt by 2030. Furthermore, the EU objective entails developing a contemporary regulatory framework for hydrogen and constructing the required infrastructure, such as storage facilities and ports. Recently, the European Commission (EC) announced the creation of the European Hydrogen Bank, an EU public support measure designed to kickstart the hydrogen economy by acting as a major funding scheme to ramp-up the hydrogen value chain [59].

From a system perspective, the EU hydrogen policy is largely driven by the need to achieve climate neutrality and therefore can be described as based on the 'distance' between the desired goal and the current situation [59]. The greater the difference between the achieved and required CO_2 emission reduction (worse situation), the stronger the policy. The smaller the difference between the achieved and required CO_2 emission reduction, the weaker the policy. Policy strength affects several sectors, such as energy demand ([39], [40]), price drivers (including tax and CO_2 price increases and financial support in different stages of the hydrogen supply chain), infrastructure support policy, and additional investment in R&D.

Several researchers have analysed the hydrogen sector through system dynamics modelling, specifically for an analysis of policy support in the field of hydrogen. Li *et al.* found that greater support consisting of different mechanisms is necessary for the initial stages of hydrogen use to ensure rapid development, followed in subsequent years by dynamic policy adjustments and subsidy reductions in line with progress [32]. Jiayang Gao *et al.*, who based their analysis on California market data, presented a similar conclusion. Their article states that moderate public funding is required to establish the scale of application of on-site hydrogen production technology in the early stages of market development and provide a buffer time for technology upgrading; moreover, they explained that excessive subsidy amounts and durations will stagnate supply and increase demand [14].

Aside from providing a policy framework for national goals, fostering cross-national collaboration is critical to the establishment of a hydrogen economy [17]. The advancement of hydrogen technology will help form international collaborations between various countries, thus boosting the chances of establishing a hydrogen economy. The International Partnership for Hydrogen and Fuel Cells in the Economy is an example of such a collaboration [60]. This organization was established to aid in the transition to sustainable energy and hydrogen-based mobility systems. Australia, Canada, the EC, India, the Netherlands, Switzerland, Austria, Chile, France, Italy, Norway, the United Arab Emirates, Belgium,

China, Germany, Japan, the Republic of South Africa, the UK, Brazil, Costa Rica, Iceland, the Republic of Korea, Singapore, and the US are members of this organization.

3.2.3. Impact of R&D

Further study is required to further enhance the effectiveness of hydrogen generation techniques while addressing related issues, such as cost and scalability. A previous study highlights how crucial it is for governments, businesses, and academic institutions to cooperate to spur innovation and accelerate the switch to renewable hydrogen generation [61]. The introduction of hydrogen energy technologies requires increasing public expectations and establishing R&D networks [9], [15], [62], [63], as confirmed by our preceding stakeholder analysis. The establishment of a specific funding program can be a powerful tool to bind academia and industry together quickly and effectively through the creation of customized solutions for the hydrogen market [9]. Investments in hydrogen technologies are needed to foster energy-efficient solutions across diverse industries as fuel cells emerge as promising alternatives to internal combustion engines, with the total energy use significantly influencing the need for such financial support. The origin of such investments may encompass both governmental backing and private-sector initiatives. This was confirmed by Yoo and Park in their study, where they analysed the history of national R&D programs in the development and commercialization of hydrogen energy technologies by studying national hydrogen vehicle development projects in Korea over the last three decades and how they have evolved with changes in the country's technological and economic levels [62]. They concluded that after commercialization, government-funded R&D projects developed cooperative networks, which then became a value chain network.

The development of renewable energy supply chains is significant, as CO_2 emissions and hydrogen production have a strong synergy due to the wide use of fossil fuels for hydrogen production. Emission reductions across the full value chain of hydrogen technologies may be possible in the distant future, but environmental policy should encourage the use of low- and zero-emission technologies and fuels [64].

The amount of R&D investment in renewable energy technology will improve the renewable energy output, and higher renewable energy production will reduce the carbon emissions of the energy sector [65]. Lower carbon emissions will promote R&D investment, which will enhance the energy output of renewable sources [65]. Thus, investment in energy technology R&D for hydrogen and fuel cells is highly correlated with CO_2 emissions [64].

The prospect of future relative profitability also drives R&D investment in a certain powertrain. Any potential future penalties for failing to achieve emissions limits are utilized as an extra impetus for investment in powertrains that are most likely to cut emissions. Investment in such powertrains is further encouraged by potential future fines for failure to meet emissions targets [17]. This takes the form of a straightforward monetary increase in the potential value of R&D, weighted by the potential environmental improvement of the engine. Avoiding future fines means higher revenues for businesses; therefore, investing in components that contribute considerably to carbon reduction is consistent with the present stance of the European industry [17].

The impact of R&D-supporting activities may be quantified by assessing the quantity of newly granted patents. The basis of the market for inventions is provided by patents, which facilitate the market's establishment in several crucial ways, including by encouraging the financing of inventions and innovation. The development of new, improved techniques for producing hydrogen has become increasingly popular in recent years, and numerous businesses and researchers have filed relevant patents [61]. The data show a rising interest

and investment in the development of greener, more sustainable methods of producing hydrogen [61].

3.2.4. Social Acceptance

Social factors, such as public acceptance, are important for the implementation of any new technology. According to the theory of diffusion [66], potential users of a technology become aware of it, are convinced of its benefits, and then choose to adopt and buy it. In other words, public acceptance occurs over time in five distinct stages: knowledge, persuasion, decision, implementation, and confirmation. If customers are satisfied during the confirmation stage, they will continue using the technology; otherwise, they will reject it [67]. This demonstrates the value of knowledge, without which new technology cannot be introduced to the market. Thus, people's mistrust of the safety of hydrogen technologies is also a barrier that should be addressed [9], [68]. Such mistrust is mostly caused by a lack of knowledge. According to Kyoko Ono *et al.*, risk information increases the acceptability of hydrogen refuelling stations next to home hydrogen refuelling stations. They concluded that good risk communication should be implemented before the installation of a hydrogen refuelling station because receiving risk information about such stations alleviates people's dread or uncertainty [69]. Furthermore, pro-environmental education among the youth will positively influence the transition to renewable energy sources, help ensure planetary justice over the long run [70], and help develop renewable technologies and resilient energy systems in production companies [71].

Justice is another important social factor that needs to be considered when developing a hydrogen economy. Dillman *et al.* assessed the inequity in the hydrogen value chain that may arise during the implementation of a hydrogen economy [72]. They found potential injustice in several areas, including unjust decision-making, socially irresponsible development, and poor distribution of misfortunes and benefits in the field of consumption. The authors emphasized the role of hydrogen in creating a green future and the resulting need for a hydrogen economy to experience a rapid rise in the coming years. Nonetheless, they explained that although a ‘move fast and break things’ mentality may be necessary for this rapid scale-up, decision-makers should question not only the green-ness of planned strategies but also their social fairness by evaluating the potential social pitfalls of a hydrogen transition. Recognizing and reducing these inequities during the development of a hydrogen economy should encourage public support for its spread.

A strengths–weaknesses–opportunities–threats study by Youhyun Lee *et al.* analyses the public acceptance of H_2 stations. Interviews with 20 experts highlighted such strengths as driver convenience, reduction of fine dust, and a positive response to climate change. The authors identified the safety of this technology as the biggest hindrance to the wide implementation of hydrogen technology [11]. In this regard, Crowl and Jo compared hydrogen and methane [73]. Hydrogen has an increased flammability range, a lower ignition energy, and a higher deflagration index; based on physical properties alone, primarily due to the increased probability of ignition, these characteristics pose an increased risk compared with gasoline and methane. The study also mentions the safety risks associated with the use of hydrogen, particularly its colourless (and thus difficult to detect) flame and its self-heating properties when it leaks from a high-pressure source. Many studies state that the safety of the use of hydrogen technology should be improved by implementing political decisions that will organize this industry, such as technical and safety standards (particularly for hydrogen transport and storage [38], as well as improved hydrogen safety [68], and human resource training [9]), provide risk management, and establish clear permitting processes [19], [74].

Another issue is that such policy decisions, which society does not understand and/or is not ready to implement, can cause a pushback effect, which is a type of information feedback to the government about the public's acceptance of its governance. The amount of pushback is determined by the balance between the strength of the policy push and the difficulty for actors to comply with the policy. Public opposition to unpopular policies should be considered because an increase in societal pushback to such policies may delay the achievement of targets by 10 years; the target can even be missed altogether if such opposition were combined with a higher-than-expected difficulty of executing critical measures [75], [76]. The implementation difficulty of a measure implies that adopting an overly ambitious policy in a short time generates challenges in execution, but this difficulty will diminish as society's experience grows.

4. DISCUSSION AND CONCLUSIONS

The increasing academic interest, political efforts, and industry developments in the field of hydrogen indicate the emerging role of hydrogen in energy transition and decarbonization. However, green hydrogen still encounters many challenges across the value chain, including hydrogen production, storage, infrastructure, and application. In addition to technological and economic issues, social and communication challenges must be resolved.

Here, we conduct desk research on the factors influencing the development of a hydrogen economy to understand existing barriers, identify stakeholders, and determine development directions. This section summarizes the most important conclusions, offers a visualization of our results, and discusses future research directions.

Fig. 2 schematically illustrates the interconnections among the stakeholders and emphasizes the outlined barriers in the desk research, their corresponding solutions, and the specific stakeholder groups accountable for implementing such solutions. The results show that all stakeholder groups emphasize, in addition to technological maturity, the necessity of increased political support for the successful implementation of a hydrogen economy, particularly concerning its barriers. For instance, for the companies accountable for ensuring the accessibility of hydrogen to end users, the primary concerns are economic viability, which can be addressed through investments in R&D initiatives, and the formation of partnerships between private companies and academic institutions. From the proposed solutions, we can distinguish support for and investment in the R&D sector, collaboration between private companies and academia, and the formulation of national hydrogen strategies; many studies (such as [9], [39], [53], [54], and [77]) state that the implementation of a proper policy framework has a major impact on the development of new technologies.

Fig. 3 illustrates the links between the stakeholders and influencing factors within the context of the green hydrogen economy considering the barriers in Fig. 2. The yellow, red, purple, blue, and green boxes in Fig. 3 denote parameters linked to hydrogen demand, policy, R&D, the economy, and the social component, respectively. Several stakeholders also appear in this figure; *public institutions* are responsible for the support of other stakeholders and, with the influence of university representatives, the formulation of policies. *Companies' stakeholder* interests appear in the production and use of hydrogen, which in turn are influenced by the interests of *society*, whereas the *R&D sector* affects cost reductions and the preparation of human resources.

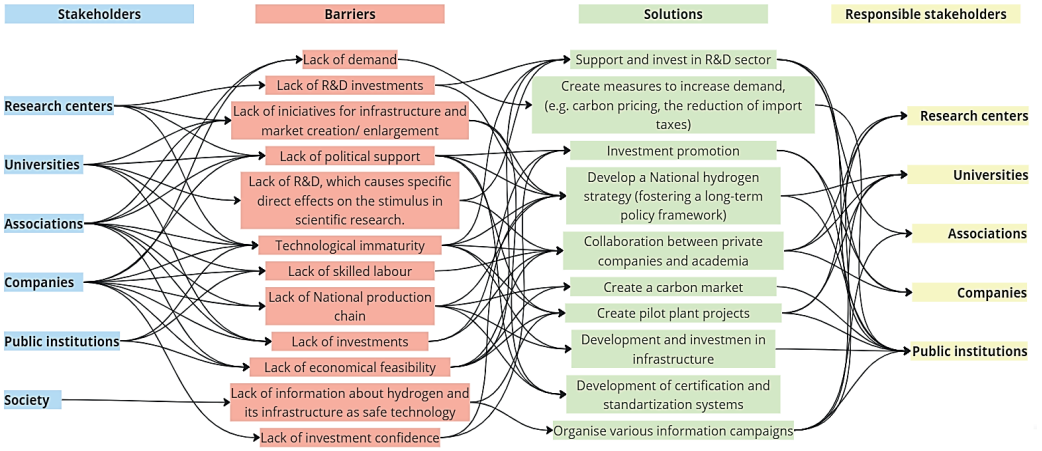


Fig. 2. Diagram of hydrogen economy barriers and stakeholder relationships.

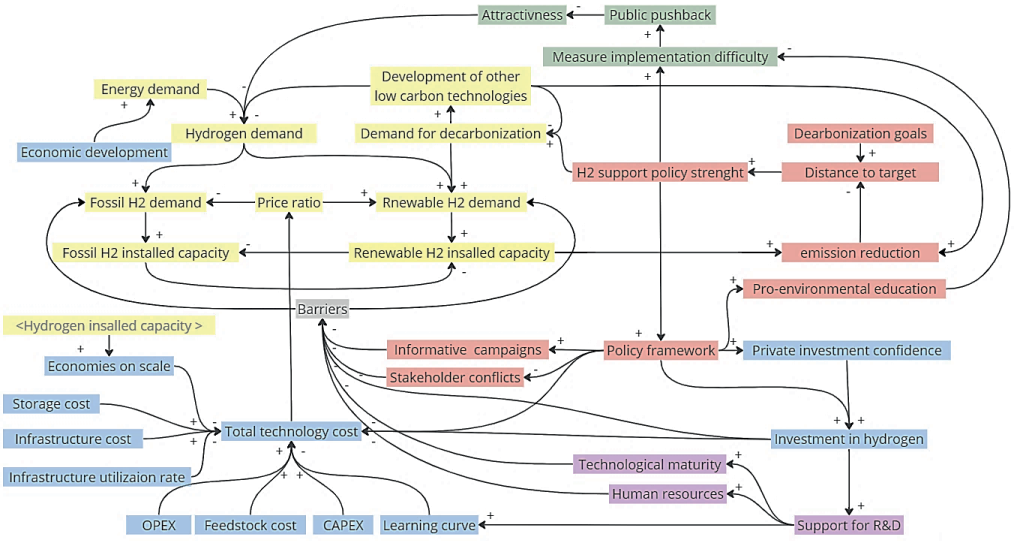


Fig. 3. Causal loop diagram of simplified system dynamic model structure. The parameters in the yellow, red, purple, blue, and green boxes are linked to hydrogen demand, policy, R&D, the economy, and the social component, respectively.

The central component of the system is the (yellow) transition from conventional hydrogen production methods, which rely on fossil fuels, to green hydrogen, which is generated via electrolysis and the use of renewable energy sources. The production of fossil hydrogen is currently a source of CO_2 emissions. The anticipated increase in the hydrogen consumption of the industry, refining, and transportation sectors will enhance the total amount of CO_2 emissions, making the transition to green hydrogen critical. The greater (smaller) the installed capacity of green hydrogen production, the smaller (higher) the required installed capacity of fossil hydrogen. Several important factors influence this transition.

First is the issue of cost, which can be characterized by the cost ratio of fossil and green hydrogen. One of the most frequently mentioned barriers to the development of a hydrogen

economy is economic viability. The price-related components are in the blue boxes in Fig. 3. The diagram depicts not only the elements determining the two hydrogen technology costs (renewable and fossil) but also the factors influencing their reduction. The feedstock prices, CAPEX, and OPEX of hydrogen production technologies contribute to the overall cost of hydrogen production. The total technology cost is influenced by storage and infrastructure costs, which include hydrogen transportation and distribution costs, besides production costs. As shown by the schematic illustration, the total technology cost encompasses a range of expenditures related to storage, infrastructure, and renewable and fossil hydrogen production (including the CAPEX, OPEX, storage, and feedstock costs). This comprehensive perspective corresponds to the subsequent correlation for each type of hydrogen with the price ratio. For example, the term 'feedstock cost' describes changes in the availability of resources for hydrogen generation, implying changes in feedstock pricing. The raw elements required to manufacture green hydrogen, such as renewable electricity and water, are considered in the defined model. The sun, hydropower plants, and wind energy are deemed primary sources of renewable electricity generation. Natural gas is the primary raw material used to manufacture grey hydrogen.

As discussed, fossil hydrogen is currently cheaper than green hydrogen; therefore, considering the price difference between green and fossil hydrogen, existing hydrogen consumption will continue to be based on fossil raw materials, thus contributing to an increase in emissions, unless policy support is provided. Fiscal and regulatory policy tools must be implemented as soon as possible to limit the expansion of the required fossil hydrogen capacity. In Fig. 3, the policy sector, which is responsible for the implementation of support measures, is colour coded red.

The starting point of the policy objective, that is, the reasons for using hydrogen, shows that the price ratio between green and fossil hydrogen may not be the first determining factor of hydrogen use. If hydrogen use were encouraged through decarbonization policies (such as in difficult-to-decarbonize sectors), a higher price would be acceptable because fossil hydrogen will fail to meet targets. Thus, the strength of policies promoting the use of green hydrogen for the decarbonization of economic sectors is critical.

However, hydrogen competes with other zero-emission energy resources and technologies in the context of decarbonization, and this circumstance acts as a balancing loop. Therefore, green hydrogen will likely be a niche product in certain industries [74]. The hydrogen demand sectors and the determinants within them that may influence hydrogen demand should then be explored in detail. For example, in the transportation sector, hydrogen technology is tightly competing with electric transport. Even though both are emission-free technologies, using hydrogen has higher technical and socioeconomic barriers, so it cannot be assumed to develop at the same rate as other green technologies in situations with policy-supported green technologies. It competes not only with fossil alternatives but also with green alternatives that are cheaper and easier to use. Therefore, hydrogen may be relevant in certain niche markets that need to be affected by specific policy instruments that are not included in the loop diagram (such as support for the production of e-fuels or low-emission heavy commercial transport). Furthermore, according to Gunther Glenk *et al.*, the observed learning curves for specific clean energy technologies reinforce each other in accelerating the transition to a decarbonized energy sector [78].

Policy now focuses on measures to build a common hydrogen policy framework, remove existing barriers, and boost private investment rather than on the fact that hydrogen is obtained from renewable energy sources. Hence, additional research on the function of green hydrogen in supporting regional development, in addition to the benefits of decarbonization, is required to demonstrate the necessity of green hydrogen development. Further study will

also help policymakers identify the sectors that should be prioritized to enhance the role of green hydrogen.

The literature analysis shows that the introduction of renewable hydrogen in the market entails the formulation of a long-term policy framework for determining national goals, standards, regulations, and support mechanisms for the production and further use of renewable hydrogen. This action of public institution stakeholders will allow them to increase the confidence of private investors, which represents the interests of private companies' stakeholders. Consequently, this will improve investments in hydrogen technologies and support for the R&D sector by assisting stakeholders from research centres. This action will contribute to future cost reduction. Prices are influenced by policy support, which affects costs through taxes; fossil hydrogen can be made less competitive through CO_2 allowance prices and other taxes, and renewable hydrogen production can be supported through tax incentives. Policy support can also be used to improve investment in technology development and create a safe environment that encourages independent companies to invest heavily in hydrogen technologies and related R&D (purple in Fig. 3). Government and corporate R&D investments are critical because they accelerate learning, which leads to additional price reductions [78], [79]. In particular settings, sustained significant learning curves imply a significantly faster hydrogen cost drop than the 80 % price reduction caused by further learning curve [78]. Moreover, the R&D industry contributes significantly to human resource preparation [9]. Furthermore, a price reduction is impacted by variables such as economies of scale, which are mostly driven by capacity development [80], [81] and may be achieved by strengthening regulations, eliminating current barriers (Fig. 2), and lowering the renewable/fossil hydrogen price ratio.

One of the barriers to green hydrogen generation and consumption is social acceptability, which is heavily influenced by governmental decisions (green in Fig. 3). Knowledge is extremely valuable because people doubt new technologies without it. This, along with overly strict, unpopular policies, may result in a pushback effect, delaying the achievement of national targets [75], [76]. The implementation difficulty of measures implies that adopting an overly ambitious policy in a short period creates execution challenges; however, as society's experience grows, these difficulties decrease. In the development of a policy framework, pro-environmental education programs must be included to increase citizens' understanding of new technologies [70].

This paper provides a comprehensive literature review on the factors influencing a hydrogen economy, presents a diagram of the barriers to such an economy and the relationships between its stakeholders (Fig. 2), and shows a causal loop diagram (Fig. 3) of the interconnections among the stakeholders and influencing factors. This study emphasizes the critical need for increased political support, particularly in addressing stakeholder concerns about technological immaturity and economic viability. The proposed solutions, which include R&D funding, collaboration between private companies and academia, and the development of national hydrogen strategies, highlight the critical role of a well-defined policy framework in advancing a green hydrogen economy. These findings contribute to a comprehensive understanding of the complex hydrogen value chain, providing valuable insights for both academics and policymakers seeking informed strategies for long-term hydrogen development. One potential future research direction is an in-depth examination of the numerous factors that lead to social acceptance in the context of green hydrogen.

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Local-Level Challenges in Sustainable Mobility: Survey Results from the Baltic Sea Region

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***Abstract* – Transportation is a substantial source of greenhouse gas emissions; therefore, achieving climate neutrality requires focus on sustainable transportation. An assessment of the literature indicates that municipalities can successfully implement sustainable transportation legislation and encourage behavioural shifts toward lower-emission mobility options by tailoring solutions to their community's specific needs. This study examines travel patterns, reasons for mobility, and transportation mode choices in four European countries – Latvia, Estonia, Poland, and Sweden – using survey data from 1151 respondents in selected municipalities. Notably, Estonia and Latvia showed a stronger preference for cycling, while private car use remained dominant in all regions, contributing to environmental concerns. The survey also investigated the elements that influence travel mode choices, and the most important ones were distance, journey time, comfort, convenience, and public transit availability. The study also includes an assessment of respondents' willingness to support various policies, based on the Avoid–Shift–Improve approach. While the support for sustainable transportation policies varies by country, the findings show a widespread desire for improved public transportation, pedestrian-friendly urban planning, and remote work options to reduce commuting. Municipalities must also address issues such as housing and job disparities as well as a lack of efficient public transportation in rural areas. These findings provide guidance to policymakers aiming to promote sustainable mobility and reduce transportation-related emissions, with an emphasis on measures tailored to regional contexts.**

***Keywords* – ASI; emission reduction; EU member states; public opinion; sustainable mobility; transportation policy; travel patterns.**

1. INTRODUCTION

Transportation accounts for over 33 % of global carbon dioxide (CO_2) emissions from energy-consuming sectors and remains one of the most challenging sectors to impact. Furthermore, the most significant increase in emissions is observed in road transportation, which contributed almost 75 % of total transportation emissions in 2022 globally and 73.2 % in the European Union [1], [2].

The European Union's (EU) transport sector is also the most difficult to decarbonize, with emissions increasing rather than reducing, as planned by the Green Deal. The observed trend indicates that emissions from the transportation sector in 2022 increased by 26 % compared

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to 1990 [2]. In total, nearly 1044 million tonnes of CO_2eq were emitted in 2022, with road transport fuel combustion accounting for approximately 760 million tonnes, the largest emission source in the transport sector, followed by navigation (14.2 %), civil aviation (11.8 %), other transport (0.5 %), and rail transport (0.3 %) [2]. In road transport, passenger cars and motorbikes accounted for the majority of emissions (60 %), followed by heavy-duty trucks and buses (27 %), and light-duty trucks (12 %) [2].

The increase in transport sector emissions is influenced by several factors, including population increase and economic growth [3], [4]. Both factors increased the demand for transportation, leading to higher emissions. Urbanization and rising private vehicle affordability are two more factors contributing to an increase in vehicle numbers and associated emissions [3], [5]. It is also a significant factor because the transport sector is mostly based on fossil fuels [3], [4], [6]. Consequently, the proportion of internal combustion engine vehicles in the EU remains high, even though the average emissions per vehicle are decreasing, a trend that is primarily attributed to the transition to electric vehicles [7]. In 2023, electric cars accounted for 22.7 % of new car registrations and 7.7 % of new van registrations [8].

A municipality, as the lowest-level administrative division of local government, holds primary responsibility for devising and executing strategies tailored to its specific geographic location. Despite fundamental laws being adopted at the national level, it has the capacity to influence transportation sector emissions [9],[10]. For instance, they can improve the range of public transportation options, encourage citizens to be more environmentally conscious, or create an urban environment that is friendly to cyclists and pedestrians [11]. However, government regulations, available technology and their costs are frequently given more attention to research on transport infrastructure development, and stakeholder significance is frequently undervalued. For example, in the Estonian Energy Roadmap to carbon neutrality, it was identified that, while carbon neutrality is achievable in the heat and electricity generation sectors, it is not achievable in the transportation sector in 2040 for Estonia, even with significant investment [12]. Cooperation from all stakeholders, including government agencies that maintain order and justice, private companies that guarantee service availability, and local citizens who will be the end users of the established systems, are crucial to ensuring that the decisions made not only satisfy the majority but also achieve the objectives of decarbonization [13], [14]. For this reason, in addition to implementing best practices, the introduced innovations must be adjusted to the municipality's characteristics and the population needs to ensure meeting the municipality's climate neutrality objectives [11]. This suggests that to effectively manage travel demand, municipalities need to develop a clear transportation policy plan based on a thorough understanding of the specific travel habits of their citizens [9].

Municipalities have the potential to be agents of change and driving forces for the energy shift, but for this to happen, it is necessary to evaluate the effectiveness of various policies and their support in society [15], [16]. This signifies that to obtain noticeable results in the implementation of low-carbon mobility, it is essential to enforce policies that guarantee emission reduction and public acceptance [17], [18].

The avoid-shift-improve (ASI) framework is widely used to structure policies aimed at reducing transportation-related emissions and developing sustainable transportation. It emphasizes three key strategies: avoiding unnecessary travel, encouraging a shift to more environmentally friendly modes of transportation, and improving the effectiveness of current transport systems [19]. Studies have shown that combining all the mentioned strategies enhances their effectiveness.

While all three strategies are important, current energy and transportation policies frequently underrepresent "avoid" policies despite their potential [19] due to implementation complexities, societal resistance, and limited municipal control over land-use planning [20] According to research, citizens prefer and support visible infrastructure improvements (a shift measure) or technological improvements (improve measures) over policies that require significant changes in travel habits or patterns. This is because the implementation of mentioned measures, such as infrastructure improvements, is visible, and citizens can easily recognize tangible benefits [21] that can boost their sense of safety [22] and fairness [23]. Furthermore, large infrastructure projects are frequently associated with increased economic growth, as they can raise property prices, which can be recognized by citizens [24]. At the same time, citizens struggle to accept policies that require lifestyle and behavioural changes [25].

The literature suggests that assessing local residents' preferences is essential for determining the true effectiveness and acceptance of ASI policies, as well as providing municipalities with tailored insights required for successful implementation. This study aims to analyse travel patterns, reasons for mobility, and the choice of transportation modes in four European countries (Latvia, Estonia, Poland, and Sweden). The study offers a new contribution to the literature by analysing municipal-level mobility habits and policy choices in four Baltic Sea countries. Using survey data, this study seeks to evaluate public opinion on existing transportation policy measures, identify preferred policies, and highlight regional differences. The ultimate goal is to provide insights that will help policymakers to promote sustainable mobility and reduce transportation-related emissions. The survey was conducted within the framework of the interregional Interreg Baltic Sea region (BSR) project "CommitClimate" (Towards Energy Transition and Climate Neutrality in the BSR municipalities).

The rest of this paper is organised as follows. Section 2 contains an overview of the methodology and the characteristics of the respondents. The results are presented in section 3. Section 4 outlines the main findings, defines policy recommendations, and examines prospective future research.

2. METHODOLOGY

Within the research methodology a survey was conducted. The survey focused on public perception of municipal policies and initiatives designed to alleviate the environmental effects of the transportation sector. An online questionnaire was developed and disseminated as part of the international project across four EU member states: Latvia (Riga and Cēsis municipalities, as well as at the national level), Estonia (national level), Sweden (Jokkmokk, Pajala, Gallivare, and Kiruna municipalities), and Poland (Pałecznica municipality). The objective of the survey was to establish respondents' perceptions of how much their municipality fosters a greener way of life among its residents, as well as the changes that must be taken to achieve climate mitigation methods. One of the goals of the project is to raise residents' understanding and confidence in the importance of their behaviour and choices in the context of municipal climate neutrality.

In total, there were six sections in the survey; however, the current study includes data from the first three sections, which are explained in more detail below. The first section included questions regarding the respondents' characteristics, such as sociodemographic and household descriptions. The questions in the second section focused on respondents' travel patterns. In the third section, respondents were asked to evaluate the municipality's actions in the transportation sector and select the steps they would be willing to support in their

municipality to reduce the environmental impact of transportation. The results of the sections describing the energy sector (Section 4), waste management (Section 5) and respondents' opinions on environmental protection (Section 6) are not covered in this work.

The respondents were asked various questions, including rating questions that required them to assess their current condition with one answer and questions with one or more options, such as those regarding their most used transport mode. The respondents were also free to share their opinions on the survey topic. Such open-ended questions provide additional opportunities for respondents to highlight the most significant factors influencing transportation choices. In the policy evaluation section, respondents were asked to choose which of 20 policies they wanted to support the most. In addition, respondents had the option of suggesting their own policy instrument by selecting the 'other' option.

A total of 1151 answers were collected, including the results of 258 responders from Sweden, 500 from Estonia, 308 from Latvia, and 85 from Poland. The survey was conducted from December 2023 to January 2024. Representatives of the local government administered the survey both online and by distributing paper forms, whereas in Estonia, the survey was administrated by a third party. The questionnaire was distributed on local government social media platforms and official websites.

3. RESULTS

3.1. Characteristics of Respondents

Annex 1 describes the respondents' sociodemographic characteristics. This demonstrates that even though people of various ages participated in the study, the average age of respondents in Poland and Latvia was 42 and 43 years, respectively, which is younger than in Estonia and Sweden, where the average age was 51 and 52 years, respectively. Further analysis of the results will be based on two important parameters – the age group of the population and the place of residence – urban (that includes respondents from cities and suburban areas) and rural areas.

3.2. Travel Patterns

According to the results (see Annex 2), most respondents in Latvia and Sweden commute every day (75.6 % and 71.3 %, respectively). Similarly, in Poland, most respondents (64.7 %) commute daily. Meanwhile, only 37 % of Estonian respondents reported that they commute every day and 25.2 % chose to commute to 3–5 times a week.

Regarding the commuting causes (see Annex 3), results showed that the main purpose of travel in all four countries is going to and from work. Shopping was the second most common response, followed by recreation and entertainment. There is a major variation in Polish municipalities, where recreation and entertainment are less prevalent and accompanying travel are more common.

Annex 4 depicts the preferred transport mode and demonstrates that private road transport is the most popular transport mode in all countries. The findings also reveal that public transport usage is significantly lower in the Polish and Swedish municipalities compared to others. Residents of these municipalities complained more frequently than residents of other countries about the insufficient use of public transportation, citing the fact that it rarely arrives or does not run on the necessary routes as well as the fact that it takes too long to use. Furthermore, Annex 4 demonstrates that bicycle transportation is more popular in Sweden and Latvia than in the other municipalities studied. Private vehicles are more common in the

rural areas of Poland and Sweden, where public transportation is less accessible than in larger cities.

Table 1 shows the factors influencing respondents' choices. According to the results, most respondents prioritize comfort, convenience, and accessibility over environmental impact when choosing a method of transportation. Only 80 out of 1151 respondents (6.9 %) care about the environmental impact of their mode of transportation, with 42 from Swedish municipalities, 28 from Latvia, 9 from Estonia, and only one from Polish municipalities. The environmental effect factor was only 2 %, on average, across all nations (Table 1). Of all the factors mentioned, only 0.5 % of respondents' methods of transportation were impacted by government regulations and incentives.

TABLE 1. FACTORS INFLUENCING THE CHOICE OF MODE OF TRANSPORT

Factors	Latvia, %	Estonia, %	Poland, %	Sweden, %
Distance	19.9	19.8	22.1	21.3
Time	18.9	20.9	26.0	19.7
Comfort	11.5	18.0	19.0	12.5
Availability	11.9	13.9	13.6	16.4
Weather and season	13.1	10.7	4.7	10.5
Costs	9.1	7.7	7.0	5.3
Health and fitness	4.4	5.4	0.4	5.7
Safety	3.0	*no data	5.4	1.1
Impact on the environment	2.3	0.6	0.4	4.9
Traffic jams	4.4	1.5	0.8	0.1
Other	0.9	1.0	0.8	2.2
Government policy, incentives	0.6	0.5	0.0	0.4

* no data – the answer option "safety" was not included in the Estonian questionnaire

3.3. Municipality Rating and Policy Evaluation

Respondents rated their municipality's transportation initiatives on a scale from 1 (very poor) to 7 (outstanding). When the average rating was calculated, it was found that inhabitants of Latvia and Estonia offered higher ratings (3.96 and 3.97) than respondents from Poland and Sweden, who gave ratings of 2.98 and 2.83, respectively, out of a maximum value of 7.0 (see Annex 5). This could be explained by the fact that respondents in Poland and Sweden were largely from rural areas, where suitable public transit, infrastructure for active modes of mobility (such as walking and cycling), and service availability are more difficult to offer.

Respondents were allowed to back up their judgment by indicating what aspects of their municipality should be improved. The most notable issue was the municipality's current cycling and pedestrian routes being poorly shaped, as well as the poor condition of the public transportation system, failing to satisfy the demands of the community, and being expensive (Latvian and Swedish respondents). Residents of Latvia have also reported that road speed limits are often exceeded.

Overall, the assessment of the work of local governments varies both by place of residence and by age group. Urban residents rate the work of their local governments significantly higher than rural residents (on average 4.17 versus 3.31), which is most likely explained by better infrastructure, more visible improvements and more active communication between institutions and the public. In rural areas, lower ratings are especially observed in middle-aged groups, who are most often faced with problems with public transport, mobility and accessibility daily. In turn, young people and the older generation are generally more positive:

younger groups are more optimistic about future development opportunities, while older ones (especially in cities) recognize visible improvements in mobility and safety. This indicates that local government initiatives more often reach and are evaluated in urban areas, while in rural regions there is still a gap between policy and its practical impact. Table 2 shows the distribution of the results by age and place of residence across all countries.

TABLE 2. DISTRIBUTION OF THE RESULTS BY AGE AND PLACE OF RESIDENCE ACROSS ALL COUNTRIES

Age group	**18–24**	**25–34**	**35–44**	**45–54**	**55–64**	**65–75**	**75**	**Total**
Rural area	4.0	3.4	3.3	3.0	3.2	3.4	3.7	3.3
Urban area	4.1	4.3	4.2	3.9	4.0	4.3	4.7	4.2
Total	4.1	3.9	3.8	3.4	3.4	3.9	4.3	3.8

To improve the existing rating, respondents were offered twenty policies as well as the opportunity to propose their initiative. The results are presented in Table 3. When comparing the number of supported policies in other nations, it was discovered that, in Poland, each respondent chose an average of 2.8 replies, whereas in Estonia, Sweden and Latvia, respondents chose more support mechanisms, 3.9, 4.5 and 4.6, respectively). Furthermore, in Estonia and Sweden, respondents under the age of 45 chose one support measure more than those over 45.

TABLE 3. MOST SUPPORTED POLICIES BY RESPONDENTS IN THE TRANSPORTATION SECTOR

Policy type*	**Policy**	**Sweden**	**Poland**	**Estonia**	**Latvia**	**All respondents**
S	P.1. Improving public transport	**36 %**	**42 %**	**38 %**	**24 %**	**34 %**
S	P.2. Improvement of cycling infrastructure	**24 %**	**29 %**	**23 %**	**31 %**	**26 %**
A	P.3. Pedestrian-friendly urban planning	**21 %**	**19 %**	**18 %**	**23 %**	**20 %**
A	P.4. Promoting remote work options	**19 %**	**9 %**	**21 %**	**22 %**	**20 %**
I	P.5. Support for low-emission car purchases	10 %	4 %	**18 %**	10 %	**13 %**
S	P.6. Park-and-ride facilities	7 %	**9 %**	15 %	15 %	12 %
I	P.7. Electrifying public transport	13 %	3 %	16 %	9 %	12 %
S	P.8. Launching public awareness campaigns	**15 %**	**11 %**	10 %	12 %	12 %
I	P.9. Smart traffic management	2 %	5 %	15 %	**17 %**	11 %
I	P.10. EV charging infrastructure	11 %	5 %	12 %	8 %	10 %
I	P.11. Using data to optimize transport services	4 %	3 %	16 %	10 %	10 %
I	P.12. Navigation & route-finding apps	5 %	5 %	12 %	11 %	9 %
S	P.13. Car-sharing & ride-sharing promotion	11 %	5 %	7 %	9 %	9 %
S	P.14. Car-Free Days & Events	7 %	6 %	6 %	14 %	9 %
I	P.15. Speed reduction measures	6 %	5 %	10 %	9 %	8 %
I	P.16. Eco-driving training	6 %	5 %	5 %	6 %	5 %
S	P.17. Higher tax on polluting vehicles	2 %	5 %	5 %	6 %	4 %
I	P.18. Public education on transport & CO_2	5 %	3 %	3 %	5 %	4 %
S	P.19. Creation of low-emission zones	2 %	3 %	3 %	4 %	3 %
–	P.20. Other	5 %	5 %	0 %	5 %	3 %
S	P.21. Congestion tax	1 %	2 %	3 %	4 %	3 %

*A – avoid, S – shift, I – improve

The highlighted values show the five top rated policies in each country and for all respondents. The proposed policies were categorized by type using the Avoid-Shift-Improve approach. Table 3 shows that respondents from different countries have similar preferences for the policy instruments that they support the most. These include measures such as improving public transportation and cycling infrastructure (both from the "shift" policy category), pedestrian-friendly urban planning, and promoting remote work options (all from the "avoid" policy category). Support for improving public transportation infrastructure ranked first among respondents in three out of four countries (36 % in Sweden, 42 % in Poland, 38 % in Estonia, and 24 % in Latvia). Similarly, improving cycling infrastructure received strong support (this measure ranks first in Latvia with 31 % importance and second in Sweden, Poland, and Estonia with 24 %, 29 %, and 23 %, respectively). Among the next most popular measures, promoting remote work is particularly popular in Latvia (22 %) and Estonia (21 %). Meanwhile, pedestrian-friendly urban planning was consistently supported in all four countries (approximately 20 %).

At the same time, support for low-emission car purchases, park-and-ride facilities, smart traffic management, electrification of public transportation, improved electric vehicle charging infrastructure, and public awareness campaigns were among the top ten policy measures. Particularly notable is the comparatively higher support for measures, such as low-emission car purchases among respondents in Estonia (18 % compared to 13 % among all respondents on average), launching public awareness campaigns among respondents in Sweden (15 % compared to 12 % among all respondents on average), and smart traffic management solutions among respondents in Latvia (17 % compared to 11 % among all respondents on average).

Among the highly rated policies, Polish respondents lacked support for electrification-related initiatives, such as support for low-emission car purchases and electrifying public transport, which gathered less than 4 % approval compared to an average rating exceeding 12 % among all respondents. The promotion of remote work options received considerably less support from Polish respondents (9 % compared with 20 % among all respondents on average). Conversely, Swedish respondents exhibited greater scepticism regarding data utilization policies, as evidenced by smart traffic management, data optimization for transport services, and navigation and route-finding applications receiving less than 5 %, in contrast to an average rating exceeding 9 % among all respondents. Tax-related policies gathered notably low ratings across all countries, with support in Sweden being markedly inferior to that of other nations.

While country-level differences provide valuable insights, the analysis revealed that age and type of residence had a greater influence on the results than nationality alone. The results also indicated that the rural–urban divide was consistent across countries. Thus, rural residents prioritized practical accessibility of public transport and infrastructure for electric vehicles (EV). In contrast, urban respondents expressed greater approval for technology-based measures such as smart traffic management and data-driven optimization of transport services.

Respondent age also revealed a few correlations (see Annex 6). First, younger age groups (18–34) are more likely to support flexible and digitally oriented solutions, such as remote working options, micromobility and smart traffic management tools. This generation tend to see mobility as a personal choice and seems to be more open to innovations that provide freedom and efficiency in their daily travel habits. Middle-aged respondents (35–54) are more likely to choose measures with a direct practical impact, such as improvements to public transport or measures to reduce congestion. Although this group is not particularly supportive of formal educational measures, their responses indicate a desire for clear and practical

communication that emphasizes the true benefits of policy initiatives. Given that their lifestyle is heavily influenced by family and professional commitments, the convenience and reliability of the transportation system is especially important to them. Meanwhile, older age groups (55+) were more likely to support policies that improve convenience and accessibility (support for public transportation and safe active travel modes like walking or cycling).

Overall, age dynamics show that support for sustainable mobility goals increases with age, but motivation changes: younger groups respond more to innovation and flexibility, while older ones respond more to safety, convenience, and social justice. Across all demographic and geographic groups, restrictive fiscal measures such as congestion taxes or higher fees for polluting vehicles received the least support. This demonstrates that people prefer "carrot-type" measures, which make things easier to get to and provide better service, to "stick-type" measures, which limit behaviour or money.

4. DISCUSSION

The European Commission established the Sustainable Urban Mobility Plan (SUMP) to address mobility needs in a sustainable manner, while also incorporating sustainable transportation policies [26]. Although developing a SUMP promotes evidence-based decision making from a long-term perspective and facilitates the application of best practices to relevant policies, it presents challenges in balancing economic, environmental, and social considerations, particularly when transitioning from automobile-centric planning to sustainable transport policies [27], [28]. Municipalities face difficulties in obtaining adequate funding and stakeholder collaboration for SUMP implementation, highlighting the complexity of balancing diverse mobility requirements and policy goals.

The main contribution of this study is a comparative analysis of the mobility habits and attitudes of residents in different municipalities of the Baltic Sea region, which allows for a better understanding of the public perception and support for various transport policy measures. The results obtained provide insight into how public behavioural trends and priorities can be considered when planning and implementing transport policies at the municipal level, even if no direct statistical analysis of the relationships between the profiles of individual respondents and their choices is performed.

4.1. Factors Affecting Travel Mode Choice

Climate neutrality is a significant trend currently being addressed by municipalities. The transport sector is particularly crucial, as it frequently represents the primary source of CO_2 emissions in municipalities and necessitates a thorough decarbonization strategy. The results from Table 1 indicate that direct environmental and climate factors are among the least significant considerations for residents when selecting a mode of transportation – they were outweighed by distance, travel time, comfort, and availability. Thus, climate neutrality in municipal planning should result in better solutions in areas related to these factors.

Despite the widespread belief that prices are a major motivator for people's commutes, the survey results show that prices do not rank among the top five factors that influence people's choice of mode of transportation. As other authors point out, customers frequently choose private transportation due to the "cost of inconvenience" [29], [30]. For example, studies show that travel time is more important than travel costs when choosing a transport mode; therefore, people in places with longer public transport travel times prefer private transport [31]. Meanwhile, public transport is more likely to be chosen when its in-vehicle time is comparable or shorter than private cars [32], [33]. Another important factor to consider

is travel comfort, considering that higher-income people value travel comfort together with waiting times as barriers to public transportation use, according to studies [29], [34]. In addition, commuters' transportation options often depend on availability, which describes whether active or public transport options are available for the commuter [35]. Rural municipalities often struggle to build sustainable transport networks because of their low population density and per capita income [36]. Investments in infrastructure that improve accessibility can lead to better transport-mode decisions [37].

Our survey results are consistent with the other factors described in the literature that influence transport mode selection. According to survey data, weather and season are rated relatively high (10.5–13.1 % importance factor in three of the four countries). From a policy implementation standpoint, it should be noted that weather and season may limit active transportation modes under adverse weather conditions [38]. Health and fitness, which provide both mental and physical advantages to active transportation users, are frequently cited in the literature as the motivating factor [39]–[42]. At the same time, according to the survey results, its importance varies by country, ranging from 0.4 % in Poland to 5.7 % in Sweden. This suggests that policymakers and stakeholders can educate residents on public health, emphasizing the importance of active mobility in improving health. This approach may also allow the benefits of climate change mitigation to be realized through the lens of health promotion.

Environmental impacts, traffic congestion, government incentives, and other barriers are among the factors that influence travel mode choice. Traffic jams are closely related to travel time. It is possible that some respondents factored this in their travel time calculations. However, as [43] pointed out, because of their psychological impact, traffic jams may be viewed as a source of concern, causing some people to avoid cars or crowded roads. It should also be noted that the survey was conducted in a variety of locations, including rural municipalities; therefore, traffic jams may not be a current issue, as they are often local and time-specific, such as during peak hours.

The impact on the environment can be defined as a decision-influencing factor because environmentally conscious people prefer public transportation to cars [44]–[46]. However, according to the survey results from the respondents, this factor is of minor importance. This is consistent with the findings of other studies, which show that environmental considerations frequently play a secondary role unless they are linked to economic incentives or regulations [38]. These results indicate the possibility of mitigating CO_2 emissions from transportation by addressing environmental concerns. However, to achieve significant improvements, further efforts are required to increase environmental awareness, as the survey indicated low interest among locals in these matters. This was also demonstrated by policy evaluation, which found that public education regarding transport and CO_2 emissions was one of the least supported measures.

Lastly, the travel mode choice influencing factors are government initiatives, as the government has legislative, financial, infrastructure, and information campaign power to create a sustainable transportation system. The government influences people's opinions when it promotes the implementation of decarbonisation targets. Long-term planning is needed to maintain stability and public trust, as studies have linked faith in government to activism, support for government programs, and willingness to pay for broad climate and environmental policies [47]. Citizens' choices are also affected by their perception that policies affect their daily lives [47]. If they do not feel understood, they were less likely to support certain policies. The survey results showed that, among the factors influencing the choice of transport mode, government initiatives were rated the lowest. This is an interesting result that can be explained in several ways. First, respondents may have lacked awareness

because they were not fully aware of the existing government initiatives or did not consider them relevant to their daily transportation choices. Furthermore, such responses may reflect the respondents' assessment, emphasizing the possibility that government efforts are insufficient, poorly executed, or slow to produce tangible results, resulting in a lack of trust or interest in such initiatives. Furthermore, respondents may not fully understand the meaning of this term.

4.2. Insights for Policy Makers

These survey results provide valuable insights for policymakers. First, policies should aim to make environment-friendly transportation alternatives more competitive with private cars in areas that have the greatest influence on mode selection. This is demonstrated by both the residents' perspectives on municipal problems (e.g., pedestrian safety, public transportation availability, and quality) and the outcomes of the most highly rated policy measures. Among the "shift" policies, those aimed at improving public transportation and cycling infrastructure received particularly strong support, ranking among the top five in all the surveyed countries. This suggests that with appropriate infrastructure investments, there is a significant opportunity for modal shifts from cars to public transport and cycling. As the primary reason for residents' travel is work commuting, both public transportation and cycling infrastructure should provide this option. Efforts to improve public transport include increasing frequency during peak hours, increasing comfort and punctuality, and reducing the distance to stops [48], [49]. Although educational measures received relatively low public support, campaigns to encourage carpooling, public transportation, and remote work can help to reduce reliance on private automobiles. One strategy could be to target young adults and middle-aged groups for active transportation initiatives because they are more mobile and adaptable to new habits [50].

There is also great potential for "avoid" measures. Although the proportion of "avoid" policies was the smallest of the measures proposed, both measures ranked third or fourth among the most supported policies across the four countries. From a local government perspective, these approaches comprehensively represent broader policy interventions aimed at reducing travel demand, such as flexible work schedules (cooperation with employers), digitalization, compact city planning, and improved local accessibility, indicating a preference for urban environments that reduce the need for motorized transportation. The recognized prevalence of remote work highlights the need for enhanced digital infrastructure and regulations that promote long-term mobility, including that of remote workers.

The second important conclusion is that the population needs to be more aware of the societal and individual benefits of environmentally friendly transportation solutions (e.g., improved air quality and health benefits). The survey results show that neither the environment nor health is a significant determinant of transportation mode choice. This is also supported by respondents' preferences for related policy instruments. The least supported policies include raising taxes on polluting vehicles, imposing a congestion tax, educating the public about transportation and carbon emissions, and establishing low-emission zones. It could be argued that the least supported policies are due to their nature: they primarily represent the so-called "stick" approach, which puts additional burdens on users. At the same time, this demonstrates that respondents do not regard private car use as a significant issue that contributes to air pollution and congestion and should be addressed as a priority.

There is another factor to be considered in relation to these policies. All countries showed low support for measures that imposed direct restrictions or financial penalties such as congestion charges or increased taxes on polluting vehicles. This emphasizes the importance of carefully assessing the need and scope of such measures to avoid generating excessive

"pushback" from society [51]. According to the survey results, only a small proportion of respondents in all countries supported the establishment of low emission zones in their municipalities. This support was particularly low in rural areas, where the introduction of such solutions is unlikely to be necessary or considered a priority due to the low traffic intensity in cities. Simultaneously, policy documents in Poland and Latvia discuss establishing low-emission zones in cities to improve air quality while minimizing negative environmental impacts [52], [53]. A comparable situation exists for policies aimed at educating citizens. A small proportion of the respondents supported the creation of educational campaigns and seminars on transportation emissions. In contrast, policy-planning documents explicitly emphasize the importance of educating citizens about environmentally friendly and sustainable transportation. These examples highlight society's low support for the currently planned policy instruments. In conclusion, people's willingness to accept political decisions is frequently influenced by the perceived benefits of innovation. This highlights the importance of governmental bodies collaborating with individuals because enforcing overly strict regulations on an unprepared society can result in a "pushback" effect. Thus, increased social opposition to unpopular policies could push the target back by a decade, and when combined with the more difficult-than-expected implementation of key measures, the target would be missed [51].

The survey results confirm the challenge of decarbonizing the transport sector, which is based on several issues that must be addressed, such as infrastructure limitations, public resistance, and available funding, which may vary from municipality to municipality, considering geographical conditions, population density, and previous achievements in developing a green transport system. For example, the large disparity in family size, with Polish towns averaging 4.3 people per home versus 2.5–2.6 in other countries, demonstrates that transportation needs vary. Larger families may require more affordable family transportation options, such as family discounts on public transportation and safe, spacious options for group travel in rural and suburban areas. Prioritizing green last-mile options in rural areas, such as e-bikes or electric scooters, could help people living outside of cities bridge the transportation gap. Urban areas, on the other hand, may prioritize congestion reduction through policies that encourage public transportation use and reduce vehicle reliance. In general, municipalities should implement robust monitoring systems that use indicators such as modal shifts, travel satisfaction, and emission reductions to continuously assess and improve the effectiveness of their policies, allowing for timely adjustments to strategies.

5. CONCLUSIONS

This article describes the results of a survey in four countries of the Baltic Sea region with 1151 respondents. The purpose of the survey was to gain insights into the citizens' vision of the transport sector moving towards climate neutrality in the context of their current travel habits, the current situation in municipalities and the existing support for policy measures.

A review of the literature revealed that citizens' willingness to accept a political choice is typically influenced by the perceived advantages of the innovation. According to the study results, time and distance are the most significant factors influencing the type of mobility chosen by respondents from Latvia, Estonia, Poland, and Sweden, and the primary reason for citizens' movement in all four countries is going to and from work. Most respondents ranked their municipality's measures to promote transportation sustainability as average or worse. The main issues raised by respondents in the municipal transportation sector are the infrequent operation of public transportation and a lack of pedestrian and cycling pathways.

The most suggested measures, supported by 20–34 % among all respondents on average in all countries, were improving public transportation, cycling infrastructure, pedestrian-friendly urban planning, and encouraging remote work options to reduce the need for daily commuting to and from work. The increase of a congestion charge was the least popular choice. Comparing these results by respondent age group and type of residence, it was determined that the same response trends persist, indicating general support for structural and accessibility-oriented solutions over restrictive or educational measures.

There were differences between urban and rural residents, with the former being slightly more supportive of technology-based traffic-calming measures and remote work options (improve and avoid measures), whereas the latter were slightly more interested in the development of public transport and EV infrastructure (improve and shift measures). Respondents from rural areas were also more likely to support public information and education campaigns, which is likely due to their age. Analysing the responses by age group reveals that people aged 45 to 64 are slightly more supportive of such measures, and this age group accounts for most respondents surveyed in rural areas.

Municipalities should strategically employ the ASI framework, prioritizing investments in public transport and active mobility infrastructure (Shift), encouraging remote work and compact urban planning (Avoid), and meticulously implementing technological improvements (Improve) in areas where infrastructure constraints restrict efficient modal shift. To guarantee that the policies implemented are effective and acceptable, they must be regularly monitored and evaluated based on data. This will ensure that the policies are closely aligned with the expressed wishes of citizens and local needs.

The study highlighted actionable insights for policymakers in many areas of action to solve the transportation-related challenges reported by respondents.

5.1. Limitations

This survey attempted to provide policymakers at the municipal level with a broader picture of population mobility issues. As part of the Interreg BSR *CommitClimate* project, this activity contributed to a better understanding and justification of the assumptions used in climate neutrality modelling tools, recognizing the critical need to supplement technical calculation tools with a social and behavioural perspective. However, the study has some limitations. First, the study's findings are based on survey results from specific municipalities (except for Estonia). Each has its own unique characteristics (for example, geographical location or economic development), so surveying other municipalities in the same country will yield different results. At the same time, the survey demonstrates that it is possible to conduct analysis and collect data for future research in this manner and that other municipalities can learn from this experience to engage their residents. Second, the number of respondents in some territories is deemed insufficient. Future studies would require the development of guidelines for reaching the population (particularly in rural areas where Internet services and social media are less widely used or where the proportion of older respondents is higher). Third, because the survey is based on self-reported data, the results may be influenced by response bias, which occurs when participants fail to correctly represent their travel patterns or beliefs due to social desirability, misunderstanding, or recollection bias. Potential risks of sampling bias related to distribution channels, age group representation, and self-selection have been considered, but the data were not weighted because the level of coverage across municipalities was uneven. Although the survey was designed to reduce these biases, future research might integrate survey data with objective travel behaviour data (e.g., GPS tracking or trip diaries) to provide a more complete picture.

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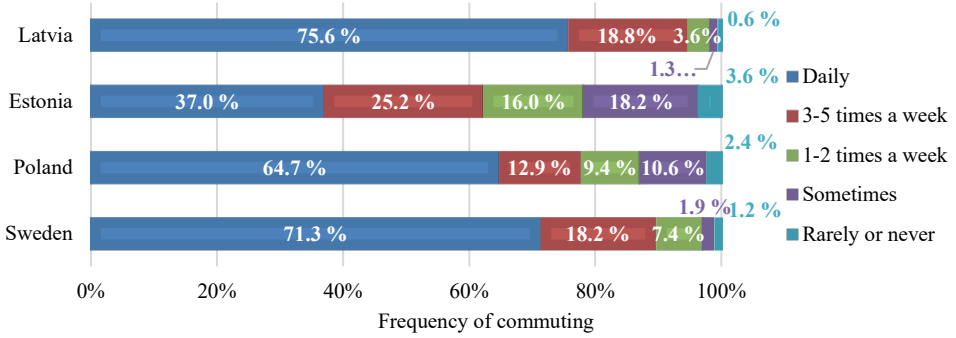
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ANNEX

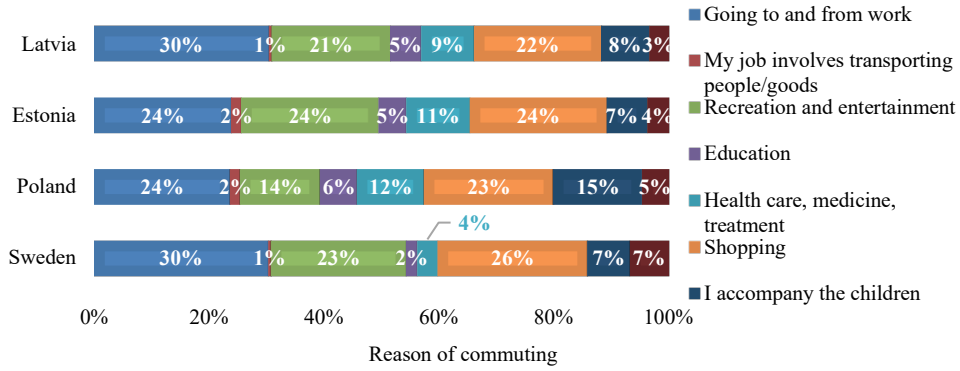
Annex 1. Sociodemographic information about the respondents

	Sweden	Poland	Estonia	Latvia	All countries
Respondent's age					
18 – 24 years	1.6 %	4.7 %	7.4 %	10.4 %	6.7 %
25 – 34 years	11.2 %	23.5 %	16.2 %	23.4 %	17.5 %
34 – 44 years	19.0 %	37.6 %	18.4 %	22.7 %	21.1 %
45 – 54 years	22.1 %	21.2 %	16.8 %	19.2 %	18.9 %
55 – 63 years	30.2 %	8.2 %	15.8 %	17.5 %	18.9 %
64 – 74 years	12.8 %	2.4 %	13.8 %	6.5 %	10.8 %
75 and more	3.1 %	2.4 %	11.6 %	0.3 %	6.0 %
Current employment status					
Full-time employee	79.5 %	60.0 %	51.2 %	79.2 %	65.7 %
Part-time worker	4.3 %	4.7 %	9.8 %	3.9 %	6.6 %
Student	1.9 %	3.5 %	4.6 %	4.9 %	4.0 %
Retired	11.2 %	8.2 %	24.0 %	6.2 %	15.2 %
Home duties	0.8 %	18.8 %	6.0 %	2.3 %	4.8 %
Other	2.3 %	4.7 %	4.4 %	3.6 %	3.7 %
Number of people in the household					
1	20.5 %	2.4 %	20.4 %	21.8 %	19.5 %
2	37.6 %	7.1 %	38.6 %	33.1 %	34.6 %
3	19.8 %	17.6 %	19.6 %	19.5 %	19.5 %
4	17.1 %	32.9 %	12.2 %	17.9 %	16.3 %
5	3.9 %	20.0 %	6.2 %	4.2 %	6.2 %
6	0.8 %	9.4 %	2.0 %	2.9 %	2.5 %
7	0.0 %	9.4 %	0.8 %	0.0 %	1.0 %
8	0.0 %	1.2 %	0.0 %	0.3 %	0.2 %
8 and more	0.4 %	0.0 %	0.2 %	0.3 %	0.3 %
Number of children and teenagers (<16 years) in the household					
0	66.7 %	24.7 %	70.8 %	62.7 %	64.3 %
1	17.1 %	24.7 %	14.2 %	21.1 %	17.5 %
2	13.6 %	40.0 %	10.2 %	13.3 %	14.0 %
3	1.9 %	8.2 %	4.0 %	2.6 %	3.5 %
4	0.8 %	1.2 %	0.4 %	0.0 %	0.4 %
4 and more	0.0 %	1.2 %	0.4 %	0.3 %	0.3 %
Housing location					
City	10.9 %	0.0 %	57.1 %	67.2 %	45.1 %
Suburban area	3.1 %	1.2 %	11.3 %	8.1 %	7.8 %
Rural area	86.0 %	98.8 %	31.5 %	24.7 %	47.1 %
Type of housing					
Private house	73.3 %	98.8 %	40.2 %	41.2 %	52.2 %
Apartment building with up to 9 apartments	10.5 %	0.0 %	8.4 %	7.5 %	8.0 %
Apartment house with 10 or more apartments	15.5 %	0.0 %	48.8 %	49.7 %	38.0 %
Another type of housing	0.8 %	1.2 %	2.6 %	1.6 %	1.8 %
Homeowner					
For you/your family member	73.6 %	95.3 %	90.8 %	75.0 %	83.1 %
Privately rented	7.8 %	0.0 %	7.0 %	22.4 %	10.8 %
Rented by the municipality	16.3 %	0.0 %	0.2 %	1.0 %	4.0 %
Other	2.3 %	4.7 %	2.0 %	1.6 %	2.2 %
Housing area					
Average value	*118*	*157*	*91*	*96*	*103.5*
Up to 50 m^2	3.5 %	2.4 %	19.6 %	22.3 %	15.4 %
From 50 to 100 m^2	31.4 %	15.5 %	47.8 %	44.0 %	40.7 %
More than 100 m^2	65.1 %	82.1 %	32.6 %	33.7 %	43.9 %

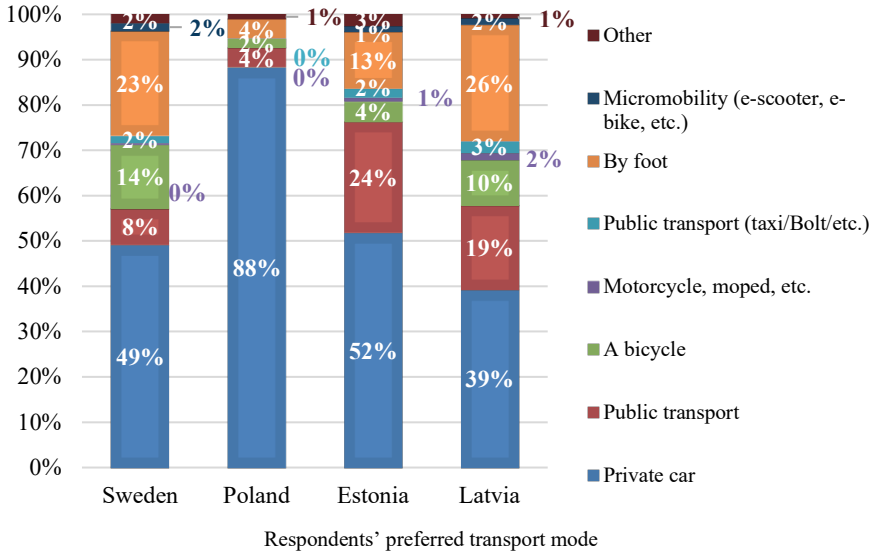
Annex 2. Frequency of commuting



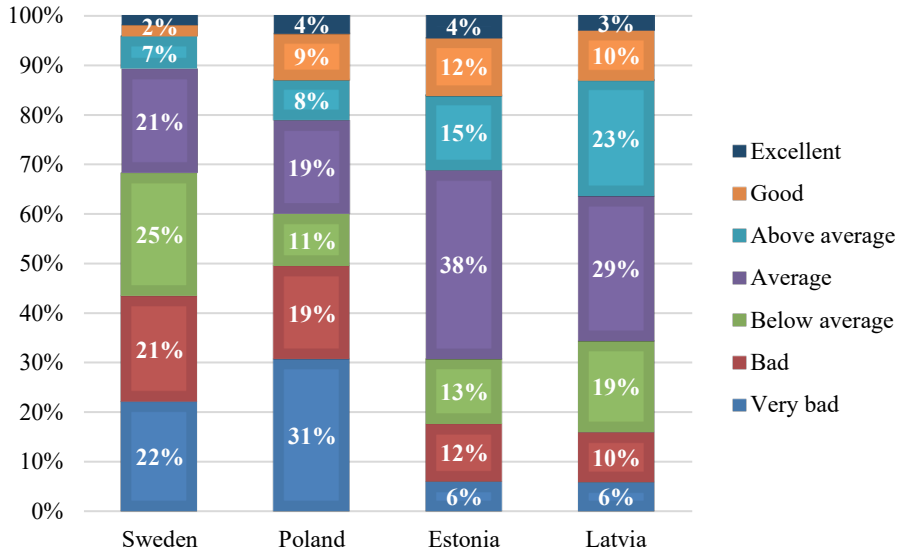
Annex 3. Comparison of the transportation causes



Annex 4. Respondents' preferred transport mode



Annex 5. Evaluation of the municipality by respondents



Respondents answer the question "To what extent the availability of services, infrastructure, municipal initiatives, etc. promote environmentally friendly movement in your municipality, what assessment would you give?"

Annex 6. Distribution of policy support across age groups in rural and urban areas

Policy Nr.	Age group of respondents from rural areas							Age group of respondents from rural areas						
	18–24	25–34	34–44	45–54	55–63	64–75	75+	18–24	25–34	34–44	45–54	55–63	64–75	75+
P.1	10	16	17	18	18	17	22	12	10	12	10	13	14	18
P.2	7	9	9	8	9	5	4	10	9	9	9	9	11	4
P.3	4	4	3	3	3	3	3	5	8	8	8	8	4	6
P.4	9	12	14	13	13	9	3	10	10	12	11	10	8	6
P.5	6	5	4	6	6	4	2	4	5	6	4	3	2	0
P.6	11	7	7	8	9	13	23	7	10	14	17	17	18	30
P.7	4	3	2	2	2	4	1	3	3	1	2	0	0	0
P.8	4	5	6	8	6	8	3	3	4	4	5	4	5	3
P.9	3	5	5	4	3	3	1	7	4	4	4	2	2	2
P.10	6	4	5	5	5	4	7	4	4	2	2	2	3	2
P.11	0	0	0	0	0	0	0	2	1	0	0	0	0	0
P.12	3	0	1	1	0	1	2	4	1	0	1	0	2	0
P.13	3	3	2	2	2	3	3	1	4	2	2	3	5	6
P.14	7	5	5	6	4	6	4	5	4	5	6	4	5	8
P.15	8	3	4	3	3	3	5	5	6	5	6	7	4	3
P.16	6	6	4	4	5	4	2	5	5	6	6	7	6	3
P.17	2	3	2	2	3	5	3	3	2	2	2	1	2	1
P.18	3	1	1	0	0	0	1	2	1	1	1	1	2	1
P.19	5	3	2	2	3	3	2	3	2	1	1	3	2	2
P.20	2	6	5	5	5	7	7	5	5	6	5	6	4	7

Respondents' support for policy measures by age group and place of residence.
(policy numbers correspond to those in Table 1).

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Research article

Climate neutrality through scenario analysis: A local authority perspective

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ABSTRACT

One of the most significant contributors to world emissions is the transportation sector, which presents a considerable obstacle to decarbonization. The presented literature review considers local factors and emphasizes the important part municipalities play in developing sustainable transport policies applying the Avoid-Shift-Improve (ASI) framework. Municipalities, however, can encounter barriers including limited data, financial resources, and competency despite the advantages of scenario-based planning; hence, simpler, insight-driven methods for efficient decision-making are necessary. This research paper develops and analyses modelling scenarios to guide local authorities in achieving climate neutrality in the transport sector. A case study of Riga shows that while "avoid" policies yield moderate results, "shift" policies achieve greater reductions with earlier implementation, and "improve" policies deliver the most significant long-term effects. Combining these strategies leads to notable emission reductions but remains insufficient for achieving climate neutrality by 2050, highlighting the need for integrated solutions such as intelligent urban planning and the 20-min city concept.

1. Introduction

1.1. Background

Climate change is a highly urgent global concern. It was concluded that the global temperature increase must be kept at 1.5 °C over pre-industrial levels to prevent the worst effects of climate change and maintain a habitable planet (United Nations). To restrict global warming to these thresholds, it is necessary to decrease emissions by 45 % by 2030 and achieve a state of zero net emissions by 2050. However, contrary to the goal of reducing emissions, the IPCC study "Climate Change 2022: Mitigation of Climate Change" projects a potential rise in emissions of 16 %–50 % by 2050 from the transport sector under the business-as-usual scenario (‘IPCC).

Transportation is responsible for almost 33 % of carbon dioxide (CO_2) emissions from sectors that consume energy, and it remains one of the most challenging sectors to reduce carbon emissions in. The main challenges can be expressed as a transport demand growth that outpaces efficiency gains (Lefèvre et al., 2021), high dependency on fossil fuels (Federal Reserve Bank of Dallas et al., 2023) together with the high relative cost of clean technologies (Santos, 2017), technical limitations (de Blas et al., 2020), infrastructure challenges (van der Zwaan et al., 2013) and additional factors. For instance, a significant barrier is the complexity of the transport sector arising from an extensive stakeholder number and the lack of cohesive regulatory frameworks, which result from medium-to long-term commitments and alignment with sustainable development goals (Lah et al., 2019).

The most significant increase in emissions is observed in road transportation, which accounted for almost 75 % of total emissions from transportation in 2022 worldwide (‘IEA). As a result of the COVID-19 issue, emissions from the transportation sector declined in 2020 globally. However, by 2022, they had rebounded and were almost back to the levels seen before the pandemic. For instance, in the EU, emissions in 2020 were 13.5 % lower than 2019 levels, but by 2022, they were just 1.7 % below pre-pandemic figures, indicating a rebound.

The choice of transportation methods significantly impacts the environment, highlighting the need for policies that encourage the adoption of alternative fuels and promote changes in public behaviour. This emphasizes the importance of implementing a sequence of measures, which include setting clear goals, advocating for alternative fuels, and modifying the behaviours of the general population, to accomplish a decrease in emissions (Stern, 2000). Besides carbon dioxide emissions, the transport industry also generates several additional greenhouse gas emissions, such as sulphur dioxide and nitrogen oxides. Research has demonstrated that they provide a significant hazard to nearly all ecosystems, particularly soil and forest habitats (Konieczna et al., 2023). Emissions have adverse consequences not just on climate change but also on human health, both in the long run and short term (Mehfooz

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et al., 2023). This indicates that governments should adopt mitigation tactics that involve implementing limitations on vehicular movement and providing incentives for the upgrading of the existing vehicle fleet (Piras et al., 2024) as studies show that the mode of transportation has the most substantial impact on the per capita carbon footprint (Arhipova et al., 2023).

The issue of mitigating emissions necessitates the implementation of effective solutions and collaboration among stakeholders at different levels. Heating, traffic, trade, industry, and craft activities are concentrated in local regions with higher population density (Schmieder et al., 2023). As a result, communities such as cities, towns, and villages consume 75 % of the world's energy and contribute to 80 % of greenhouse gas emissions. A municipality is the lowest-level administrative division of local government and typically has the primary responsibility for devising and executing strategies that are appropriate for its specific geographic location (Phupadtong et al., 2023). Municipalities have a distinct advantage in being able to promptly address the issue of reducing greenhouse gas emissions since they have significant control over decisions on land use, buildings, local transport, and waste management at the local level (Ocean Eise Research Institute, 2020).

1.2. Research objective

The literature analysis suggests that to achieve net zero emission targets at the local community level, it is necessary to have well-defined plans and an action framework. A municipality's effectiveness in regulating released pollutants is determined by its ability to adopt diverse policy measures that, when combined, form a cohesive policy package. These principles are purposely implemented as a specialized management technique to achieve continuous improvement (Schmieder et al., 2023). A well-defined municipal strategy can help simplify the execution of climate plans (Phupadtong et al., 2023). However, before implementation, municipalities must assess the measures they wish to support and determine the level of support they intend to provide. At this stage, many municipalities may face challenges with data processing and the accessibility of information. Expert-developed tools can assist responsible municipal personnel. One such tool is designed to enhance the decision-making process under the international project *CommitClimate* (Interreg Baltic Sea Region Program) ('CommitClimate). The tool features a user-friendly interface that allows municipalities to enter the transport sector-related data and model the emission level by 2050 under various policy scenarios. By changing and implementing the new policies in the tool municipalities can find the most successful strategies that they may employ to promote the adoption of environmentally friendly technology and encourage citizens to choose non-motorized or other eco-friendly modes of transportation.

This article aims to present a case study on the application of the tool. The authors analyse the case of Riga municipality, a medium-sized European capital characterized by a population density of 2409 individuals per square kilometre (2023 data) and a vehicle registration rate of 360 passenger cars per 1000 residents (2020 data), alongside its accessible public transportation options, including bus, trolleybus, tram, and train (Riga City Councli, 2022). Problems common to Eastern European countries include a low share of sustainable forms of transportation, aged vehicles, a high amount of fossil energy, limited public support for change, and technological backwardness (Riga City Councli, 2022). The main goal of the presented case study is to evaluate.

(1) which policy strategies are the most effective in reducing urban transport sector emissions,
(2) how do combined impact of different strategies compare in terms of their overall impact on achieving climate neutrality goals for municipalities?

2. Literature analysis

The implementation of sustainable development strategies at local levels, such as in cities or municipalities, is the subject of several studies, and mobility greening policies receive a lot of attention. This section will undertake a literature analysis of studies that investigated current trends in the transportation sector, as well as hurdles and solutions to existing barriers at the local level.

2.1. Avoid-shift-improve (ASI) approach

The avoid-shift-improve approach was used to develop strategies to reduce the environmental effect of the transport sector. This approach was initially used in a German Parliamentarian study in 1994 to identify policy solutions for minimizing the environmental effect of transportation. "Avoid" refers to actions that lessen the need to travel and overall distances; "shift" refers to efforts that help shift initial transportation demand from high-to low-emission modes; and "improve" refers to measures that aim to make cars more energy-efficient and fuels less carbon-intensive ('Bakker et al., 2014).

Implementing strategies that promote shorter travel distances can help reduce negative impacts on the environment (Akrami et al., 2024), (Elldér, 2024). The best practices suggest that streets should be regarded not merely as vehicle paths, but as comprehensive public spaces for all users. This approach enhances the experience of other users while also lowering congestion and pollution (Kaparias and Wang, 2020). Prioritizing smart planning of land also ensures accessibility (Akse et al., 2021). Supporting such accessibility promotes the resilience of urban networks, aiding communities in recovering from economic disruptions by preserving connection and access to essential services (Östh et al., 2018). The "avoid" policies appear at the municipal organizational level, including the planning of densely populated and human-scaled cities, the development of transit-oriented urban areas, and the optimization of the road network and its utilization (Bongardt et al.). One approach is the implementation of the 20-Minute City Concept, which facilitates urban design to ensure that all critical services are accessible within a 20-min distance via active transportation or public transit (Capasso Da Silva et al., 2020). Other "Avoid" policies may encompass telework or remote work, which experienced a surge in interest during the COVID-19 epidemic and is still widely adopted (Leroutier and Quirion, 2023), (Krasilnikova, 2024), (Elldér, 2020). The creation of co-working spaces also allows for minimizing the demand for transportation and accompanying emissions, especially in rural and suburban locations (Krasilnikova, 2024). It is vital to consider the employment status of car users, their commuting method, and the feasibility of working from home while implementing this policy, as studies have shown (Hook et al., 2020). Hence, M. Leroutier and P. Quirionet include physical labourers, farmers, dealers, crafters, and chief executive officers in the category of occupations that cannot be carried out remotely (Leroutier and Quirion, 2023).

"Shift" policies also encompass a range of initiatives aimed at promoting the use of active (cycling, walking) or public transportation. Promoting the abolition of private transportation is an important policy since it improves public welfare and reduces traffic-related issues such as air and noise pollution, as well as the number of road fatalities (Arnz, 2024). Research indicates that such a modal shift can not only diminish daily mobility emissions but also generate annual climate and health benefits which can be expressed in monetary terms (Leroutier and Quirion, 2023). This policy considers an individual as the centrepiece of transportation rather than the vehicle itself. Numerous factors delay the modal shift; for example, in the case of the spread of bicycles, the typical cause is a lack of infrastructure and an inadequate sense of security, including fear of theft (Leroutier and Quirion, 2023). The presence of pedestrian infrastructure and a sense of safety are also important factors that regulate the number of pedestrians. Thus, although walking as a transport mode is crucial, in numerous regions worldwide, it is

associated with poverty, vulnerability, road violence, gender-based violence, and various forms of discrimination (Sagaris and Palacios, 2024). For individuals to adopt walking as their primary mode of transportation, it is essential to establish a secure environment. Research indicates that isolating the most vulnerable members of society from outdoor environments contributes to an escalation in crime rates (Sagaris and Palacios, 2024). To improve political persuasion, gain community support, and generate synergistic advantages, local governments must develop an extensive range of sustainable transportation measures that promote appealing mobility options (walking, cycling, public transit, and vehicle sharing) (Müller and Reutter, 2021). The "city street experiment" is one strategy to encourage the shift to more environmentally friendly and alternative modes of transportation. It involves temporarily or permanently banning motorized vehicles from using a portion of the road and encouraging the use of a pedestrian-friendly, safe, and equitable space (VanHoose and Bertolini, 2023). Furthermore, there is a growing trend towards the use of transition and micro-mobility solutions. The advancement of micromobility enhances the sustainability metrics of the transportation sector, particularly when its implementation is demand-driven, involving the collaboration of all three stakeholders: the municipality, the operator, and the general public (Shahal et al., 2024). Moreover, it is essential to consider alternative policies that could be implemented to mitigate any further harm to the climate.

All policies that enhance vehicle efficiency and encourage the shift towards renewable fuels can be seen as “improve” measures. Some authors consider the concept of transitioning just to electric vehicles, while other studies explore alternative options for utilizing clean energy (Arnz, 2024), (Breuer et al., 2021), (Zhang et al., 2022). Furthermore, the enhancement strategies may encompass modifications to fuel and carbon prices, along with the implementation of restrictions on fossil fuels, such as the elimination of diesel subsidies (Yan et al., 2021) (“stick” measure), or the promotion of renewable energy sources (“carrot” measure) (Kwilinski et al., 2024). Another way to implement the improvement policy is by improving the efficiency of vehicles (Zuo et al., 2018).

At times “share” policies that affect car ownership are also distributed separately. These include shared mobility solutions and carpooling. For example, bike share systems effectively promote sustainable mobility as they benefit the economy, society, and the environment (Papadakis et al., 2024). Research indicates that in some cases by sharing 80 % of autonomous vehicles, there might be a potential reduction in net emissions by up to 20 % (Dia, 2019). Furthermore, studies show the advantages of this approach might become more significant as the use of autonomous shared electric vehicles becomes more widespread (Dia, 2019). The study by Elena Alyavina et al. argues that the spread of car-sharing should be limited through financial incentives, making its utilization justifiable solely for first or last-mile journeys, while sustainable transport systems should be based on public transport (Alyavina et al., 2024).

2.2. Sustainable urban mobility plan development in municipalities

A sustainable transport system can be defined as providing basic access to transportation and operating in an affordable, safe, and fair manner while minimizing environmental impact and supporting economic and social well-being (Bamwesigye and Hlavackova, 2019), (Jelti et al., 2023). This implies that while planning policy framework policymakers must think on several levels – economic, environmental, and social. On the contrary, many local governments fail to execute optimal practices within their municipalities or cities. The issue frequently lies in the mobility paradigm, where automobile-centric planning remains dominant.

The Sustainable Urban Mobility Plan (SUMP) was established by the European Commission to address people’s mobility demands sustainably and to integrate sustainable transport policies. This approach promotes evidence-based decision-making with a long-term perspective and provides a chance to apply best practices under relevant policies (Papadakis et al., 2024). Research shows that the application of the SUMP strategy delivers significant benefits to communities of all sizes (Jordová and Brůhová-Foltýnová, 2021). However, when designing sustainable transportation policies, various factors must be considered. The review of the most significant factors is offered further.

2.2.1. Characteristics of the municipality

It is crucial to keep in mind that there is **no one-size-fits-all model** when examining the successful examples of other nations. As such, when implementing the experiences of other nations, it is crucial to understand that each city and urban society must create its own transition path and that city examples cannot be easily transferred across city contexts. Liu et al. analysed emissions from the transport sector across four municipalities in China and determined that variations in emission levels were affected by income, energy composition, and transportation infrastructure (Liu et al., 2021). Municipalities in rural locations have poor results in the development of sustainable transport systems, often correlated with lower population density, per capita income, and a more pronounced digital divide (Ghinoi et al., 2024). A Swiss study indicated that bike-sharing systems exhibit poor economic viability and usage rates in small communities characterized by a high prevalence of private transportation and insufficient population density (Audikana et al., 2017). The Spanish study in turn states that the creation of walking and cycling routes, along with public acceptance of these transportation methods, can even mitigate depopulation rates and enhance tourism in rural areas (San-Martín González and Soler-Vaya, 2024). This signifies that best practices must be tailored to local circumstances.

2.2.2. Financial resources

A comprehensive review of economic, social, and environmental variables is essential for communities to formulate a transformation plan, with cost-effectiveness analysis being an essential component (Phupadtong et al., 2023). However, a significant challenge for municipalities is the reality that local governments have little potential to influence national policy while having a significant impact on local-level solutions. For example, while municipalities can greatly influence the development of sustainable transport at the local level, their activities are often limited by available **financial resources**. Financial resources are typically allocated through national financing, which frequently provides inadequate support for local sustainable transportation initiatives (Liu et al., 2024). Conversely, public funds are frequently allocated to tackle pre-existing acute issues associated with the current modal split, often counterproductive to resolving automobile mobility challenges. As a solution, the authors mention the diversion of funds from infrastructure-related projects to wider multilevel cooperation between state representatives and interested parties (Liu et al., 2024).

2.2.3. Discourse among various stakeholders

Possible challenges during the decision-making process may be classified as **political and cultural barriers**, implying that certain groups of society reject new policies (Papadakis et al., 2024). Thus, when establishing and executing sustainable urban mobility plans, coordination is essential both among stakeholders and residents, and with different decision-making levels, sectors, and public sector bodies (Carvalho et al., 2023).

2.2.4. Degree of competence

Other major barriers include **limited competence** in defining and characterizing actions and objectives, as well as a lack of a framework for conducting long-term quantitative environmental assessments (Baltazar et al., 2024), (Papadakis et al., 2024). This is one reason for the frequent disparity between the defined framework and real practices (Baltazar et al., 2024). Conversely, some argue that this gap should be regarded as a window of opportunity, with favourable implications for

innovative policy implementation (Chien and Lin, 2023), however, this approach still requires investment in competence building.

2.3. Scenario analysis approach

The formulation of several scenarios enables decision-makers to be "wise before the event" instead of "wise after the event". The scenario analogy facilitates enhanced comprehension of the future and the formulation of more sustainable strategies. The continual creation of new scenarios mitigates the inclination to stick to established ones and enables a broader examination of solutions to the challenges within the transport sector (Lyons et al., 2021). Prior policy testing may utilize a wind-tunnelling approach, wherein stakeholders evaluate and assess the performance of various courses of action across different scenarios and determine the success metrics (Lyons et al., 2021).

Modelling is a tool that enables local authorities to comprehend the complexity of the transport system and examine the potential results of selected tactics, hence facilitating the formulation of resilient policy options that perform effectively under various (uncertain) scenarios (Marchau et al., 2019), (McPhail et al., 2018). Given the significant issue of increasing emissions from the transportation industry, there is a wealth of study on the descriptive models and emission reduction strategies specific to this sector. Commonly observed research focuses on the impact of economic and technical factors on the selection of transportation modes (Korkmaz et al., 2020), (Thomas and Serrenho, 2024), (Sununta et al., 2019) yet, an increasing number of studies are emerging that focus on the significance of behavioural factors in achieving climate-neutral transportation (Ahanchian et al., 2019), (Li et al., 2022).

The transport sector is also frequently analysed using a systems dynamics method (Watabe et al., 2019), (Gómez Vilchez and Jochem, 2019), (Keles et al., 2008), (Pasaoglu et al., 2016). Yung-Hsiang Cheng performed research that examined several modes of transportation, including private automobiles, motorbikes, light trucks, heavy trucks, and city buses. Results showed that free bus services do not significantly improve the number of generated emissions as do parking management and fuel tax (Cheng et al., 2015). N. Saraf and Y. Shastri utilized a system dynamics methodology to analyse the transition from traditional vehicles to alternative fuels, identifying vehicle costs and lack of infrastructure as the primary barriers to electric vehicle development (Saraf and Shastri, 2023). Wanjie Hu et al. assessed the effectiveness of the urban rail-based freight transport system, together with the existing stakeholders and necessary support measures for its enhancement (Hu et al., 2020). Authors examined various factors such as social and environmental impacts, pricing, investment, and subsidies (Hu et al., 2020).

3. Methodology

While previous studies have provided valuable insights into the effectiveness of various transport emission reduction strategies, there is a need for more integrated models that can be easily adapted by municipalities. This study aims to fill that gap by developing a scenario-based emissions model for the municipality's transportation sector.

The model facilitates assessing future policy scenarios to support the decarbonization of urban transport systems by 2050. The research is limited to the transportation sector within the authority of a single municipality.

Scenario analysis was chosen to evaluate the impact of various transport policies under different future conditions. This methodology facilitates informed decision-making in urban transport planning, advocates for stakeholder goal setting, identifies potential risks and helps to encourage conversation about the development of scenarios among diverse stakeholders (Hannah and Gassner, 2007). The chosen methodology is described in Fig. 1.

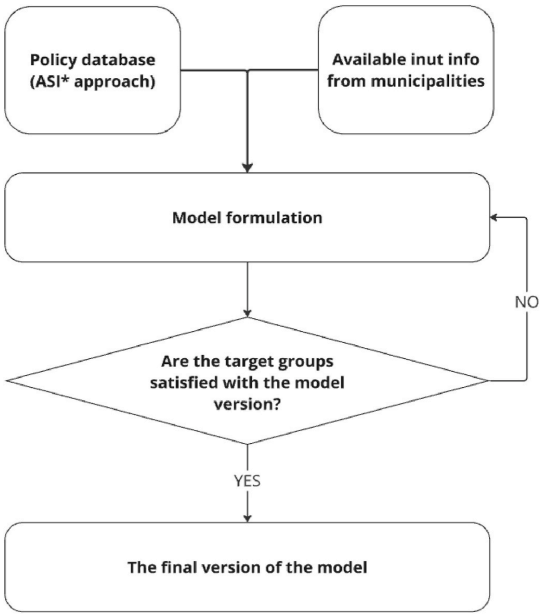


Fig. 1. The methodology used in the study.

First, a comprehensive review of municipal transport emissions and policy instruments was carried out to establish a foundational understanding and identify key variables. Based on this information, a draft model was developed. Simultaneously discussions were conducted with stakeholders to collect information, evaluate their preferences, and comprehend the needs for the usability and functioning of the model. Local governments are the major target group in the consortium of partners, which provides an additional advantage. Participating municipalities were Cēsis and Riga in Latvia, Palecznica and Raciechowice in Poland, and *the Lapplands Municipal Association in Sweden* (Gällivare, Kiruna, Jokkmokk, and Pajala municipalities). The target audience's involvement helped increase the study's credibility and overall effectiveness. The designed initial model framework was progressively modified based on stakeholder feedback to guarantee alignment with practical requirements. After developing the final version, we validated it by applying it to a real-world case study in Riga Municipality, evaluating its performance and efficacy in a practical setting.

Greenhouse gas emissions have been calculated with SECAP and IPCC methodologies, tailored to the municipality's input data. The primary novelty of this study is the innovative interface that was developed by Stella Architect software to improve the municipality's understanding of its transportation sector (Road transport 2024,), ('EEA, 2024). The constructed transportation system model is a component of the comprehensive municipal emissions accounting tool, encompassing the

transportation sector and the energy, waste management, and agriculture sectors.

3.1. Model structure

The model uses a multi-level input approach, each representing a distinct degree of information availability and control.

- The first level, the municipality's own fleet, provides customers with the most comprehensive data on mileage, fuel efficiency, vehicle numbers, and fuel consumption. This enables exact assessments of fuel consumption and emissions, and the flexibility to apply alternative policies, such as switching to renewable energy cars or increasing fuel economy.
- The next level is general passenger transport demand, which is more difficult to forecast since it is based on wider assumptions about transportation modes and trip purposes (e.g., work, leisure, shopping). Users must estimate the distribution of travel across various means of transport (private automobiles, public transit, cycling, and walking) and inhabitants' daily transportation demands. Assumptions regarding vehicle occupancy, fuel choices, and trip reasons increase uncertainty, but the model still provides strategies to influence modal changes, decrease travel demand, and improve transportation system efficiency.
- Finally, freight transport provides the least direct information and control for municipalities. While they may lack specific data or major effect possibilities, freight emissions are included to help towns understand the emissions created in their region. Users may enter estimates about the volume of freight transported by road or rail, the fuel types utilized, and prospective transitions to renewable energy, although policy choices in this sector are more restricted than in passenger and municipal fleets.

3.2. Data collection and GHG emission calculation

The following is a description of the assumptions that define the model's emissions calculation process. For the majority of emission sources, greenhouse gas emissions were calculated per the 2006 IPCC Guidelines by multiplying the activity data by the corresponding emission factor (). The user can modify the embedded data to ensure that the emission factors in the model correspond to the real conditions. The equations used in the study are shown in Annex 1.

3.3. Scenario development

The individual effects of different policies and their combinations were analysed to assess the possibility of decreasing emission volumes. The policies under discussion are detailed in Table 1.

A more detailed description of each policy is available in Annex 2.

To compare the impact of policies based on the ASI approach, four additional scenarios were established, each containing a combination of various policies.

- AVOID - TD1, TD2, M2
- SHIFT (Moderate) - H3, PR3
- SHIFT (Optimistic) - H4, PR2
- IMPROVE - H1, H2, PU1, PR1

Table 1
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.

A hybrid of all policies was also investigated, which contained a combination of all policies ("Avoid", "Shift (Optimistic)", "Improve").

3.4. Case study: Riga municipality

Riga, as the capital and largest city of Latvia, acts as the economic, political, and cultural centre of Latvia. Riga, with a population exceeding 600,000, and a total of over 850,000 when including surrounding residents, has been selected for the EU Mission for 100 climate-neutral and smart cities by 2030. This status envisions a reduction in emissions and ensures that these cities serve as hubs for experimentation and innovation, enabling all European cities to replicate this model by 2050 (‘Climate-neutral and smart cities).

The transport sector constitutes a significant source of emissions in Riga municipality. In 2020, Riga produced 1628 $ktCO_2$ emissions, with private transport accounting for 42 % and public transport contributing approximately 2 % of total municipal emissions (Riga City Councli, 2022). The transport sector in Riga exhibits high fossil fuel consumption, limited adoption of electric transport, and a significant rise in private transport usage, particularly following the COVID-19 pandemic. The sustainable energy and climate action plan of Riga was developed to facilitate the transition to climate neutrality, highlighting key challenges within the transport sector (Riga City Councli, 2022).

- Reducing the need to move
- Promotion of public transport and active modes of transportation
- Development of bicycle infrastructure
- Increasing the role of railway transport

- Increasing the share of renewable energy
- Creation of a system for regular collection of data/information for monitoring population mobility parameters

To calculate the number of emissions generated, Riga's demographic indicators, transportation habits and available car park data were analysed. Data on the population, birth rate and distribution by age groups were taken from the data of the Statistical Office of Latvia. Data characterizing municipal transport were taken from *Riga sustainable energy and climate action plan for 2022–2030*, while data characterizing public transport was taken from the local public transport company's report (Riga City Councli, 2022). The year 2022 was taken as the base year, when the population of Riga was 605,802 inhabitants (Riga City Councli, 2022). The characteristic data of Riga municipalities on the number of inhabitants and movement habits are summarized in ANNEX 3.

The baseline scenario assumes alterations solely in the population size, predicated on current data regarding birth and death rates. In turn, it is assumed that the modal distribution, the migration rate, the share of renewable energy in the fuels, the demand for freight transport, and the daily number of moves per individual stay constant. Additional assumptions in the baseline scenario include a daily migration rate of 70 %, alongside the overall population.

4. Results

4.1. Riga municipality: baseline scenario

Modelling the baseline scenario indicated an expected reduction in emissions levels within the Riga municipality, primarily attributed to population decline. This trend does not align with the established objectives for achieving climate neutrality by 2050. Fig. 2 illustrates the emissions derived from the baseline scenario. The figure does not represent walking and cycling as their emissions are zero. The graph indicates a minor drop in all emissions, except for freight transport emissions, which aligns with the initial assumption of steady demand for such transport.

According to the distribution of emissions by mode of transportation, private transportation represents over fifty percent of all emissions at both the starting point of the simulation and in 2050. In 2050, no significant changes in the distribution of transportation modes are projected.

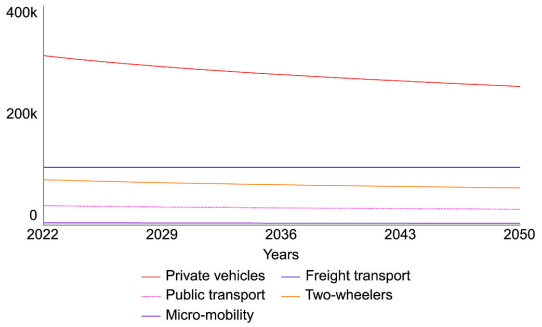


Fig. 2. Distribution of generated emissions by mode of transport.

4.2. Riga municipality: sensitivity analysis

A sensitivity analysis was conducted to address the challenges of acquiring municipal-level data, in which several initial input parameters were modified to assess the model's compliance with logical principles and evaluate each parameter's impact on the results. The values were mainly selected from 50 % to 150 % of the baseline scenario, and 100 scenarios with uniform distribution were simulated for each parameter, yielding a graph that illustrates the probability of various outcomes.

In the Riga case study, cargo transport emissions are assumed to remain constant in the baseline scenario due to limited forecast data, historical stability, and the need to simplify the model for clearer comparison with policy scenarios, especially since freight is not the primary focus of the analysis. Hence, a sensitivity analysis was conducted to assess variations in cargo transport demand ranging from −50 % to +50 %. A similar approach was applied to the alteration in freight transport demand, which ranged from −1 % to +1 % rather than remaining at 0 % as in the baseline scenario. The results are presented in Fig. 3.

A similar process was implemented for the parameters that define passenger transportation. For instance, Fig. 4 illustrates how the results vary as the population grows under the influence of migration at intervals ranging from −1.5 %/year to +1.5 %/year, as well as the impact of changing the number of movements from 0.5 to 1.5 times.

The effect of car occupancy on the results was also investigated by changing car occupancy from 1 to 2.5 (see Fig. 5).

The sensitivity analysis showed that the created model works in compliance with logical principles, and how much the results are affected by the considered parameters. It revealed that the parameters under consideration can have a significant impact on the final results, emphasizing the importance of collecting more precise data and making corrections when newer data becomes available.

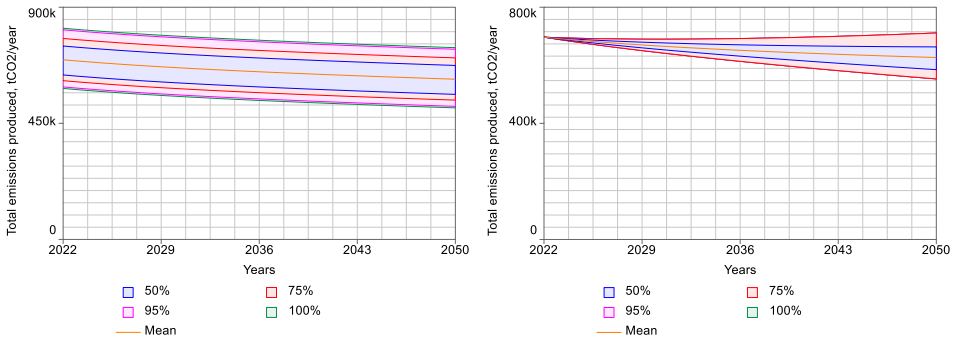


Fig. 3. The probability of the amount of emissions produced by changing the demand for freight transport (a) and by changing the rate of change in the demand for freight transport (b).

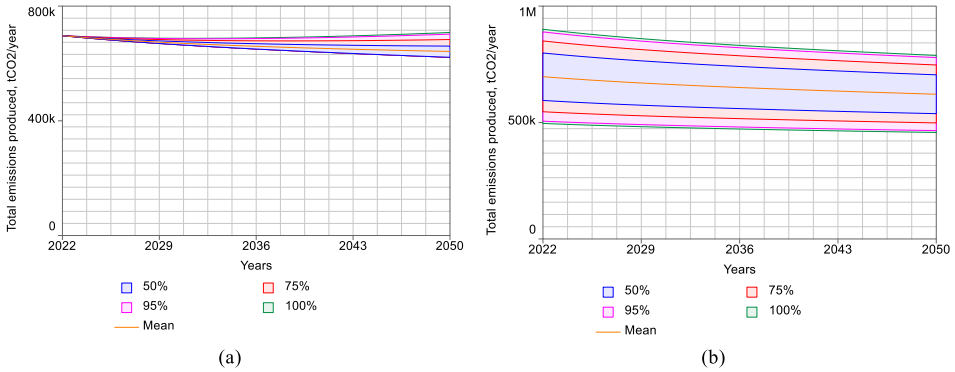


Fig. 4. The probability of the amount of emissions produced by changing the rate of change of migration changes (a) and the number of movements (b).

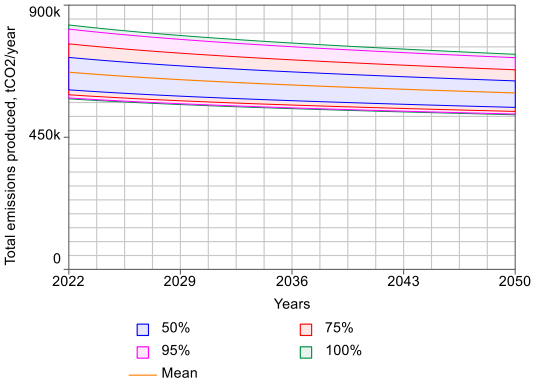


Fig. 5. The probability of the amount of emissions produced by changing the rate of car occupancy.

4.3. Riga municipality: scenarios with alternative policy instruments

In total, 12 individual policy analysis simulations and 5 policy combination simulations were performed to determine their impact on road passenger transport emissions. In the baseline scenario, it is presumed that the demand for freight transport remains constant, and specific policies directly affecting freight transport are not addressed; hence, only the emissions resulting from passenger transport are detailed. The results for individual policies are shown in Fig. 6.

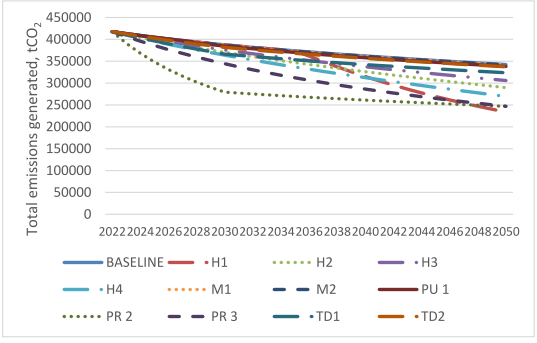


Fig. 6. Comparison of the impact of the developed policies on the amount of generated emissions.

The study found that the transition to more efficient public transportation vehicles (PU1) has the least impact, followed by the development of e-services (TD1) and the reduction of municipal transport mileage (M1 and M2). This is explained by the fact that these measures only address a small portion of the transportation sector's emissions. Meanwhile, the highest emission reduction potential was estimated for the internal combustion engine ban policy (H1), increasing the share of renewable fuels (H2), and optimistic mode shift policy (H4), which applied to all mechanical transport modes. Increased average car occupancy (PR2, PR3) also resulted in significant emission reductions, as it greatly impacts demand for private cars, which account for more than half of total emissions in the baseline scenario.

Combinations of several policies are discussed further down (Fig. 7.)

In policy combination scenarios, "avoid" methods produced the poorest cumulative outcome, which could be attributed to the fact that, while these policies reduce transportation demand, they are unlikely to eliminate enough car usage to achieve significant emissions reductions. A combination of these strategies might yield a 7.2 % reduction in emissions relative to the baseline scenario for all subsequent years post-2030.

Upon comparing the "shift" policy combination, it is noticeable that in the optimistic scenario, a more substantial reduction in generated emissions is achieved, with a 30 % decrease in 2030 relative to the base scenario values for that year, whereas the moderate policy combination yields only a 13 % reduction. By 2050, the emission reduction remains greater under the optimistic shift policy, achieving a 35 % decrease compared to the baseline scenario, whereas the moderate shift policy attains a 32 % reduction.

Initial implementation of "improve" policies yields poor results; nevertheless, these policies initiate significant emissions reduction post-2035, achieving a 52 % decrease by 2050.

In the context of the combination of all policies, optimal outcomes are achieved (by 2050, a 68 % reduction in emissions is projected relative to the baseline value for that year); however, these results remain inadequate for achieving climate neutrality, as they total 108,129 $ktCO_2$, representing a 74 % decrease from the baseline value in 2022. When considering the emissions attributable to freight transportation, this figure diminishes to 66 %.

5. Discussion

As urban populations increase, cities possess significant potential to tackle urban mobility demands and associated challenges in the shift towards sustainable transportation. A supporting tool was developed to

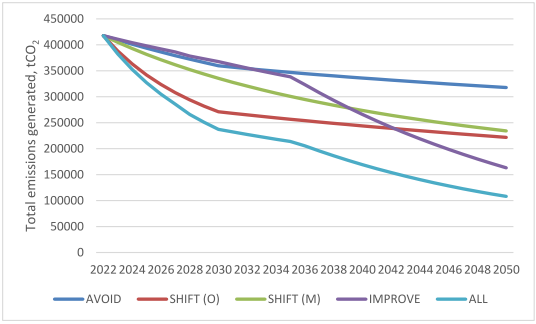


Fig. 7. Comparison of the impact of the developed policy combinations on the amount of generated emissions.

enable local decision makers to make data-driven decisions. The case study utilized data from the Riga Municipality. The analysis of the present situation revealed that, in the case of Riga, the predominant source of pollution occurs from private vehicles. This trend aligns with other literature and highlights a primary mobility issue. Although the observed level of emissions in Riga is expected to decrease by 2050, this is primarily due to population reduction.

Sensitivity analysis revealed that the examined parameters (freight transport demand and its annual change rate, population and its annual change rate, and car occupancy rate) significantly affect the outcomes. This consequently underscored the significance of data precision - in transport policy planning, policymakers face *deep uncertainty*, which can be defined as "(i) the external context of the system, (ii) how the system works and its boundaries, and/or (iii) the outcomes of interest from the system and/or their relative importance" (Marchau et al., 2019). A strategy to mitigate the effects of limited foresight on achieving future objectives is dynamic adaptive planning. This approach facilitates the formulation of an initial action plan while examining different development scenarios to identify potential adjustments to the earlier plan (Marchau et al., 2019). Ariza-Álvarez et al. employed the concepts of tipping points and adaptive pathways in scenario-building methodologies, wherein tipping points define the conditions that, if fulfilled in the future, will divert the current policy trajectory from its intended objective (Ariza-Álvarez et al., 2023). Although such an approach allows evaluating different scenarios as dynamic checkpoints that support policy-makers ability to adjust strategies according to changing conditions, it can be challenging for policymakers, as it requires knowledge of scenario analysis and adaptive planning (Ariza-Álvarez et al., 2023). Conducting workshops is another effective method to encourage local authorities to consider potential outcomes under deep uncertainty modelling. These workshops aim to identify current issues, clarify the links within the transport system, develop policies that foster sustainable transport development, and explore possible futures and uncertainties that may impact policy decisions ('Führer et al., 2024).

After discussing the significance of planning in the face of uncertainty, the following section assesses the particular policy scenarios applied in the Riga case. To evaluate the impact of various policies, multiple scenarios were created to examine the influence of both individual policies and policy combinations. Policies that covered all vehicle categories resulted in the most significant reduction in emissions. Both mode shift policies and initiatives such as the internal combustion engine ban policy (H1) and the increase in renewable fuel share (H2) demonstrated favourable outcomes, preserving the current distribution of vehicle usage while diminishing fossil fuel consumption (enhancement policies). The findings suggest that, to attain enhanced emission reductions, policymakers must propose regulations that encompass all vehicle categories (horizontal policies). The simultaneous shift to more efficient public transportation vehicles (PU1) and the decrease in municipal transport mileage (M1 and M2) contributed the least. This is primarily because these measures only target a minor segment of the transportation sector's emissions, compared to those that address private transport segment. Consequently, in the realm of public transportation, it is anticipated that as the significance of private transport diminishes and the relevance of public transport escalates, the influence of PU1 policies will increase. Additionally, the implementation of PU1 policies may indirectly support a mode shift as more convenient vehicles make public transportation more attractive, improving residents' perception and encouraging broader adoption. An examination of various policy combinations reveals that "avoid" policies produce the lowest emissions reduction outcomes. This is explained by the premise that, while avoiding travel does not produce emissions in the transportation sector, reducing travel demand is difficult to achieve in practice (Gulbe and Barisa, 2023). "Shift" policies resulted in superior emissions reductions, indicating that while the outcomes projected for 2050 in both scenarios (moderate and optimistic) are nearly identical, accelerating the phase-out of private transport can yield greater cumulative emissions savings by 2050. "Improve" policies resulted in significant emission reductions, primarily driven by the prohibition of internal combustion engine vehicles in 2035. In combination with other "improve" policies, it is important to acknowledge that the biofuel blending policy provides a clearly measurable reduction in emissions; however, to maximize its impact, the utilization of modern fuels in greater concentrations is essential. The most significant decrease in emissions from the transportation sector occurs when all policies are combined. This aligns with the findings of the literature review and suggests that decision-makers must adopt an extensive variety of policies to attain the most beneficial results.

In addition, from the literature analysis it was also concluded that utilizing diverse methodologies, formulated scenarios facilitate the establishment of a preliminary action plan; nonetheless, it is essential to recognize that the developed policies require frequent adjustments to reduce the effects of uncertainty (Ariza-Álvarez et al., 2023). Therefore, developing a monitoring program is essential, yet it is frequently weakly implemented (Mozos-Blanco et al., 2018), (Faherty et al., 2024). Moreover, monitoring helps track progress, address challenges, and optimize resources to achieve long-term goals.

6. Conclusion

Municipalities, being a local authority, have a significant impact on the quantity of emissions produced within the transportation industry. To assist municipalities in formulating further policies, a comprehensive examination of existing literature was undertaken, and a user-friendly scenario analysis tool was subsequently developed. The tool enables users to input the parameters that define the municipal transport sector and evaluate the anticipated modifications after the adoption of different policies. The tool will be publicly available in 2025 on the project's website (https://interreg-baltic.eu/project/commitclimate/) ('CommitClimate). The literature analysis concluded that advocating for non-fossil fuel transportation modes, such as bicycles, and adopting environmentally friendly technologies are the primary strategies to mitigate greenhouse gas emissions from the transport sector. The suggested model used the avoid-shift-improve method while formulating diverse policy instruments. The proposed model assists municipalities in making informed decisions by illustrating the long-term implications of their policies. The Riga municipality was selected as a case study.

The results demonstrated the effects of individual policies as well as the effects of various policy combinations on the quantity of emissions produced. The findings indicated that the transport of the Riga municipality represents a minimal proportion of the overall transport fleet; thus, the execution of policies alone within municipal transport cannot significantly improve the sustainability of the transport sector. The "avoid" strategies relate to a limited segment of the population, resulting

in consistently moderate outcomes. Secondly, the "shift" policies indicate that earlier policy implementation leads to more substantial overall reductions in emitted pollutants, despite the annual outcomes of these reductions being comparable by 2050. Thirdly, "Improve" policies launch at a slower pace but show the most significant long-term effects due to technical progress. The combined effect of these policies can yield a substantial decrease in emissions; yet the outlined scenario is insufficient for attaining climate neutrality by 2050. Potential solutions include minimizing transport demands through the development of intelligent urban land use planning and the implementation of the 20-min city concept.

Although the model was tested with Riga municipality data, the method and analysis apply to other cities attempting to assess the effects of transport policies under uncertainty, particularly those with similar data constraints, transport structures, or climate objectives.

6.1. Limitations

The current model possesses certain limitations that impact the outcomes. A limitation is a certain level of uncertainty that prevents the accurate description of the baseline scenario. The demand for freight transit is simplified, with the assumption that freight transport demand is stable. In other municipalities where freight transport is essential, more research into the influence of local policies is needed. Furthermore, different assumptions outlined in section 3.4 influence the accuracy of the results. To mitigate the effects of this error, further study should be undertaken on the trends in transport demand, along with supplementary surveys in the specified municipality. A further limitation is that this methodology evaluates policy implementation solely from an environmental perspective, specifically, the quantity of emissions reduced. Subsequent tasks entail doing a case study and including economic variables into the model. This would allow communities to evaluate precisely the costs related to the proposed regulations and determine the most effective alternatives that cut costs per metric ton of CO_2 emissions. The created approach is applicable across several municipalities, suggesting that a prospective future study could involve a comparative analysis with more municipalities.

CRediT authorship contribution statement

Alīna Safronova: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aiga Barisa:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This work has been supported by the Interreg Baltic Sea Region Programme project CommitClimate [grant number #C026]. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ANNEXES

ANNEX 1

The calculation of generated emissions is conducted using Equation (1).

$$E = A \times EF, \tag{1}$$

where.

E total emissions, tCO_2/year.

A energy consumption, MWh/year;

EF emission factor, tCO_2/MWh.

In cases where the user had access to only the vehicle number, the annual energy consumption was calculated using equation (2):

$$A = N \times M \times EC \times FE \div 100000, \tag{2}$$

where.

N number of vehicles on the street;

M annual mileage of the vehicle, km;

EC energy content, MWh/t;

FE fuel economy of the vehicle, kWh/100 km.

The volume of generated emissions was determined using statistical data, while subsequent alterations in the quantity of statistical data were computed using the compound annual growth rate outlined in formula (3).

$$AGR = \left(\left(\frac{AD_{ni}}{AD_{n1}} \right)^{\frac{1}{N}} \right) - 1 \tag{3}$$

Future alterations were estimated using formula (4):

$$AD_n = AD_{(n1)} \times AGR \tag{4}$$

Kur

AGR – annual growth rate.

N – number of collection years.

AD_n – activity data in the projection year n

$AD_{(n1)}$ – activity data in the first year

The fuel economy information is derived from a research conducted by Ankur et al. (Khan Ankur et al., 2022).

ANNEX 2

H1 - Starting from 2035, the ban on internal combustion engines policy stipulates that alternative engines will replace old engines of this kind.

H2 - Increasing the share of renewable fuels policy begins in 2030, targeting a biofuel mix ratio of 30.5 % for diesel and 7.8 % for gasoline. The values were selected based on the previous example set by Sweden, where this biofuel blend rate persisted until 2023 ('Global Commodity).

H3, H4 - Mode shift policy envisages that citizens change their travel habits and choose to use public transport and active modes of transportation more often. In the case of moderate mode shift policy (H3), it is planned to reduce the use of private cars by 25 % of the existing volume, while in the case of optimistic mode shift policy (H4), the reduction of the proportion of machine use compared to the current situation will reach 50 %. In such scenario, the distribution between private cars, public transport, pedestrians, cyclists, micro-mobility solutions and motorized two-wheelers will be 36 %, 43 %, 13 %, 4 %, 1 %, 2 % in the optimistic scenario and 54 %, 31 %, 9 %, 3 %, 1 %, 2 % in the moderate scenario.

M1 - Moderate reduction of municipal transport mileage (by 10 %) starting from 2027.

M2 - Optimistic reduction of municipal transport mileage (by 20 %) starting from 2027.

M3, PU1, PR1 - Starting from 2027, the transition to more efficient vehicles policy stipulates that more efficient vehicles will replace old vehicles for each type of fuel.

PR 2 - Increase of average car occupancy rate to 2 by 2050.

TD1 - Using the travel reason assumption, the model calculates the percentage of the average daily distance travelled (km/day/person) allocated to each trip purpose. Work-related distance is calculated using survey findings, and respondents are divided into groups based on their opinions about remote work (Gulbe and Barisa, 2023). The full potential of the survey data to determine the rate at which remote work lowers travel is considered.

TD2 - The operating principle is like the previously described remote work policy operating principle. The difference lies in the assumptions used about the potential for reducing travel (Gulbe and Barisa, 2023). It should be noted that because the survey did not include "services" as a travel purpose category, the data is utilized from the "shopping" travel purpose group to estimate the possible reduction in distance travelled.

ANNEX 3

Table 3.1
Trip distribution by type of vehicle (Jurijs Kondratenko, 2022)

	Share of trips, %	Average mileage of a trip, km
car	45.334	13.65
public transport	12.24	8.18
walking	2.80	1.51
cycling	36.32	6.09
motorcycles/snowmobiles	1.66	13.65
micro-mobility	1.66	1.6

Table 3.2
Trip distribution by reason (Jurijs Kondratenko, 2022)

	Trips share by travel reason, %
work and study	33.21
shopping	26.78
Leisure	29.94
Accompany	8.19
Other	1.88

Data availability

Data will be made available on request.

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